

DIDACTIC GUIDE FOR TEACHERS

DIG-MAN: Integration of digital tools into product development and manufacturing education

Title of guidebook: Didactic guide for utilization of digital manufacturing tools for product development and manufacturing (ProDeM) in higher education



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I. INTRODUCTION

I.1. General objectives of PRODEM education

Teaching of product development requires various digital tools. Nowadays, the digital tools usually use computers, which have become a standard element of manufacturing and teaching environments. In this context, an integration of computer-based technologies in manufacturing environments plays the crucial and main role, allowing to enrich, accelerate and integrate different production phases such as product development, design, manufacturing and inspection. Moreover, the digital tools play important role in management of production. According to Wdowik and Ratnayake (2019 paper: Open Access Digital Tool's Application Potential in Technological Process Planning: SMMEs Perspective, https://doi.org/10.1007/978-3-030-29996-5_36), the digital tools can be divided into several main groups such as: machine tools and technological equipment (MTE), devices (D), internet(intranet)-based tools (I), software (S). The groups are presented in Fig. I.1. Machine tools and technological equipment group contains all existing machines and devices which are commonly used in manufacturing and inspection phase. The group is used in physical shaping of manufactured products, measurement tasks regarding tools and products, etc. The next group of devices (D) is proposed to separate the newest trends of using mobile and computer-based technologies such as smartphones or tablets and indicate the necessity of increased mobility within production sites. The similar need of separation is in the case of internet(intranet)-based tools which indicate the growing interest in network-based solutions. Hence, D and I groups are proposed in order to underline the significance of mobility and networking. These two groups of the digital tools should also be supported in the nearest future by the use of 5G networks. The last group of software (S) concerns computer software produced for the aims of manufacturing environments. There is also a possibility to assign the defined solutions (e.g. computer programs) to more than one group (e.g. program can be assigned to software and internet-based tools). The main role of tools allocated inside separate groups is to support employees, managers and customers of manufacturing firms focused on abovementioned production phases. The digital tools are being developed in order to increase efficiency of production, quality of manufactured products and accelerate innovation process as well as comfort of work. Nowadays, digital also means mobile.

Universities (especially technical), which are focused on higher education and research, have been continuously developing their teaching programmes since the beginning of industry 3.0 era. They need to prepare their alumni for changing environments of manufacturing enterprises and new challenges such as Industry 4.0 era, digitalization, networking, remote work, etc. Most of the teaching environments nowadays, especially those in manufacturing engineering area, are equipped with many digital tools and meet various challenges regarding an adaptation, a maintenance and a final usage of the digital tools. The application of these tools in teaching needs a space, staff and supporting infrastructures. Universities adapt their equipment and infrastructures to local or national needs of enterprises and the teaching content is usually focused on currently used technologies. Furthermore, research activities support teaching process by newly developed innovations.

Figure I.2 presents how different digital tools are used in teaching environments. Teaching environments are divided into four groups: lecture rooms, computer laboratories, manufacturing laboratories and industrial environments. The three groups are characteristic in the case of universities' infrastructure whilst the fourth one is used for the aims of internships of

students or researchers. Nowadays lecture rooms are mainly used for lectures and presentations which require the direct communication and interaction between teachers and students. However, such teaching method could also be replaced by the use of remote teaching (e.g. by the use of e-learning platforms or internet communicators). Unfortunately, remote teaching leads to limited interaction between people. Nonverbal communication is hence limited. Computer laboratories (CLs) usually gather students who solve different problems by the use of software. Most of the CLs enable teachers to display instructions by using projectors. Physical gathering in one room enables verbal and nonverbal communication between teachers and students. Manufacturing laboratories are usually used as the demonstrators of real industrial environments. They are also perfect places for performing of experiments and building the proficiency in using of infrastructure. The role of manufacturing labs can be divided as:

- places which demonstrate the real industrial environments,
- research sites where new ideas can be developed, improved and tested.

Industrial environment has a crucial role in teaching. It enables an enriched student experience by providing real industrial challenges and problems.

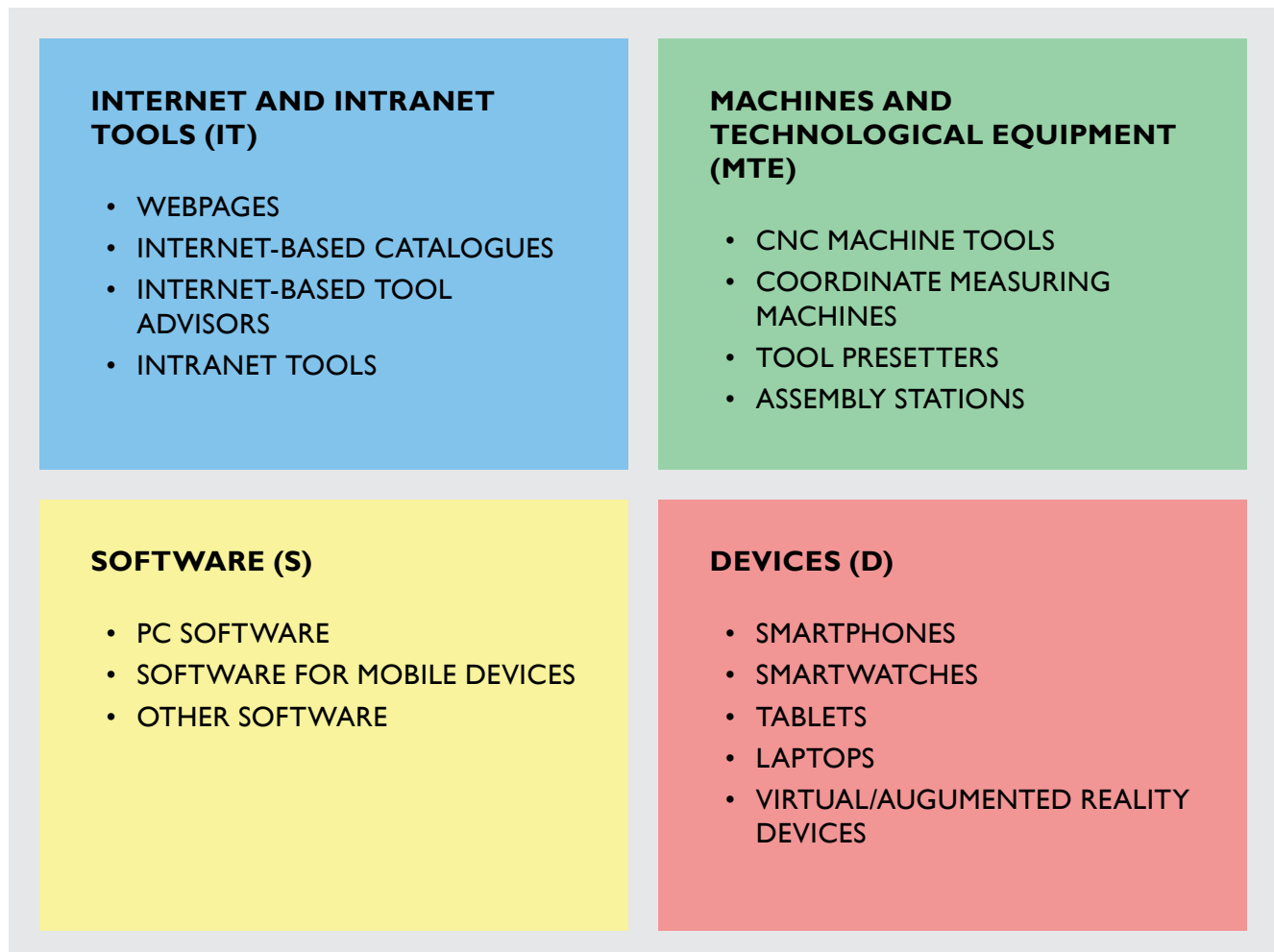


Fig. 1.1. Types of digital tools

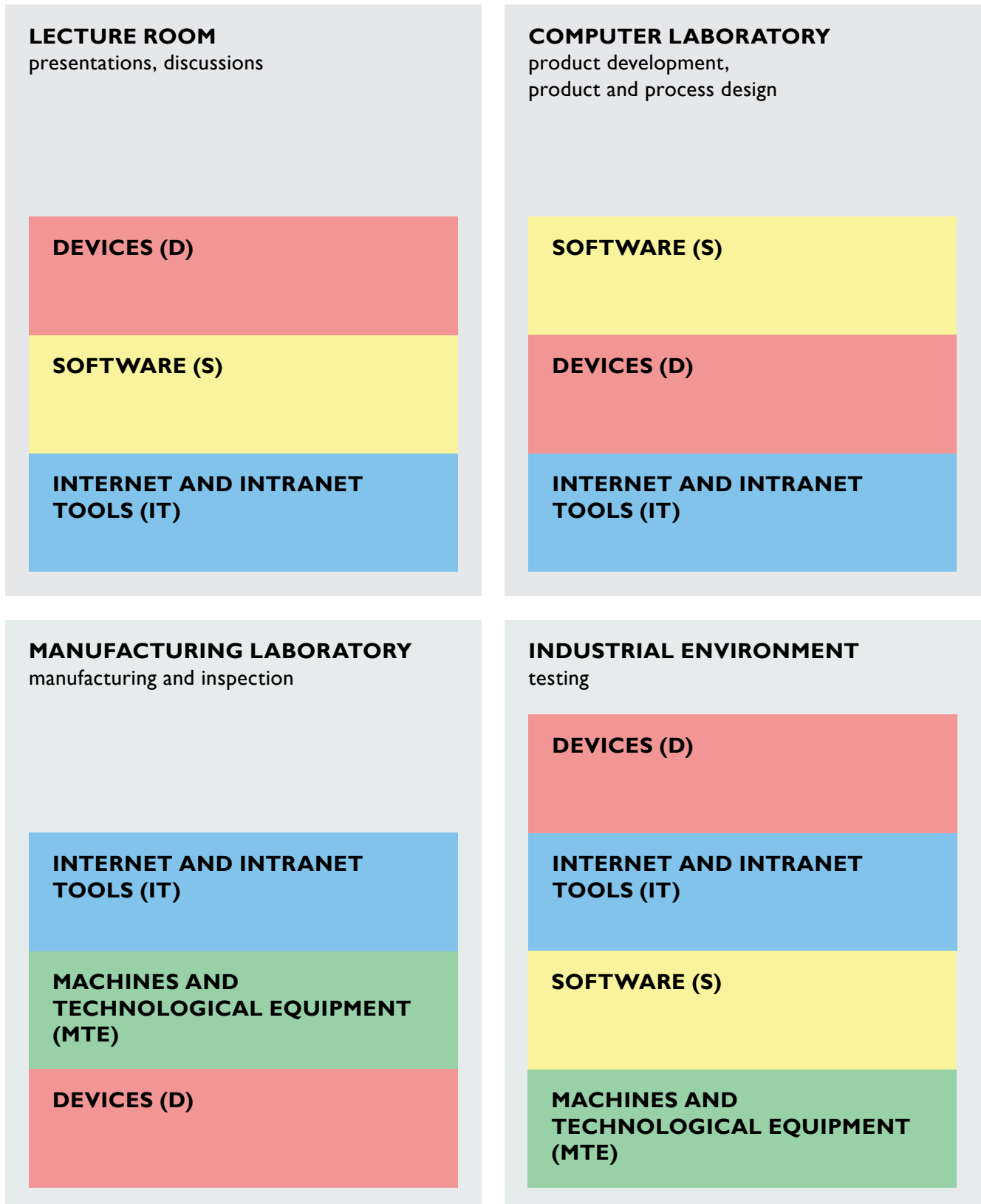


Fig. 1.2. Application of different digital tools in various teaching environments

Methodology of teaching is usually based on the local, national and international requirements of industrial companies. The DIG-MAN project partners have been analysing the local educational conditions (Table I.1) in order to produce results which are useful for individual institutions, the whole consortium and other stakeholders in Europe.

University/ partner	
Country/region (Important clusters/ associations of partners)	Estonia/southern and middle part of the country
Exemplary relevant skills of PRODEM master students	manufacturing and mechanical engineering
Relevant Industry sectors	Metal fabrication. Mainly of the subcontracting nature. Component manufacturing to some worldwide known brands in automotive as well as in home appliances
Relevant webpages of organizations presenting educational offer for students	http://te.emu.ee/en/main-page/

Table I.1. The relevant digital tools-related skills of PRODEM students and their general usefulness in regional industry sectors

University/ partner	
Country/region (important clusters/ associations of partners)	Poland/Subcarpathian Voivodeship https://przemysl.prz.edu.pl/klastry
Exemplary relevant skills of PRODEM master students	design and advanced development of components, technological process planning including complex and modern processes, advanced programming including advanced CNC programming and postprocessors, modern quality control skills including automation of measurements
Relevant industry sectors	aerospace sector, automotive sector, IT sector supporting PRODEM Source: http://rot.podkarpackie.pl/images/assets/files/bazawiedzy/opracowania_wlasne/Wiodce-brane-wojewdztwa-podkarpackiego---inteligentne-specjalizacje-2018_ duy.pdf
Relevant webpages of organizations presenting educational offer for students	www.prz.edu.pl https://wbmil.prz.edu.pl/ https://w.prz.edu.pl/en/ https://dwm.prz.edu.pl/en/

Table 1.1. The relevant digital tools-related skills of PRODEM students and their general usefulness in regional industry sectors

University/ partner	
Country/region (important clusters/ associations of partners)	<p>Norway/Rogaland https://www.uis.no/en/lean-6s-learning-academy https://www.uis.no/nb/nettop-avdeling-utvikling-av-digitale-laeringsressurser-ved-uis https://www.uis.no/nb/nettverk-smartby-forskning</p>
Exemplary relevant skills of PRODEM master students	<p>product development (use of simulation and 3D printing), design (for additive layer manufacturing), manufacturing/fabrication and life cycle support (inspection and maintenance), technological process planning including manufacturing and fabrication/construction (Building information modelling – BIM), ISO and conversational programming of CNC machines, modern quality control and measurement with coordinate measuring tools and NDT simulations with CIVA, advance NDT equipment use (Ultrasonic)</p>
Relevant industry sectors	<p>https://www.sintef.no/manufacturing/manufacturing-engineering-sub-contractors-for</p> <ul style="list-style-type: none"> • offshore oil and gas industry • wind energy industry
Relevant webpages of organizations presenting educational offer for students	<p>https://www.uis.no/en https://www.uis.no/en/finn/tags/studies-1 https://www.uis.no/en/student</p>

Table 1.1. The relevant digital tools-related skills of PRODEM students and their general usefulness in regional industry sectors


University/ partner	
Country/region (important clusters/ associations of partners)	Lithuania/Kaunas https://linpra.lt/ https://ftz.lt/apie-kauno-lez/ http://kaunomtp.lt/ http://bacc.lt/
Exemplary relevant skills of PRODEM master students	development of production processes (CAM, robotisation), development of new products (CAD, CAE, 3D printing), production planning (CAP), control and optimisation, quality assurance and control (CAQ)
Relevant industry sectors	manufacturing, automotive sector, industrial automatisaton, rubber and plastics, fabricated metals, machinery” production Source: https://apzvalgos.vz.lt/2019/pramone/proгноzes/skaitmenine-pramone-revoliucijos-laikai/#1103
Relevant webpages of organizations presenting educational offer for students	https://ktu.edu/ https://en.ktu.edu/ https://midf.ktu.edu/ https://fmed.ktu.edu/

Table I.1. The relevant digital tools-related skills of PRODEM students and their general usefulness in regional industry sectors


University/ partner	
Country/region (important clusters/ associations of partners)	<p>Italy/Emilia-Romagna https://www.confindustriaemilia.it/home, https://mech.clust-er.it/en/ http://www.unife.it/tecnopolo/cento, https://www.comune.cento.fe.it/ https://www.confindustriabrindisi.it/, https://www.centocultura.it/ http://www.associazioneforis.it/, https://www.ilmantelloferrara.it/ https://www.itstec.it/, https://www.luiss.it/%E2%80%8E https://www.phormamentis.it/it/, https://www.sfc.it/ https://www.elsa-italy.org/formazione/study-visits/, http://www.unife.it/it http://www.sistemaidea.org/, https://agrifood.clust-er.it/ https://build.clust-er.it/, https://feder.bio/, https://www.gruppogema.it/</p>
Exemplary relevant skills of PRODEM master students	<p>IFTS course (Post Diploma – non tertiary education), secondary level course in Mechanical Design - EQF IV - Training Title: TECHNICAL SUPERIOR SPECIALIZATION CERTIFICATE: read and understand mechanical drawings (symbols, dimensional models, measurements, etc), Knowledge of materials used and their performance reaction, Ability to conceive mechanical design, Ability to realise project (from the idea to the final product), Respect Quality and Safety Standards, Realise prototypes, Reverse Engineering, 3D printing</p>
Relevant industry sectors	<p>manufacturing, automotive sector, industrial automatisaton, packaging, rubber and plastics, fabricated metals, machinery and equipment production, engine and hydraulics components, agrifood (agriculture machineries, food packaging), housing (machinery for building and ceramic), health care (electro-medical equipment, packaging)</p>
Relevant webpages of organizations presenting educational offer for students	<p>http://www.centoform.it/courses/courses/256</p>

Table I.1. The relevant digital tools-related skills of PRODEM students and their general usefulness in regional industry sectors

I.2. Terminology in PRODEM education

PRODEM education requires a general understanding of production phases which are analyzed within The DIG-MAN project. The chapter presents a relevant terms which are used in product development, design, manufacturing and inspection phases. They can help to understand the meaning of the production phases in PRODEM education.

I.2.1. Product development terms

Product development

A general definition of product development phase concerns all activities which lead to formulation of the final properties, shape and manufacturing techniques, and in addition activities regarding improvement of a product.

FEM software (Finite Element Method software)

Software that enables advanced calculations of stress, deformation, displacement, transfer (e.g. heat). Calculations are based on the finite elements of a product's model. The FEM software helps to solve complex problems during product development phase. It automates time consuming computations and helps to visualize physical phenomena. There are various software tools delivered by different producers and their final use depends on the implemented algorithms. The usage of FEM software requires the proper interpretation of obtained results and their adaptation to real-world conditions. Some of the examples of FEM software tools are as follows: NASTRAN by MSC Software, ADINA by ADINA R&D Inc., ANSYS by ANSYS Inc., etc.

Material selection software

Materials engineering is a discipline that is developed very fast nowadays. A wide range of advanced materials is available for product developers and designers. Their classification, proper selection of properties, market availability are taken into account in the development of software tools. There are different software tools which enable and ease the materials selection. The examples are as follows: Alloyselect (<https://alloyselect.com>), Granta selector (<https://www.ansys.com/products/materials/granta-selector>),

Concept generation and analysis

Product development phase requires to analyze at least several variants of a product. This process is named as a concept analysis. The variants are compared by a designer in order to meet requirements of a market and technological process. Concept analysis requires verification of materials, shape of elements, connections of elements in proposed assemblies, constraints of manufacturing environments (e.g. available production equipment and machines) as well as newest trends and expectations of customers. The final decisions regarding a product are made on the basis of all abovementioned factors.

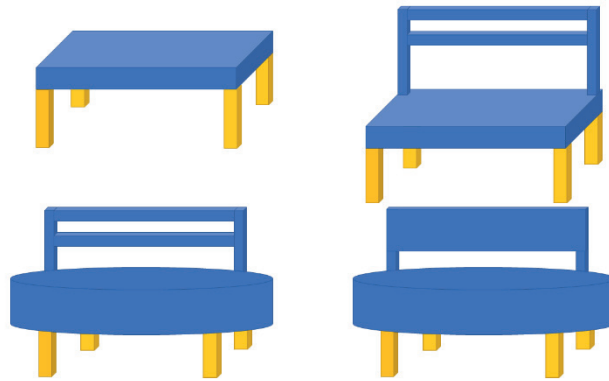


Fig. 1.3. A product concept generation (four variants of a product)

Data exchange between designers

Sharing of product concepts between people requires an access to different files. CAD files, calculation files, etc. can be shared. Software tools use many formats of files depending on the type of software. Because of this, the data files should be adapted to the used software tools or the tools are adapted to the used data files.

Product lifecycle

Product lifecycle refers to the period starting from the idea up to the final product recycling. A product which is introduced to a market goes through different lifecycle phases as indicated in Fig. 1.4.

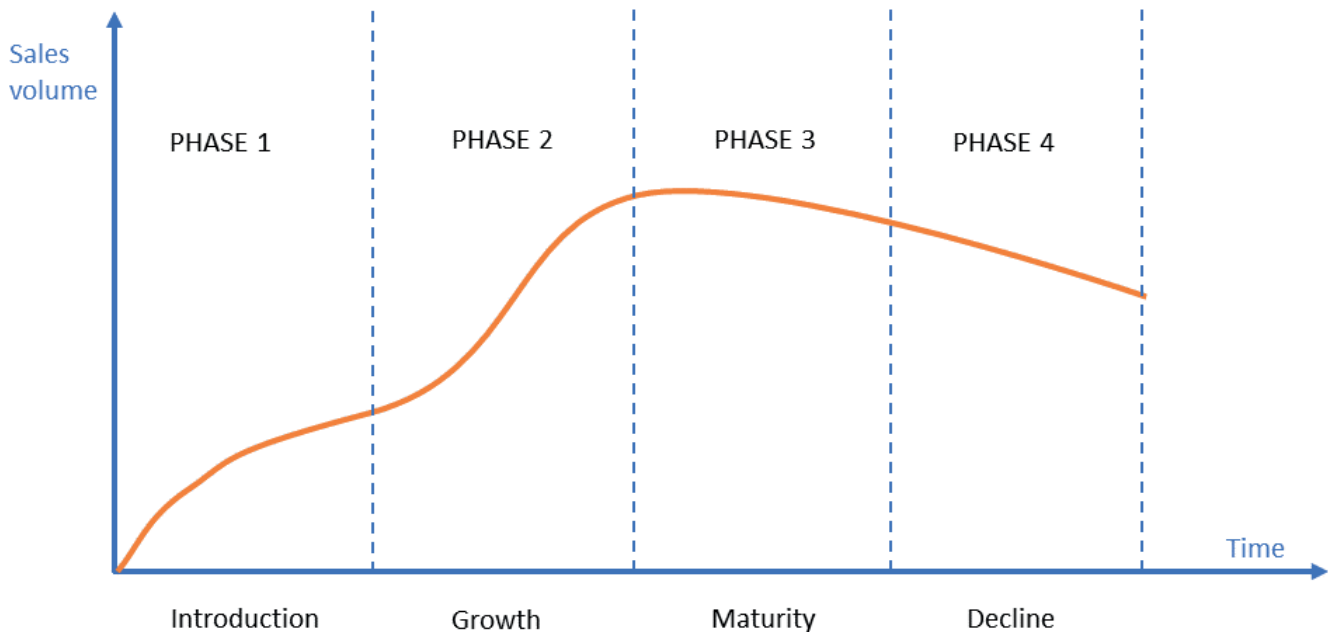


Fig. 1.4. A product lifecycle phases

Source: self-prepared figure on the basis of <https://productlifecyclestages.com>

Product virtual reality presentation

Virtual reality is a promising technique that can help to develop various products in the area of mechanical engineering. Virtual environment increase safety of testing and may reduce the total testing cost.



Fig. 1.5. An example of a product testing in the virtual reality

Product customization

Nowadays, customers require a frequent changes of used products or their far-reaching adaptation to the specific customers' needs. It is, inter alia, caused by accessibility to various products in open markets. This approach is based on the flexible production environment which can be adapted to changing expectations of customer.



Fig. 1.6. An example of a product customization: tool used for writing

Product reliability development and testing

Reliability of products may be shaped in product development phase. If the structure of reliability system is known, and reliability of separate elements is defined, the reliability of the whole system can be calculated. Reliability of products can also be tested in the case of series of products of the same type.

Product standardization

Standardization enables manufacturing and assembly by the use of standard elements. It accelerates production and enables manufacturing of new products.

1.2.2. Design terms

Computer – Aided Design (CAD)

A general concept where computer is used to capture, refine, reproduce and spread design intent of a specific physical object. Mainly referring to technical subjects like mechanical engineering, automotive, aeronautical and production engineering etc. Where it is used to design and detail parts and assemblies. Specialized modules for pneumatics, hydraulics and electrical engineering common supplements to majority of the mainstream CAD packages.

It is custom nowadays to speak about 3D modelling in mechanical engineering. Where as in construction engineering generation of 2D drawings is the main intent.

There are numerous other specialties using computer graphics to their benefit. Medicine, cinematography, digital arts and so on to name a few. Creation of artistic illustrative shapes is commonly not considered as CAD. The term being mainly used in relation to technical disciplines.

Geometry types

CAD geometry is traditionally divided into three main categories.

- Wireframe geometry that consists of curves (points, lines, arcs, and splines). This type of geometry includes only information about the edges of the part. It is not possible to shade the models. Nowadays it is somewhat obsolete type of geometry that is being occasionally used with straight forward prismatic geometry;
- Surface geometry can be imagined when an infinitely thin “skin” is stretched over the wireframe model. This way faces are generated in addition to edges that describe the model. Surface modelling is the main tool for modeling complex and organic shapes common to automotive, aeronautical and consumer goods industries;
- Majority of the models today are simulated as solids. It is arguably the easiest and most natural way of processing 3D data. Solids are entities that have interior structure. In essence solids are created from 2D profiles either by extrusion or revolution.

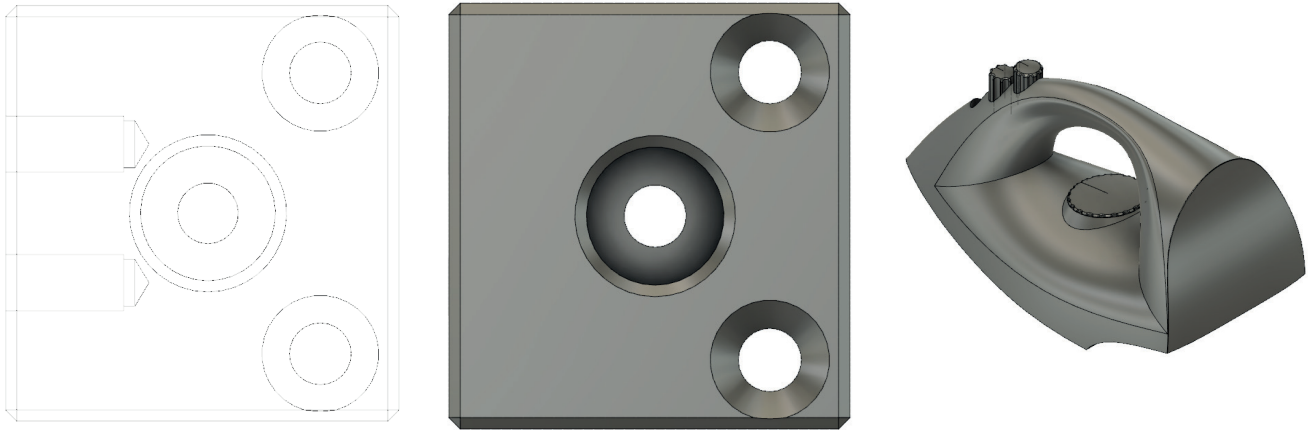


Fig. 1.7. Geometry Types. From the left to right: wireframe, solid (B-rep), surface model

Feature (Geometrical feature)

According to international standard ISO 14660-1 Geometrical Product Specifications (GPS) - Geometric features - Part 1: General terms and definitions the term feature refers to geometrical entities i.e. points, lines, and surfaces.

In computer aided design the term “feature” has more wide spread usage. It is also used for bosses, holes, slots, key ways etc. that can be found on a part or detail. Some solid modelling packages use the term “feature” to describe modelling operations too. For instance in a wide spread solid modelling programme “SolidWorks” there is a central component of the Graphical user interface named “Feature tree”.

In conclusion it is an overall term used in several contexts related to CAD/CAM/CNC technology, where it can take different meanings in different areas. For example: in CNC context one might speak about machining a feature, whereas in design one might model a lofted feature.

Solid modelling

Arguably it is the most predominant computer aided modeling concept used in mechanical engineering. This is said in comparison with wireframe and surface modeling concepts.

Solids occupy a closed volume of the space this adds possibilities for different types of analyses and simulations to be performed. For example, assigning physical material properties enables to simulate the possibility for mechanical simulations and so on.

In their basic setup solids are composed of features, sometimes referred to as items. Most common of those are faces, edges, cuts and bosses.

In that way solid modelling can be visualized as first starting with the base feature and then applying different operations like additions, removals and modifications to alter the geometry towards the final shape of the part.

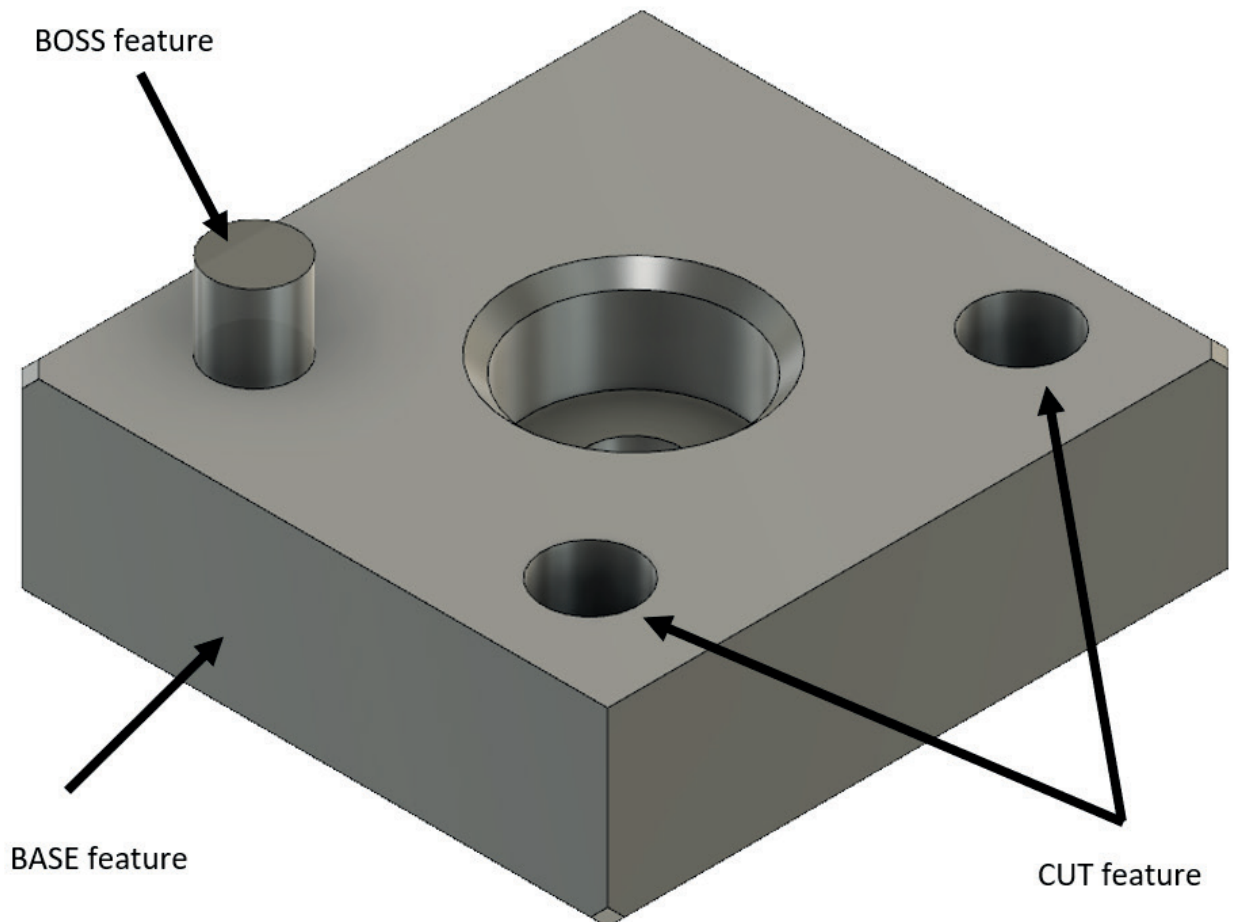


Fig. 1.8. An example of a solid model

Surface modeling

In general in heavy industry, machine technology and in mechanical engineering the shape of the parts tend to be prismatic like, straight edges, perpendicular corners, cylindrical holes etc. Although it is relatively easier to make but definitely not that comfortable to handle and pleasing to the eye. In consumer product design shapes are more organic. Sudden changes in the flow of the surfaces are not preferred. For that the concept of surface modelling can be utilized.

Surface modeling is a modelling approach useful when modelled geometry consists of smooth surface with literally invisible transitions between them. Fundamental to this modelling method is the concept of the spline. That is a curve with variable curvature. Spline can be bent and driven through control points.

An alternative mode of surface modeling is the usage of faceted type geometry. Where each face can be edited separately and the software takes care of the transitions. Like for an example T-spline body in the Fusion360 CAD/CAM program.

Top-down design

Modelling approach where the bulk of design intent is captured on a single base sketch. All consecutive components are built on this. Thus design changes made on the original base sketch will transmit through the whole assembly. The original sketch is equipped with the necessary relations and dimensions.

This is in opposition with the approach where every single component is built separately or independently. Ending up in a design where modeling information is dispersed among components.

Generative Design

Based on manufacturing and performance needs a modern method of design creation or refinement.

When using shape optimization, part is first modeled using traditional methods, then a set of restrictions are applied and algorithms are used to optimize the topology of the geometry for example for weight reduction. It is implemented in conjunction with the additive manufacturing technology since the shape optimized geometry doesn't lend itself to traditional machining methods easily.

In generative design there is no need for full initial geometry. Basically the 3D geometry is created by the generative algorithm based on the initial loading constraints and geometry entities one needs to preserve or obstacles to be avoided. Generative design can have manufacturing method set up as an initial condition. Meaning that the design will yield a solution that can be manufactured using an existing technology.

Parametric modeling

In a parametric modelling process design history is being recorded and all operations have a parent-child relationship. This way a model is built up with features that have a straight forward relations to each other. For example, if a cut feature is modeled into the model, whenever designer is going back and altering the dimensions used for the circle the cut feature will also change. This parametric chain can flow through the entire modeling process i.e. when the part is fixed into assembly.

Sometimes making parametric edits later on in the design process is not the best option. This be especially true when several other features downstream in the modelling history are made dependent. Altering parameters in this case can result in un-solvable geometry and in a timely error detection.

Direct modeling

Opposed to parametric modeling concept in direct modeling the modeling operations are applied to "plain geometry". It is not into account the modeling history and relations to other geometrical entities. Depending on the modeling software direct modeling operations might be saved to the design history but not necessarily.

In essence direct modelling techniques are following. Pulling – a line pulled in space will create a surface. Pulling surface will create a 3D solid. Moving – faces, edges and vertexes can be moved i.e. geometry altered in this manner. Combining – Boolean operation with geometry entities. Deleting – adjacent faces can be removed.

It is quite common practice that direct modeling is used in conjunction with the parametric modeling. Where it is used at the later stage of design process where minor changes, tune ups must be introduced.

Majority of the CAD-packages at the market today have both options included i.e. parametric and direct modeling. There are few that are dedicated to one method only.

Reverse engineering

Reverse engineering when referred in the context of production engineering stands for a set of operations for recreating 3D digital model out of a physical body. In its most basic setup the process is started with capturing the geometry of the original body. This can be accomplished either by photography, physical measurements or some means of digitizing technique. From that original geometry a CAD model is built using either parametric or direct modeling approach.

When a physical object is being digitized with the dedicated measuring system (tactile, optical or x-ray scanning) it results in a representation of the physical body in the form of the point cloud. Considerable number of points fixed in space representing the outer and inner features of the body. Inner geometry will be revealed only with the x-ray scanning. A “zoomed in” and “zoomed out point cloud example is given below at Fig. I.9, I.10.

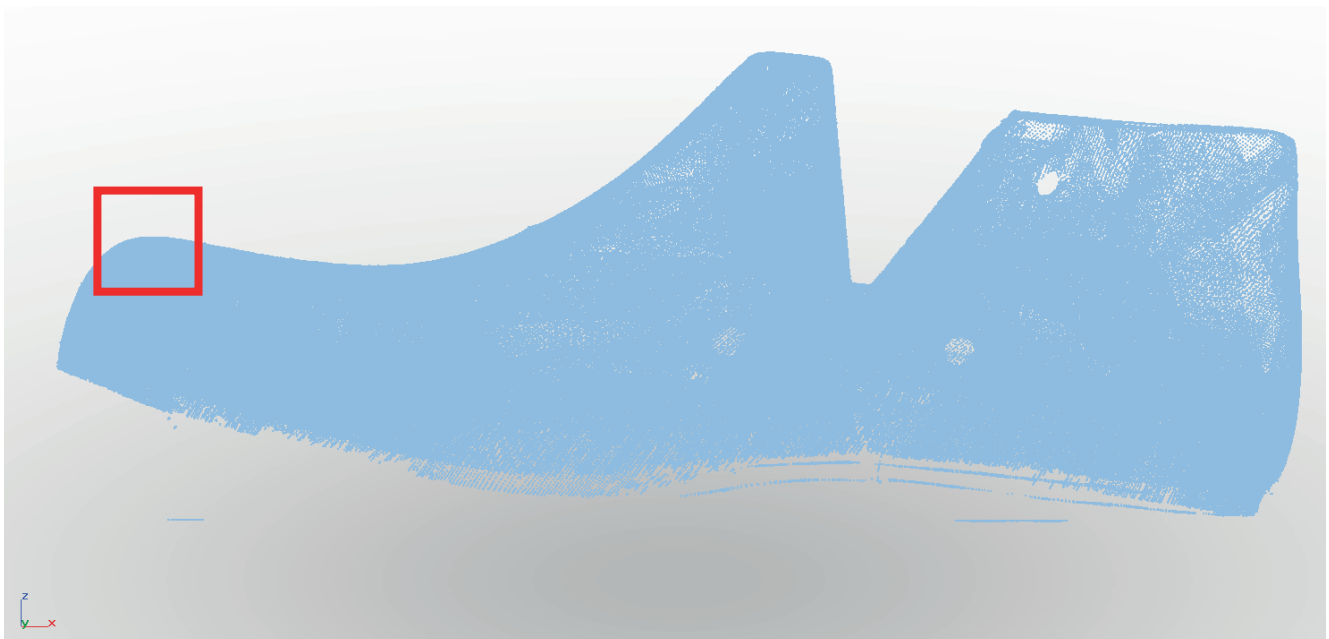


Fig. I.9. Point cloud representation of a physical object. Here there are close to 1 million points in the model

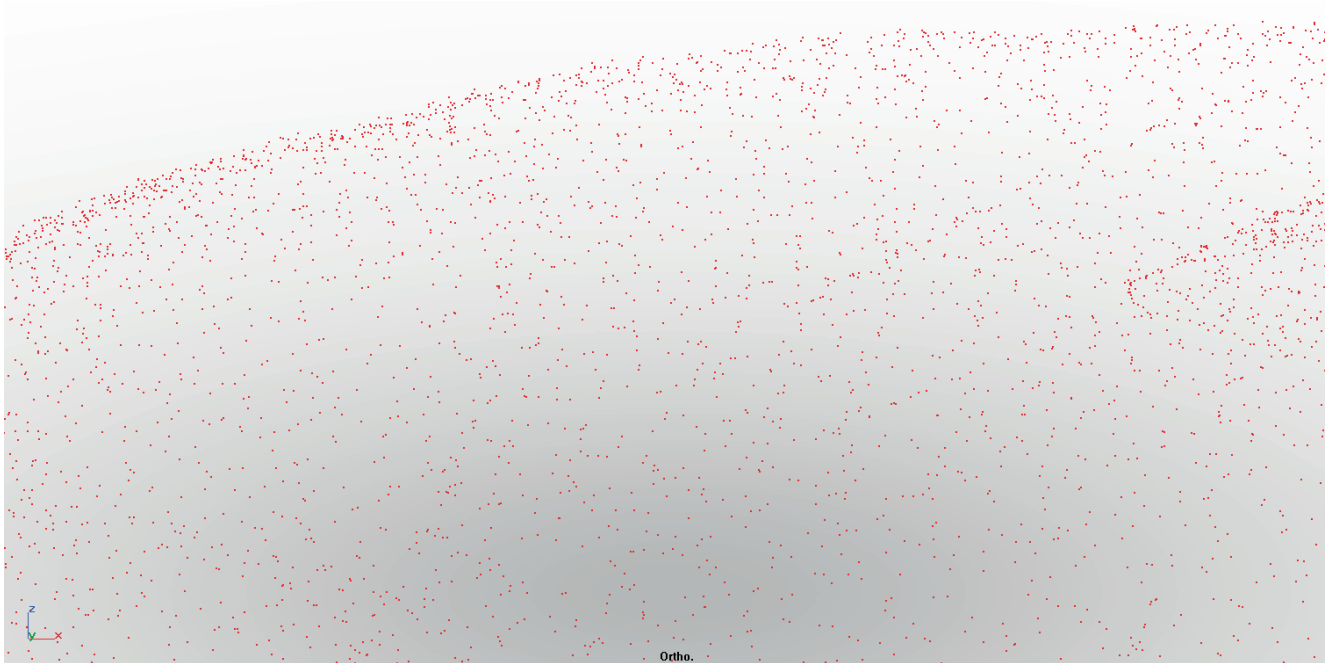


Fig. 1.10. Zoomed in section to bring out the discrete nature of the point cloud. Points are shaded in read for the illustrational purposes.

Common next step from point cloud model is a polygon mesh model. Essentially this consists of miniature facets that have been created when point cloud points were interconnected with straight lines. The polygon mesh model facets can have either three sides or four. In former case they are referred to as triangular and in the latter case quad meshes.

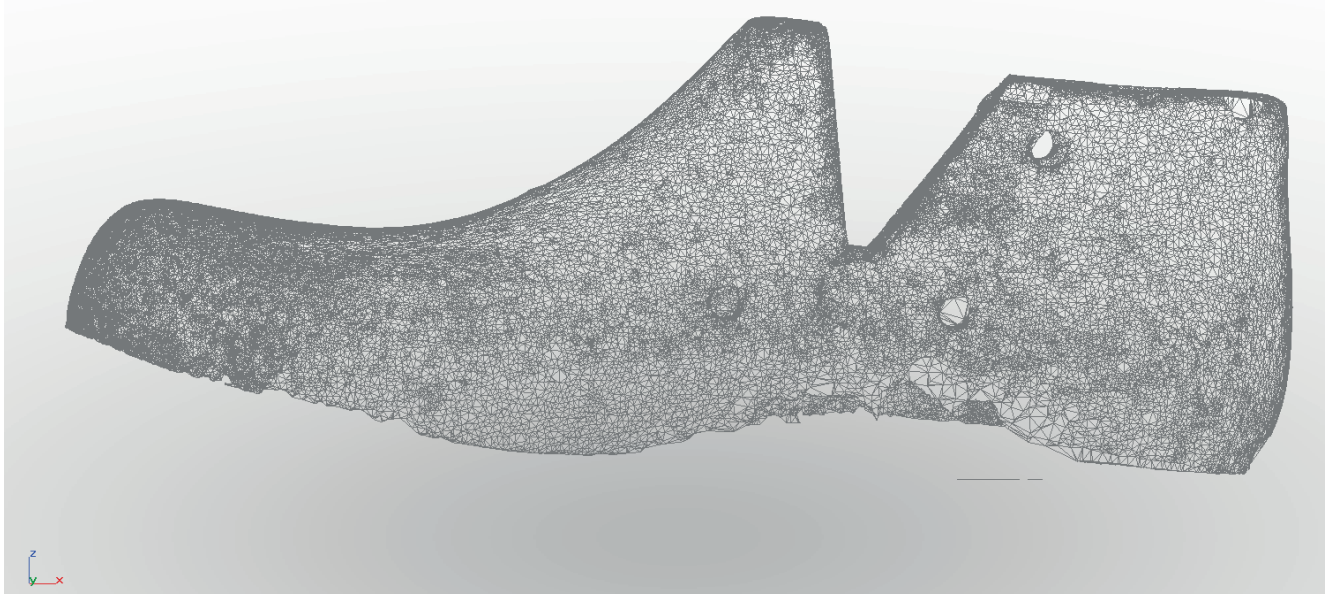


Fig. 1.11. Polygon mesh model

I.2.3. Manufacturing terms

Manufacturing

Process of technological process planning, CNC programming and shaping of products with the use of machines and technological equipment. Manufacturing phase in mechanical engineering is based on the know-how of manufacturing firms and knowledge of process planners which have been acquired over generations. Manufacturing phase requires an application of machines and this phase is strictly dependent on overall development of technology.

CNC machine tool

CNC machine tool (computer numerical controlled machine tool) is a machine tool controlled by a dedicated, open or network-based CNC control unit. It is usually used in technological processes of mechanical machining such as turning, milling, grinding, electro

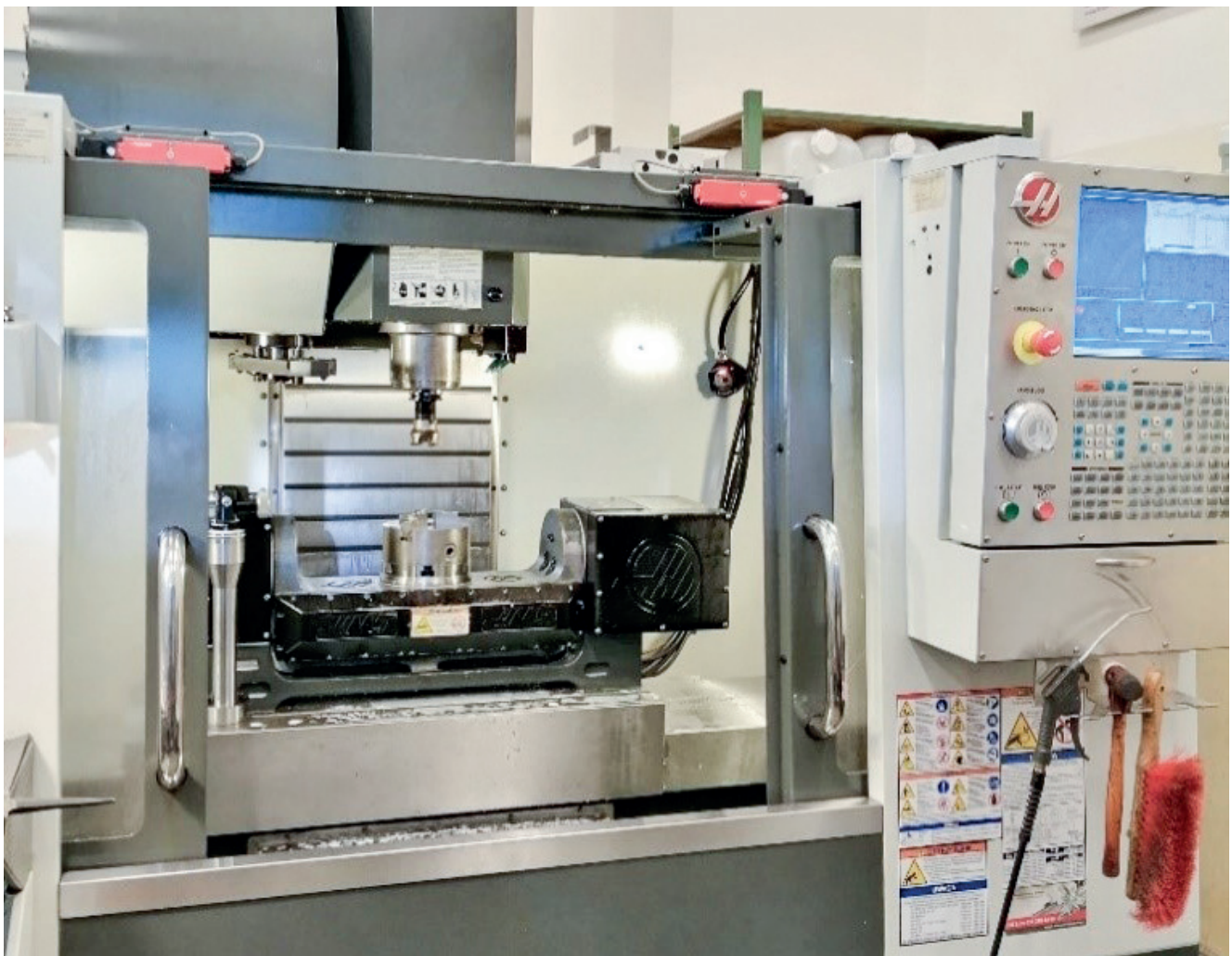


Fig. I.12. CNC machine tool

discharge machining, hybrid machining, drilling, laser cutting, water jet cutting, etc. CNC machine tool enables to automate technological operations and tasks by the use of tool/head path control in the defined coordinate system. In this context the moves of machine tool's elements are not generated by the manual control of operator (human) as it is in the case of conventional machine tools but they are controlled by CNC controller on the basis of the developed programs dedicated for machined workpieces. CNC machine tools are used for subtractive machining operations, additive processes and also in other processes such as forming or welding. CNC machine tools have enabled to automate machining processes and caused the increased repeatability of final parts.

Nowadays, machine tool companies develop very complex machines often using dedicated modules delivered by different producers. There are also machines which incorporate different processes in one machine tool. Machine tools are also adjusted to conditions of Industry 4.0 requirements by the increase of connectivity, reconfigurability, reliability. There are several main machine tool-related areas which could be interesting for master students such as development and design of machine constructions for advanced processes (e.g. micromachining, hybrid machining, high speed machining), development of communication techniques and tools between CNC machine tools, application of new materials, development of monitoring systems, software advancements and new solutions, implementation of coordinate measurements into machine tools, etc.



Fig. 1.13. Conventional machine tools

Technological process and process planning

Technological process is a kind of recipe and a guide which indicates the order and content of operations performed with the use of various machines. It is a part of production process which is focused on:

- the change of properties, dimensions, shape, etc. of materials in the case of subtractive machining operations but also in the case of forming and welding,
- the generation of new products in the case of additive processes,
- using abovementioned technologies in complex production of various products,
- the proper assembly of parts,
- integration of manufacturing systems used in production.

Technological processes are usually developed in process planning tasks by qualified engineers named process planners who are responsible for the proper realisation of the proposed technological operations. Nowadays, the work of technological process planners is aided by different software solutions which increase the efficiency of planning activities.

Master students could be interested in optimization of existing plans regarding technological processes, adaptation and involving of the newest technologies into process plans, developing software digital tools and their integration using existing platforms. Technological process planning also follows existing trends such as machine learning or 5G networks so master students could be interested in the development of new approaches which help to redefine existing procedures.

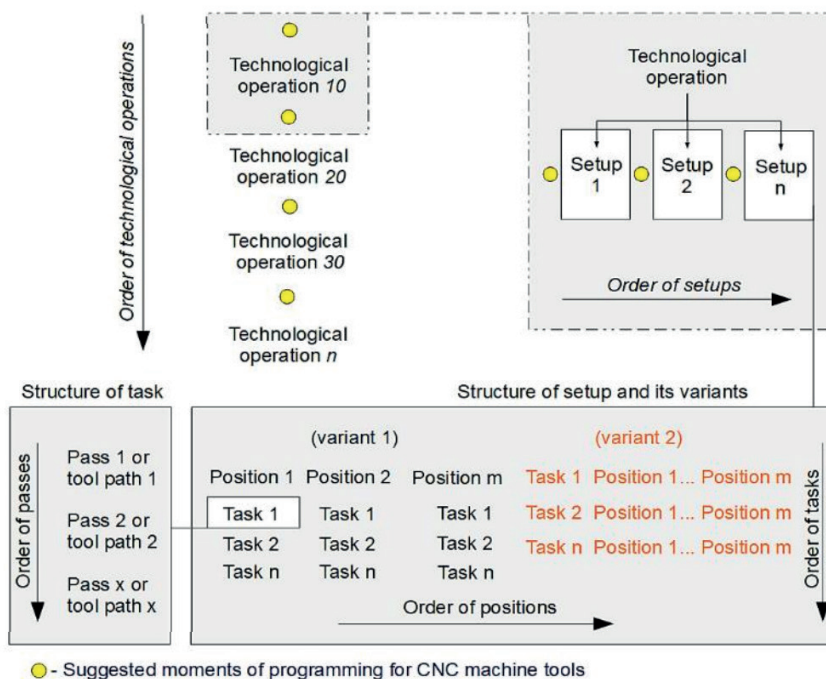


Fig. 1.14. Technological process structure

Source: Wdowik R., Magdziak M., Ratnayake R.M.C., Borsellino Ch.: Application of process parameters in planning and technological documentation: CNC machine tools and CMMs programming perspective. Procedia CIRP, 78, 2018, 43-48, <https://doi.org/10.1016/j.procir.2018.09.054>.

CAD/CAM/CAE software and simulation

CAD (Computer Aided Design), CAM (Computer Aided Manufacturing), CAE (Computer Aided Engineering) – groups of computer-based methodologies supported by the use of software digital tools which enable to design products (CAD), manufacture parts (CAM) or analyse the design, manufacturing, quality control activities by the use of advanced simulation and computation engines. They are a part of CAx software tools used in computer aided production.

They enable to obtain the specific results such as:

- CAD: drawings, virtual models, virtual assemblies, etc.,
- CAM: CNC programs, postprocessors, machine tool configuration, etc.,
- CAE: results of calculations used in product development phase such as deformations, pressures, thermal phenomena, time consumption, etc.

Nowadays such software tools usage has the following main aims:

- the simplification of calculations and faster data sharing for the further use in manufacturing systems,
- simulation of real manufacturing conditions in safe (virtual) environments for the further improvement/adaptation/changes.

Master students could be interested both in the development of new software tools in the area of CAx or exploration of existing technologies for achieving new aims.

Technological equipment

Technological equipment is the set of necessary objects (often complex) which support the use of existing machine tools and manufacturing systems. Furnaces, tool presetters, fixtures, tools, rotary tables and indexers, coating machines, measuring devices, etc are in the group of technological equipment. Furnaces may be used for heat treatment of the products. Tool presetters are used in measurements of tool geometry for their further applications in machine tools. Fixture are applied in order to clamp workpieces and give them proper position in machine tool. Tools such as cutting tools or grinding wheels are used in machining processes for removal of material. Rotary tables enable multi-axis machining while indexers enable positioning of parts in the space of CNC machine tool. The wide group of coating processes lets to obtain anti-corrosion layers or anti-wear layers or regenerate worn parts. Measuring devices help to control accuracy of machines, parts and processes.

Master students could be interested in new applications of technological equipment and the development of new products in this area.

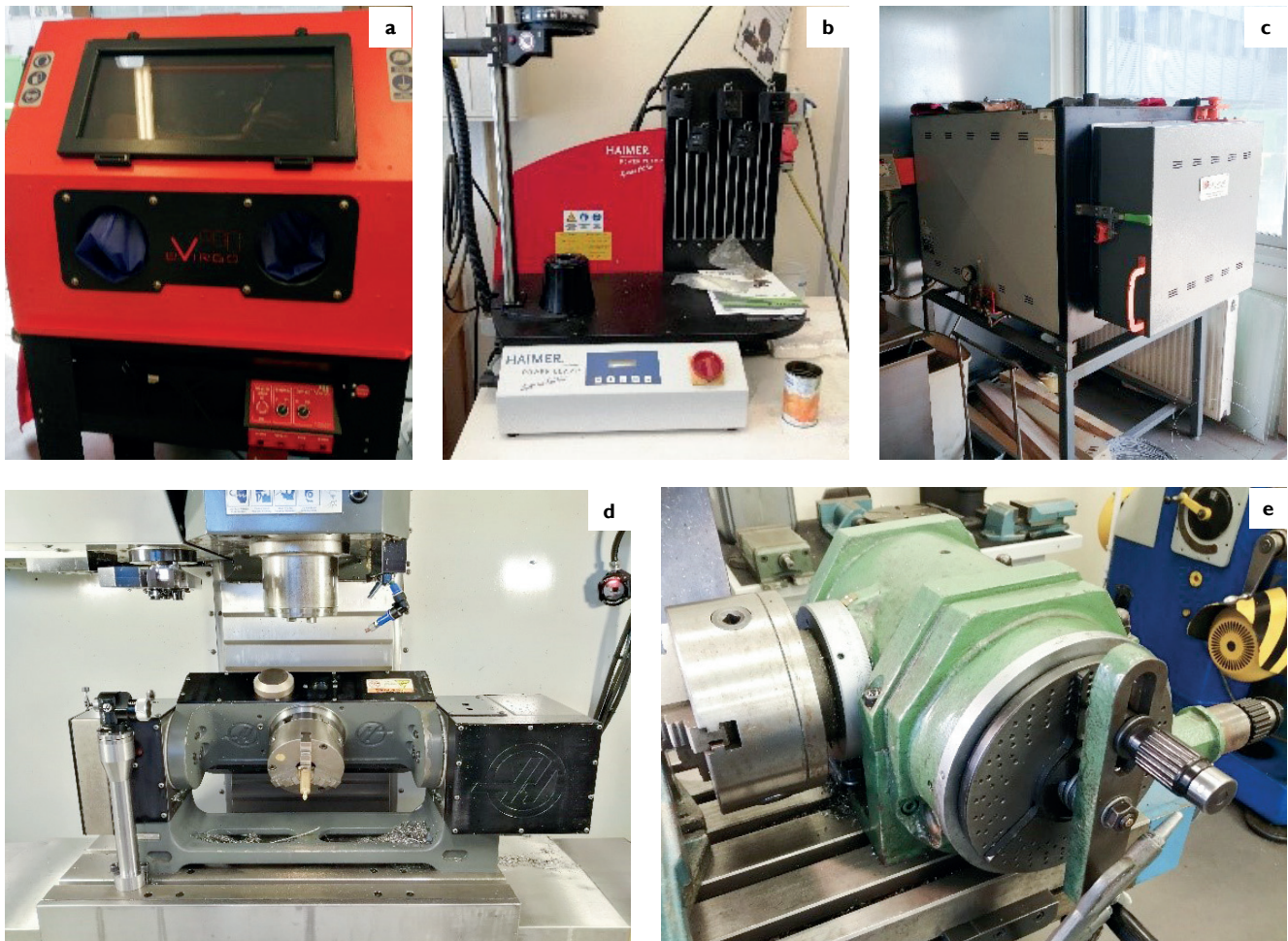


Fig. 1.15. Exemplary technological equipment

a – sandblasting machine, b – shrink-fit machine, c – furnace, d – rotary table (2 axes), e – universal indexer

CNC programming

CNC programming is a process which is focused on preparation of NC code/program for CNC machine tool. Program may be developed by manual programming approach which is focused on preparation of NC code line using the ISO standard language or dedicated languages of CNC controller's producer. Moreover CNC programs may be developed by the use of CAM software. In this case two main stages are indicated. First stage of CAM programming is indirect data development while the second stage concerns post-processing by the use of algorithm dedicated for the defined CNC machine tool and CNC controller. The following, relevant CAM software can be indicated: NX CAM, Mastercam, Edgecam, SprutCAM, Hyper Mill, etc. The final product of CAM programming is the NC code generated by postprocessor. Moreover there are a lot of conversational tools which are usually connected to the defined CNC controllers. Examples are as follows: Siemens ShopTurn, Heidenhain Smart.NC, Haas VQC.

Nowadays, CNC programming methodology may be developed in the area of new standards such as STEP, NC code optimization, macro programming, cloud/network concurrent programming, etc.

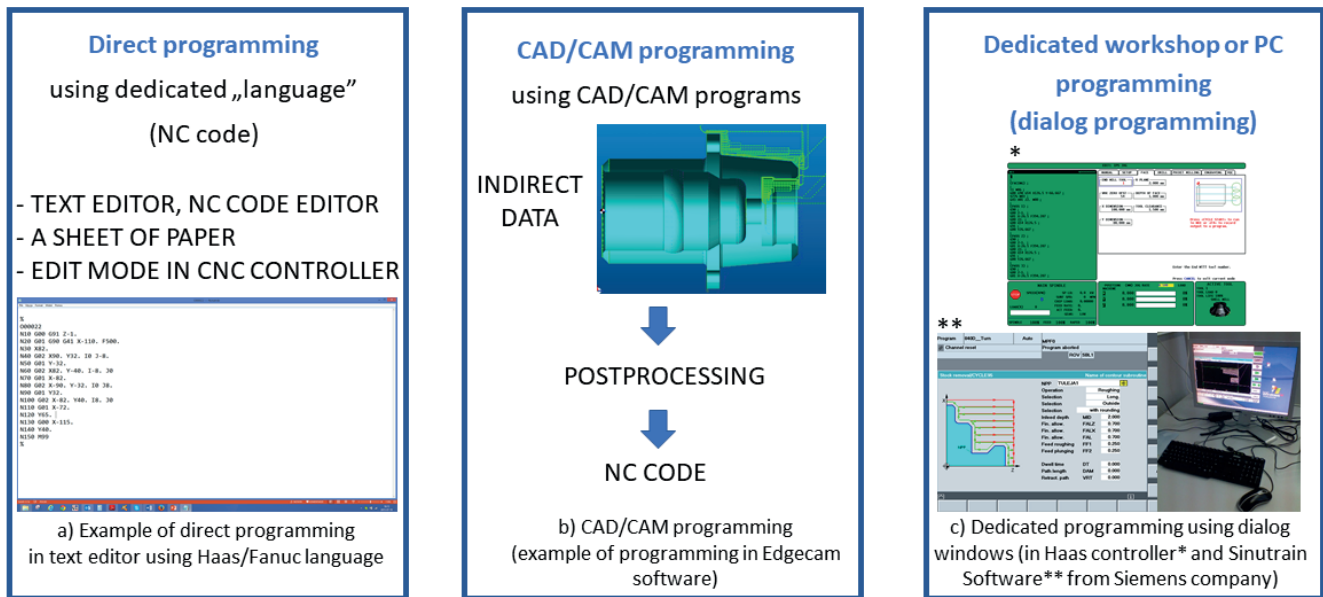


Fig. 1.16. Methods of CNC programming (based on figures from R. Wdowik’s master thesis, Rzeszów University of Technology, 2009, and general division of programming methods)

Factory communication and Industry 4.0 context

Fourth industrial revolution is a term which describes the current time and the nearest future of modern industrial firms. The end of this revolution is not defined. It also indicates that the new perspectives, innovative solutions and changes become reality. The innovations are mainly focused on redefined communication approaches inside factories and between them. Industry 4.0 is inseparably connected to artificial intelligence, mobility, increased data transfer, storage and computing. Industry 4.0 cannot be recognized only by automation which used to be a crucial element of Industry 3.0. Nowadays, the application of mobile communication techniques, sensors and computers together with customization of products and environmental friendly production environments and machinery seems to meet the basic requirements of fourth revolution’s assumptions. It is also expected that Industry 4.0 will significantly increase the use of internet, mobile networks, new materials and drastically decrease the need for human interventions at all stages of production. In this context, future manufacturing/mechanical engineers should be mainly focused on programming of manufacturing systems and communication with IT sector. Industry 4.0 realizes an utilization of digital tools and fulfill all requirements of digital transformation.

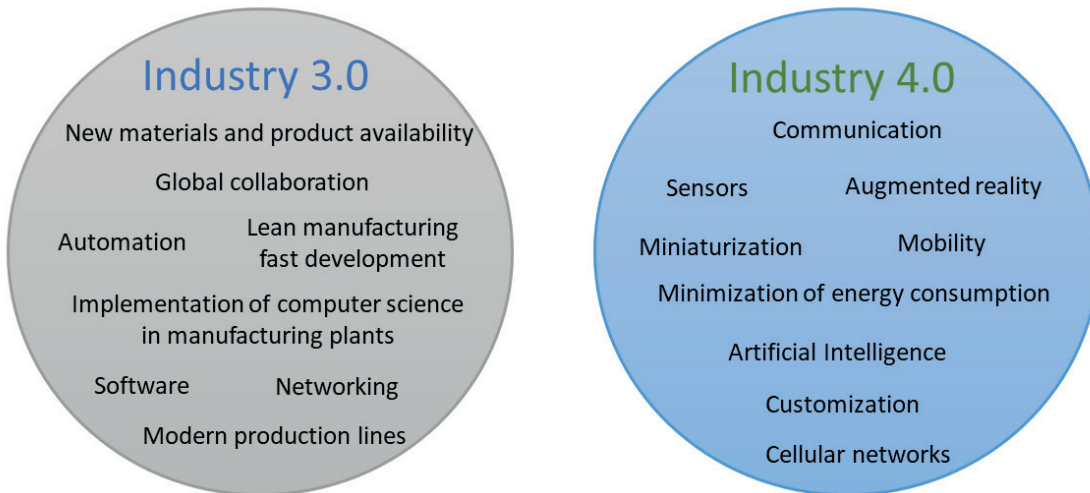


Fig. 1.17. Comparison of Industry 3.0 and Industry 4.0 concepts

Manufacturing processes general description

Manufacturing processes may be classified (see Fig. 1.18) as:

- subtractive processes (turning, milling, grinding, etc.),
- additive processes (selective laser sintering, fused deposition modeling, selective laser melting, binder jetting, etc.)
- forming processes (forging, rolling, bending, drawing, etc.)
- complex processes (assisted machining, nanomachining, biomachining).

In subtractive processes material is removed from a workpiece by the use of tool while in additive processes material is added to a workpiece. Forming changes a shape of part and selected mechanical properties of materials without material removal or additive processing. Complex processes are emerging technologies which are not fully developed and these which require further research.

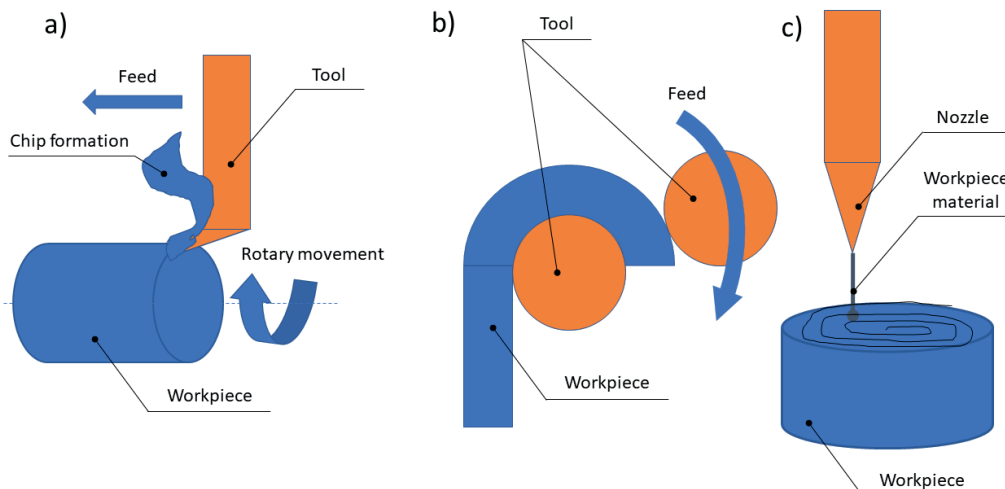


Fig. 1.18. Exemplary manufacturing processes: a) subtractive b) forming, c) additive

Selected physical phenomena in manufacturing processes

Physical phenomenon in manufacturing process reveals the natural changes of manufactured objects. Physical phenomena such as chip formation in turning, heat generation resulting from friction, cracking caused by load or the change of properties as the results of phase change may be inter alia indicated within manufacturing technologies.

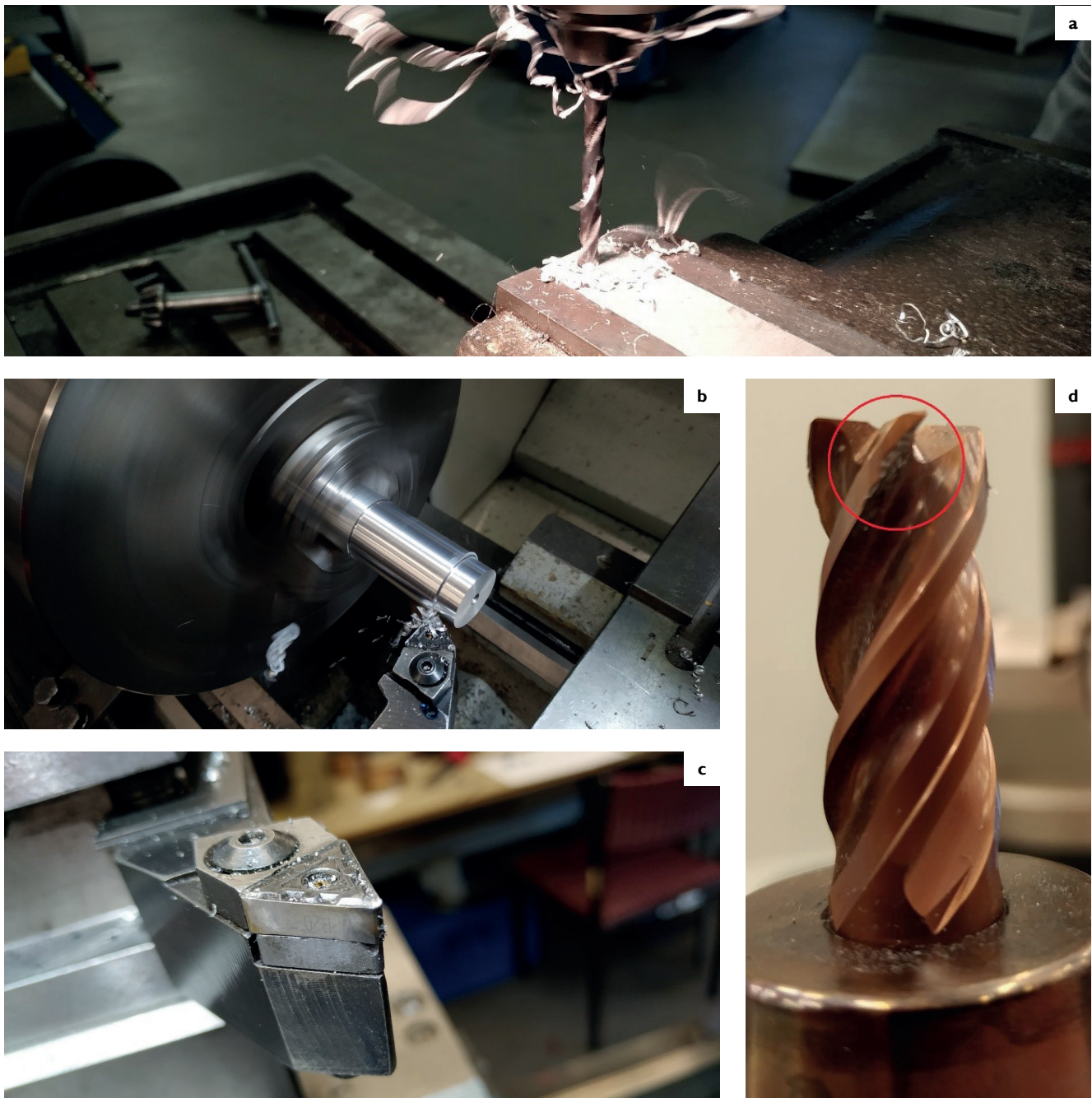


Fig. 1.19. Exemplary physical phenomena: a – chip formation in drilling, b – chip formation in turning, c – cutting tool wear as an effect of tribological phenomena, d – cutting tool wear as an effect of load

Trends in manufacturing

The following may be indicated as exemplary trends in manufacturing:

- artificial intelligence application,
- hybridization, robotization, real data collection and analysis,
- mobile communication, 3D printing technologies,
- customization, augmented reality tools,
- concurrent engineering.

I.2.4. Inspection terms

Coordinate measuring technique

The coordinate measuring technique is an integral part of the modern manufacturing processes of products. This technique can be used at the last stage of a production process when checking the final accuracy of a manufactured product and at the first step of the reverse engineering, which is applied to prepare technical documentation of a product based on its points clouds, during digitization.

The coordinate measuring technique is used by many aviation, automotive, medical and shipbuilding companies. Coordinate measurements may be performed in both contact and non-contact modes. If high measurement accuracy is required, the contact mode is still used, the steps of which are as follows:

- coordinate measurements of indicated measurement points which represent a centre of a stylus of a measuring probe during its contact with a measured workpiece,
- the probe radius correction process and the calculation of corrected measurement points representing the real measured surfaces of an investigated product,
- the computation of associated elements fitted to measurement points and the calculation of deviations of manufacturing,
- the comparison of calculated deviations to tolerances defined in technical documentation of a product.

The graphical representation of the selected stages of the coordinate measuring technique is shown in Fig. I.20.

The user of a measuring system may use different types of associated elements dedicated to various geometric elements used when defining coordinate systems and geometrical tolerances. The example of the associated element is the Gaussian feature which is based on the least squares method. The selection of the type of an associated element is performed when defining a measurement strategy. The most popular measuring systems are so far coordinate measuring machines (CMMs), which can be equipped with contact and non-contact measuring probes but coordinate measurements can be also conducted by means of CNC machine tools equipped with measuring probes. CMMs may be applied in the case of measurements of curvilinear surfaces of products e.g., turbine blades and coordinate measurements of workpieces characterized by regular geometric shapes. CMMs are very popular under industrial conditions because of their versatility and high measurement accuracy.

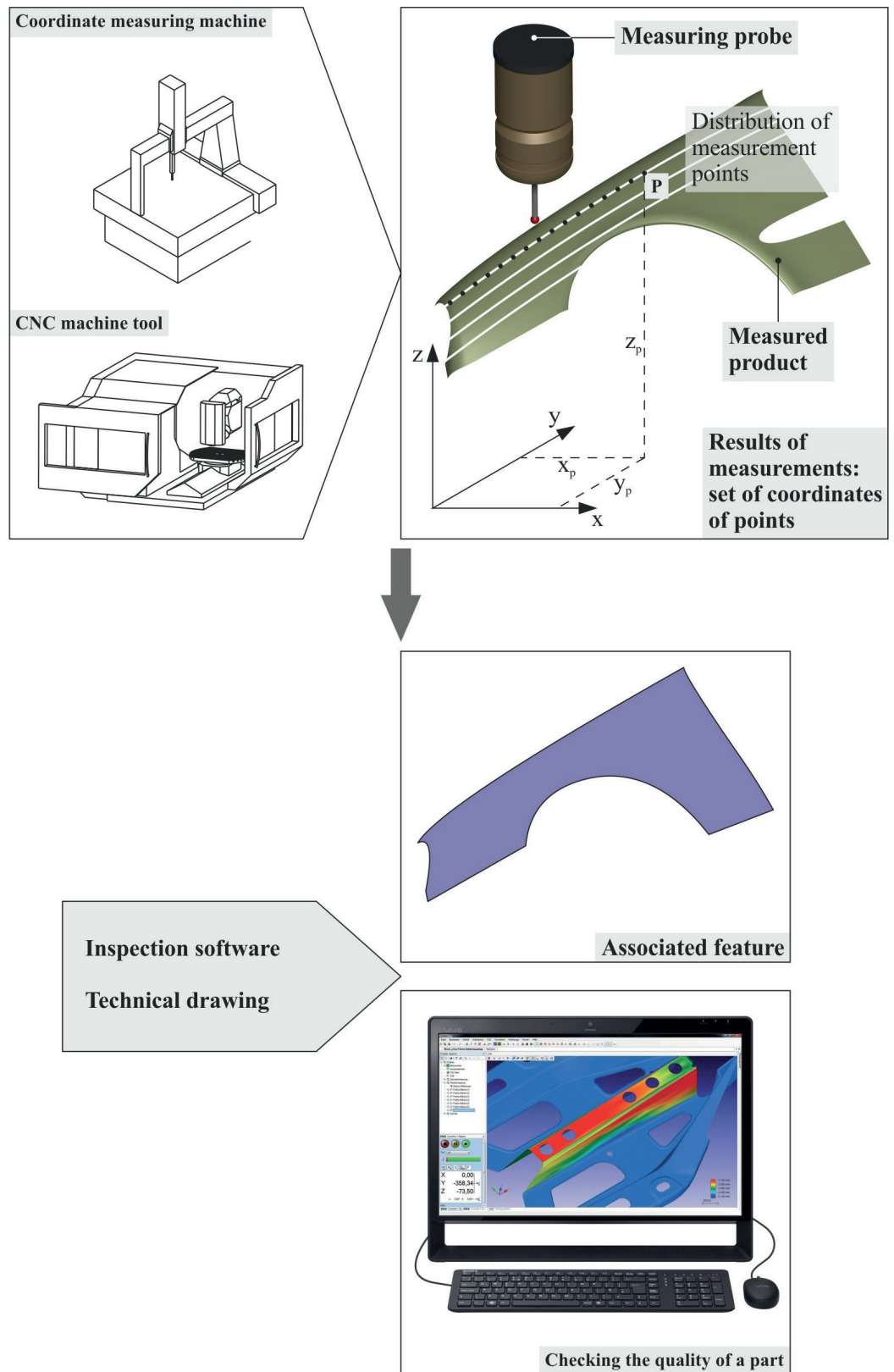


Fig. I.20. Selected stages of the coordinate measuring technique

Programming of coordinate measuring systems can be carried out by using on-line and off-line modes. On-line programming of a CMM is conducted by means of a measuring machine. In the case of the second type of programming, it is possible to prepare a measurement program, controlling CMMs, without using a machine, at the initial stages of a product production process when working on product's technological documentation. Moreover, off-line programming may decrease the time of coordinate measurements and thus the total time of a manufacturing process.

There can be used different types of coordinate measuring machines: shop floor CMMs (the quality control is conducted directly in production halls), gantry CMMs, horizontal-arm CMMs and bridge CMMs. These measuring systems may cooperate with different software and measuring probes enabling coordinate measurements of different types of products (e.g., turbine blades and gears) and measurement characteristics. The final selection of the type of a coordinate measuring system depends on the types of measured products, their dimensions, products' weight and the expected accuracy of coordinate measurements which results from the accuracy of a manufacturing process.

Coordinate measurements of curvilinear surfaces

Coordinate measurements of free-form surfaces may be conducted by using e.g., coordinate measuring machines. The results of measurements of curvilinear surfaces concern mainly the following measurement characteristics: line and surface profiles. However, during coordinate measurements of complex products composed of free-form surfaces, like in the case of measurements of turbine blades, there is the possibility of analysing more measurement characteristics, which may be as follows: the length of a profile chord, the length of a mean camber line, the angle of a profile chord, the angle of a tangent line, the maximum length, the maximum thickness, the form deviation, the surface area, the radius of a leading edge, the radius of a trailing edge, the average radius of a leading edge and the average radius of a trailing edge.

The very important stage of coordinate measurements of free-form surfaces is the probe radius correction process, which is applied when using e.g., coordinate measuring machines equipped with contact measuring probes. The probe radius correction process consists of calculating the coordinates of corrected measurement points, which represent the real contact points computed between a stylus tip of a measuring probe and a measured free-form surface. Corrected measurement points are calculated based on indicated measurement points representing centres of a stylus tip of a measuring probe during its subsequent positions along a measured profile.

The probe radius correction process influences the results of contact coordinate measurements and it can be conducted by using e.g., the method based on the Bézier curves [1]. In the case of this method, indicated measurement points are interpolated by means of the second- and fourth-degree curves passing through successive groups of measurement points which are composed of three and five points, respectively. The main idea of the probe radius correction process is presented in Fig. 1.21.

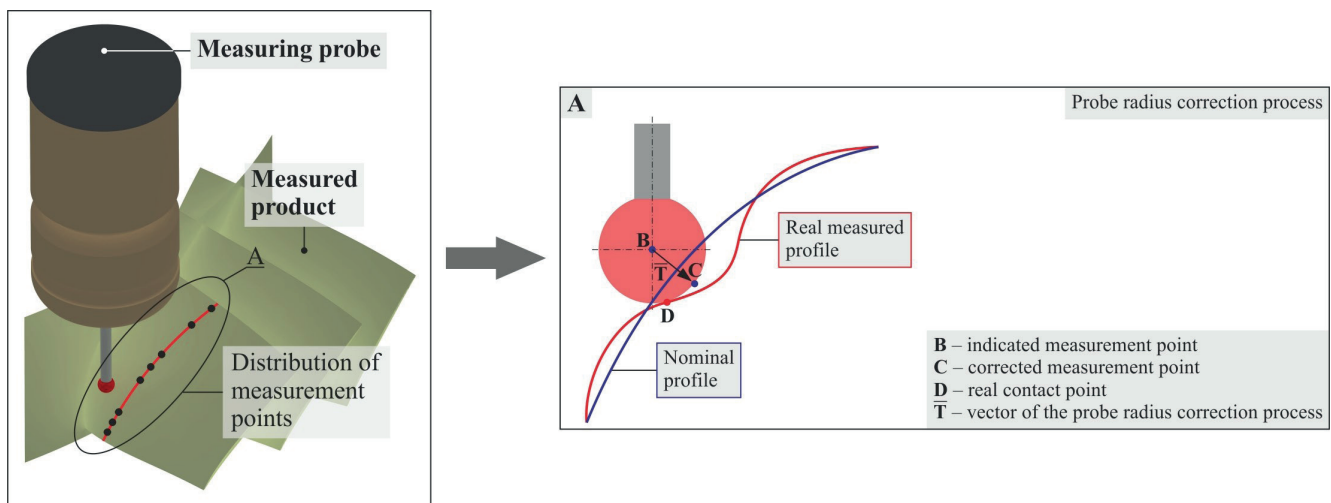


Fig. 1.21. The probe radius correction process in the case of coordinate measurements of a free-form surface

Another factor which determines the results of measurements of curvilinear surfaces is the distribution of measurement points. Points should be in the parts of measured products characterized by the worst quality of manufacturing. There are many methods of determining locations of measurement points. Some of them are described in the papers [2,3].

On-machine measurement

Coordinate measurements of manufactured products may be conducted under industrial conditions by means of CNC machine tools. This type of a measurement is called the on-machine measurement (OMM). Measurements on machine tools are possible due to measuring probes mounted in spindles. It is currently strived to make on-machine measurements as similar as possible to coordinate measurements conducted by using coordinate measuring machines (CMMs), which are mainly used in separate air-conditioned measurement laboratories. Therefore, there is now possibility of measuring both products characterized by regular geometric shapes and workpieces composed of free-form surfaces by using measuring probes cooperating with CNC machine tools. On-machine measurements may be conducted by using contact measuring probes in the single-point probing and scanning modes.

The place of on-machine measurements in a production process is shown in Fig. 1.22. The results of the OMM may be used to improve a technological process of a product and increase the productivity of a production process.

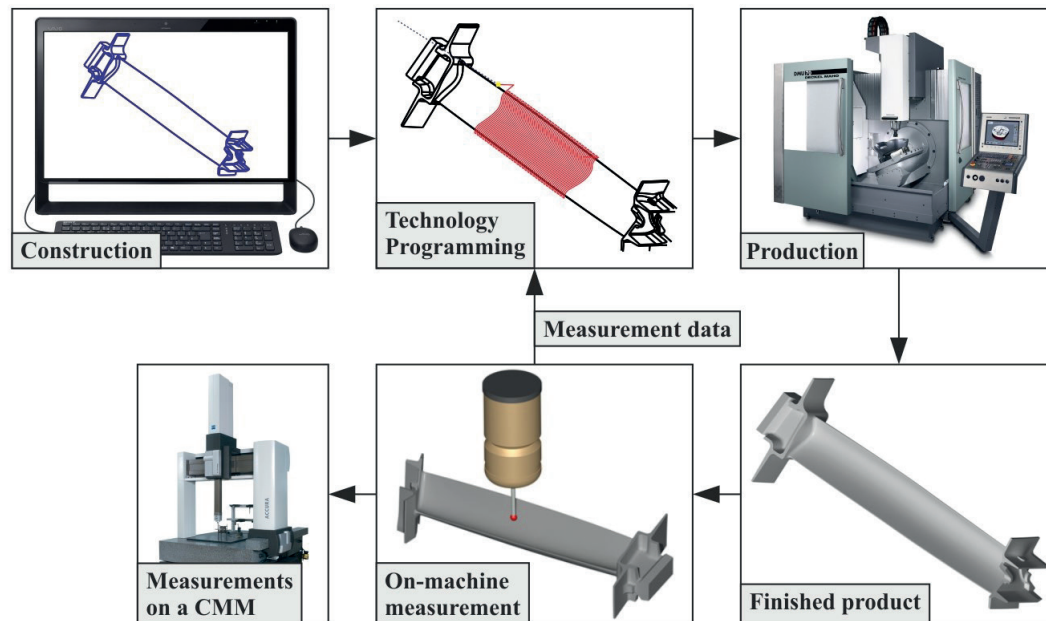


Fig. 1.22. On-machine measurements in a production process

Unfortunately, the accuracy of on-machine measurements is less than the accuracy of coordinate measurements performed by using CMMs. This accuracy of the OMM results mainly from e.g., the accuracy of applied CNC machine tools and environmental conditions in production halls. The main factor determining accuracy of on-machine measurements is temperature. However, this factor may be monitored and the measurement results may be compensated by taking into account the results of measurements obtained by means of reference measuring systems e.g., coordinate measuring machines. The advantage of conducting on-machine measurements is no need to transfer measured objects from CNC machine tools to quality control departments, which leads to shorter measurement time and a reduction in total time of a production process of a product.

Programming of measuring probes may be performed by using measurement cycles available in a control system of a CNC machine tool and by means of computer aided inspection (CAI) software. CAI software packages enable programming of on-machine measurements in the off-line mode e.g., at the stage of developing the technological process of a product. The results of coordinate measurements conducted on CNC machine tools may be used to correct a machining program controlling the work of a machine tool during machining a part in order to increase the accuracy of a manufactured workpiece.

Accuracy of contact coordinate measurements of free-form surfaces

The accuracy of coordinate measurements depends on many different factors which may include a measurement strategy, accuracy of an applied measuring system, environmental conditions, an operator of a measuring system and elements associated with an investigated workpiece (Fig. 1.23). All mentioned factors affect final measurement results, which should be given with the uncertainty of measurements.

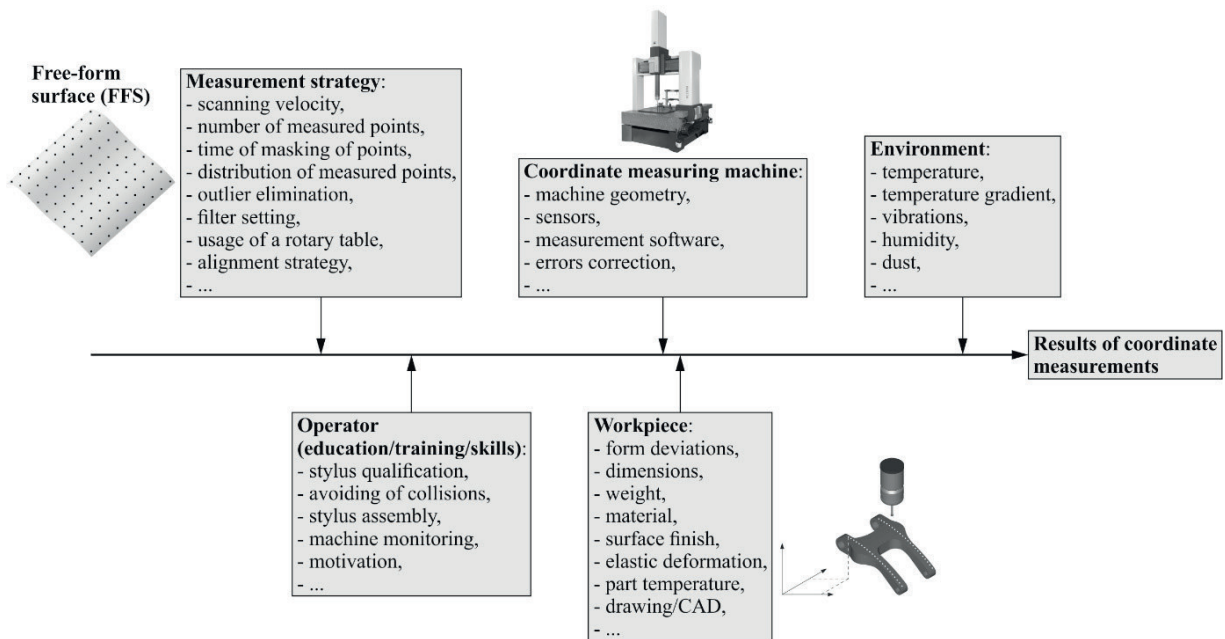


Fig. 1.23. Factors having the influence on the accuracy of coordinate measurements of, e.g. curvilinear surfaces of products [4]

For example, in the case of a measurement strategy, the user of coordinate measuring machines (CMMs) must pay attention to the proper selection of a measurement speed and number of measurement points, time of masking of measurement points, the distribution of measurement points and the proper settings in the field of removing outliers and filtering results of measurements. The selection of the best parameters of coordinate measurements may be conducted based on the statistical analysis performed by using the robust design approach [4]. The paper [4] presents the procedure of selecting a measurement strategy in the case of coordinate measurements of four selected free-form surfaces.

In the case of operators of CMMs, results of coordinate measurements are affected by their training level, which determines the correct preparation of a measurement program, the ability to avoid collisions, the proper selection of a probing system and monitoring of a coordinate measuring system. Results of measurements also depend on the accuracy of an applied system, the accuracy of measuring probes cooperating with a coordinate measuring machine and the accuracy of algorithms being parts of inspection software of CMMs.

The evaluation of the accuracy of measuring systems may be carried out by using the Repeatability & Reproducibility (R&R) tests which enable to estimate the correctness of selection of a measuring device for a measurement task. For example, the user of a CMM may check the influence of a selected measurement strategy on measurement results and whether the change in strategy affects results of coordinate measurements.

Non-contact coordinate measurements

The coordinate measurements conducted by using coordinate measuring machines (CMMs) may be also performed in the non-contact mode. This mode is possible because of using e.g., laser measuring probes cooperating with CMMs. The accuracy of coordinate measurements conducted by means of non-contact measuring probes is less than the accuracy of measurements performed by using contact probes. Further disadvantages of using laser measuring probes are the following: results of measurements depend on an RDS-angle of a CMM, shadowing effects and surface dependence of results of non-contact measurements.

However, the main advantage of using laser measuring probes is the possibility of obtaining many measurement points in the form of points clouds in a relatively short time compared to time of contact measurements, even conducted in the scanning mode. Moreover, the next advantages of using non-contact probes are as follows: high speed of measurements and wear resistant. Non-contact coordinate measurements may be also conducted by using photogrammetry measuring systems and computed tomography. The selection of a measuring system should depend on measurement characteristics that must be measured.

Non-contact coordinate measurements are often used at the first stage of the reverse engineering process – digitalization. The next steps of this process are as follows: technical documentation preparation based on points clouds by using computer aided design software, programming of machine tools by using computer aided manufacturing software, production of parts and their final inspection, which is sometimes performed by means of computer aided inspection (CAI) software.

When applying laser measuring probes (e.g., the LineScan probe produced by the Carl Zeiss company), the user of measurement software cooperating with a coordinate measuring machine and a measuring probe has the possibility of:

- best-fitting of measured data to nominal one,
- filtering or delating measurement points,
- using the region filter,
- performing a triangulation process,
- checking the accuracy of a measured part by comparing the results of non-contact coordinate measurements to a nominal model of a workpiece.

In the case of the Calypso measurement software of the Carl Zeiss company, the region filter enables removing erroneously measured points resulting from applying fixtures or optical reflections. Eliminating points function of measurement software helps the user of a CMM to delete wrongly measured points, which may be located on surfaces of other objects which do not belong to an investigated workpiece. Additionally, the user of a coordinate measuring machine has the possibility of reducing the number of measurement points and/or decrease overlapping of scanned points by performing the filtration process.

Different software packages have different types of filters. The influence of the type of a filter on the results of non-contact measurements of the selected free-form surface is presented in [5]. The investigations were conducted by means of a measuring arm equipped with a laser measuring probe. Moreover, the results of a digitalization process of products may be exported to a text file including the coordinates of scanned measurement points or to STL files, which is possible due to e.g., functions of the Calypso software. Both formats can be used by many computer aided design software packages in order to create 3D models of investigated parts.

Contact contour measurement

Contact contour measurement is a process then different part contours are measured with stylus by touching surface. For many years standard way of profile features measurement were optical projector. However, the modern alternative method is contact measurement called contour tracing with a carbide-tipped or diamond-tipped stylus. Geometries of the stylus can be selected according to the part which should be measured. The perfect example of part which could be measured with contour tracer can be part which has internal threads. In nowadays quality of complex products from different materials should be tested. Some materials for example semi-transparent or flexible cannot be tested with optical inspection methods. Then contact measurement with possibility to adjust measuring force can be used then. In fact, contact force of contour measurement device can be made feather light but still large enough to allow measurement of contour without damaging or deforming of the part. Moreover, different configurations of arm and stylus can be used for complex contours measurement, for example dual stylus can be used for measurements of internal profiles. Different form of the arm can be used for measurements of hard to reach surfaces.

All new contour measurement machines allow to use Statistical Process Control (SPC) for faster and more precise analysis of the results. Contour measurement devices are easily controllable and can be programmed for batch measurement. Moreover, all measured results can be exported to other programs while contour can be exported as dxf or other file.

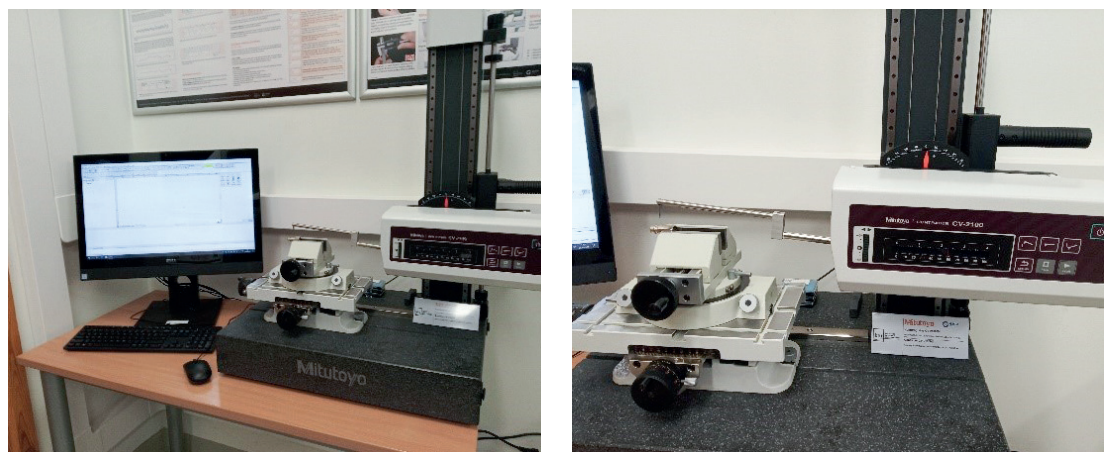


Fig. I.24. Contour measurement device

Linear height measurement

Linear height measurement is a process then single axis measurement are performed. Usually during this process dimensions by z axis are measured. During last few decades vertical measuring machines changed drastically form Vernier Height Gauge to compact single axis Coordinate Measuring Machine (CMM). Possibility of programming, automated measurement and data analysis are the functions which can be found in nowadays Linear height measurement devices. Moreover, very wide range of probing accessories allows user to measure various complex workpiece features. Measurements points are detected by feeding the probe at the predefined rate into contact with a surface. Measurement results including GO/ NO GO judgements can be immediately evaluated and results can be showed on the screen or sent to the file. Moreover, data output enables more advanced analysis of results on the PC with other SPC tools. Although these machines are called single-axis usually it enables two dimensional measurements to be made. Minimum and maximum height, internal and external diameter, perpendicularity measurements are common functions in such types of the devices, moreover basic calculations (addition, subtraction, multiplication and division) are also possible. After batch measurement simple statistical results (average, maximum and minimum values, process capability indexes and other) can be calculated.



Fig. I.25. Linear height measurement device

Data Management and SPC software MeasurLink

Quality data management process is becoming more and more important. Therefore, amount of data which needs to be analysed significantly increasing and according the trends in industry it will increase even faster in nearly future. It is well known that integration of Computer Aided Quality (CAQ) control and data analysis are also important because it can help to decrease process time and to make better decision. Software MeasurLink which includes data collection, analysis and statistical process control (SPC) can be great example of integrated quality data management and SPC software. Measurement tools (calipers, micrometres, microscopes, optical vision, coordinate measurement machines and others) can be easily connected with software through RS-232 or wireless connection which allows to use data immediately after measuring. Another huge advantage is possibility to use quality data management software as a part of Enterprise Resource Planning (ERP).

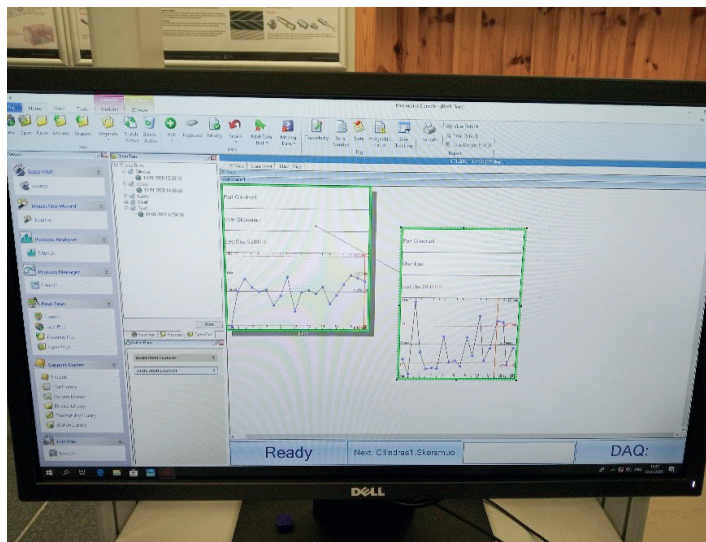


Fig. 1.26. Contour measurement device

Roughness test

Surface roughness is an important parameter used to determine the suitability of a surface for a particular purpose. The irregularities on a machined surface impact the quality and performance of that surface and the performance of the end product. Rougher surfaces typically wear more quickly than smoother surfaces and are more vulnerable to corrosion and cracks, but they can also promote adhesion. A roughness tester (Fig. 1.27), also referred to as roughness gauge or roughness meter, is a portable device that is used for quick and easy measurement of object surface roughness (surface finish).

The size and configuration of features have a significant influence on the quality and functionality of processed surfaces and the performance of the final products. Consequently, it is important to measure the roughness of surfaces to meet high performance standards for end products.



Fig. I.27. INNOVATEST Surface roughness tester TR-220

Surface irregularities are measured by classifying the height/depth and intervals of surface features to evaluate their concavity/convexity. The results are then analyzed in accordance with predetermined methods, subject to a calculation based on industrial quantification.

The measurement and evaluation of surface roughness is an old concept with numerous established parameters indicating various roughness criteria. The progress of processing technology and the introduction of advanced measurement instruments enable the evaluation of diverse aspects of surface roughness.

Typical roughness testers provide a linear roughness measurement, tracing a mechanical tip along a surface to measure roughness along an arbitrary line (Fig. I.28). More sophisticated versions provide an areal roughness measurement, which measures an area of the surface using non-contact methods, such as lasers, optics, interferometers, and more, to give finer resolution and wide area measurements.

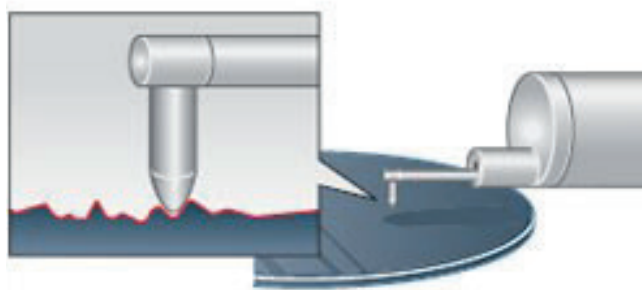


Fig. I.28. Schematic illustration of surface roughness measurement

Roughness values (Fig. I.29) are typically reported in R_a (*Arithmetic mean deviation of the profile*), which is the average absolute deviation from a central line of a surface; R_z (*Maximum height of profile*), which is the total of highest profile peak point (Z_p) and lowest valley point (Z_v). For most applications R_a and R_z provide an adequate indication. For specially designed surfaces, the other parameters may be more appropriate.

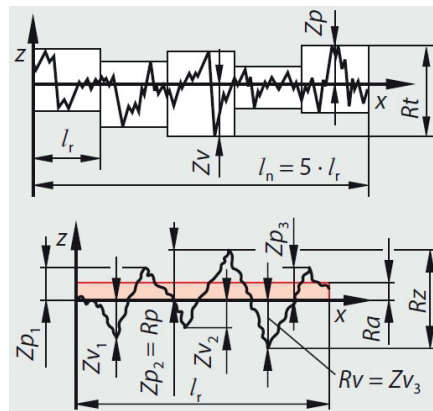


Fig. 1.29. Surface roughness profile measurements

Hardness tests

Hardness is a characteristic of a material, not a fundamental physical property. It is defined as the resistance to indentation, and it is determined by measuring the permanent depth of the indentation.

The application of hardness testing enables you to evaluate a material's properties, such as strength, ductility and wear resistance, and so helps you determine whether a material or material treatment is suitable for the purpose you require. The definition of hardness testing is a test to determine the resistance a material exhibits to permanent deformation by penetration of another harder material.

A hardness test is typically performed by pressing a specifically dimensioned and loaded object (indenter) into the surface of the material you are testing. The hardness is determined by measuring the depth of indenter penetration or by measuring the size of the impression left by an indenter. Hardness tests that measure the depth of indenter penetration include: Rockwell, Instrumented Indentation Testing, and Ball Indentation Hardness. Hardness tests that measure the size of the impression left by the indenter include: Vickers, Knoop, and Brinell.

The type of material and expected hardness will determine test method. Materials such as hardened bearing steels have small grain size and can be measured using the Rockwell scale due to the use of diamond indenters and high PSI loading. Materials such as cast irons and powder metals will need a much larger indenter such as used with Brinell scales. Very small parts or small sections may need to be measured on a microhardness tester using the Vickers or Knoop Scale.

When selecting a hardness scale, a general guide is to select the scale that specifies the largest load and the largest indenter possible without exceeding defined operation conditions and accounting for conditions that may influence the test result.

The Vickers hardness test method, also referred to as a microhardness test method, is mostly used for small parts, thin sections, or case depth work.

The Vickers method is based on an optical measurement system (Fig. 1.30). The Microhardness test procedure, specifies a range of light loads using a diamond indenter to make an indentation which is measured and converted to a hardness value. It is very useful for testing on a wide type of materials, but test samples must be highly polished to enable measuring the size of the impressions. A square base pyramid shaped diamond is used for testing in the Vickers scale. Loads are very light, ranging from 0.05gf to 1kgf, although “Macro” Vickers loads can range up to 30 kg or more.

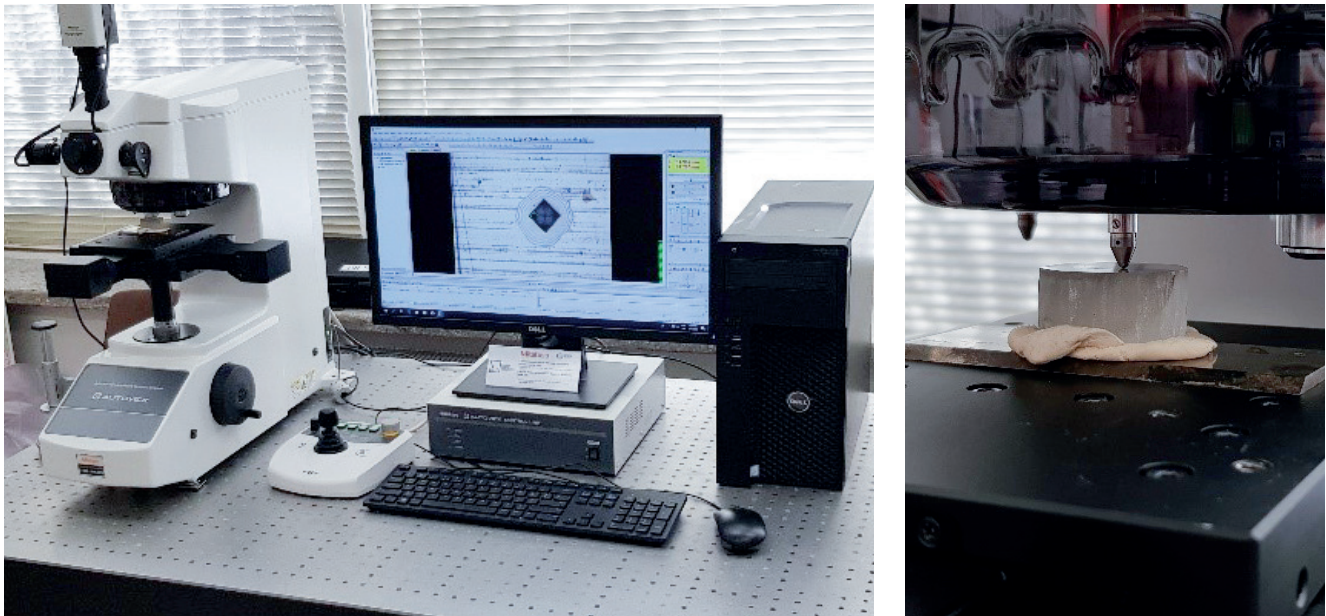


Fig. 1.30. Mitutoyo HM-200 Micro hardness testing machine

The Microhardness methods are used to test on metals, ceramics, composites - almost any type of material. Since the test indentation is very small in a Vickers test, it is useful for a variety of applications: testing very thin materials like foils or measuring the surface of a part, small parts or small areas, measuring individual microstructures, or measuring the depth of case hardening by sectioning a part and making a series of indentations to describe a profile of the change in hardness.

Sectioning is usually necessary with a microhardness test in order to provide a small enough specimen that can fit into the tester. Additionally, the sample preparation will need to make the specimen's surface smooth to permit a regular indentation shape and good measurement, and to ensure the sample can be held perpendicular to the indenter. Often the prepared samples are mounted in a plastic medium to facilitate the preparation and testing. The indentations should be as large as possible to maximize the measurement resolution.

1.3. Infrastructure in PRODEM education

PRODEM Infrastructure concerns a configuration of space, hardware and software. Usually lecture rooms are designed for larger groups of students and laboratories enable to run classes with smaller groups. It is caused by a character of classes. The lecture rooms nowadays are similar for all scientific disciplines and a main attention is paid on presentation of teaching content to many persons by the use of projectors, boards, etc. However, laboratories are usually adapted to the requirements of scientific discipline and course which is taught inside. There are two types of laboratories used in PRODEM education: manufacturing/inspection laboratories and computer laboratories. Manufacturing laboratories consists of machines and technological equipment which reflect the real industrial environments and are also used in research activities. Computer laboratories consists of computer workstations for students which can be equipped with CAD manipulators. Fig. 1.31. present a computer laboratory which is used for computer aided manufacturing classes. Workstations should meet requirements of software. Students are gathered in a groups of 10-15 people and are led by a lecturer who can presents current issues on a board by the use of projector.



Fig. 1.31. Exemplary computer laboratory at Rzeszów University of Technology

The similar laboratory to the previous one is presented in Fig. 1.32. The laboratory is the part of the Faculty of Mechanical Engineering and Aeronautics of the Rzeszów University of Technology. The shown laboratory is also used to teach computer aided manufacturing. It is equipped with 16 DELL workstations, a projector and a board. The main software available in this laboratory is the Siemens NX, which is used by students to create CNC programs for advanced multi-axis CNC machine tools. Moreover, there is also the Calypso software installed. This inspection software is applied for programming of a coordinate measuring machine in the off-line mode. Students have the possibility to learn the fundamentals of the coordinate measuring technique and prepare optimal programs for manufacturing and inspection processes thanks to the equipment presented in Fig. 1.32.

The created programs are tested by using real machines, which are also available at the Rzeszów University of Technology, under industrial conditions. Moreover, all computers, shown in Fig. 1.32, are networked and teachers have the remote access to files saved by students. Additionally, a teacher can remotely correct students' works.



Fig. 1.32. Computer laboratory available at Rzeszów University of Technology

The next examples of computer laboratories are presented in Fig. 1.33 and 1.34. The laboratories are the part of Kaunas University of Technology. As shown in the photos, the approach to the teaching process is similar to that at Rzeszów University of Technology in Poland. Students also have the access to the computer workstations and a teacher can conduct the teaching process by means of a computer with specialized CAD/CAM software installed, a board and a projection, which are used to present examples and basis of computer aided designing and manufacturing to students.



Fig. 1.33. Computer laboratory at Kaunas University of Technology



Fig. 1.34. The next computer laboratory available at Kaunas University of Technology

Fig. 1.35 and 1.36 show manufacturing laboratories. They are used to teach machining. As presented in the figures, students of Kaunas University of Technology have the access to different types of CNC machine tools. They learn the fundamentals of turning, milling and programming of CNC machine tools by using two methods of programming (manual and dialog-based programming). Students work together to develop a CNC program, which can be tested under real industrial conditions. Moreover, a teacher can present the fundamentals of machining processes in order to select the best machining parameters and strategies for created CNC programs.



Fig. 1.35. CNC machine tools laboratory at Kaunas University of Technology



Fig. 1.36. Another view of the CNC machine tools laboratory at Kaunas University of Technology

Manufacturing laboratories may also be equipped with conventional machine tools, as it is presented in Fig. 1.37. The shown laboratory is the part of Estonian University of Life Sciences. Not only machining processes are taught in manufacturing laboratories in PRODEM education. These labs may also be used, e.g. to present rapid prototyping techniques.



Fig. 1.37. Conventional machine tools laboratory at Estonian University of Life Sciences

Inspection laboratories are also available at universities. The examples of inspection labs are presented in Fig. I.38-I.42. Fig. I.38 shows the laboratory located in the Department of Manufacturing Techniques and Automation at Rzeszów University of Technology. It is equipped with many different manual measuring instruments and advanced measuring systems working in the automatic mode. These instruments are mainly applied for teaching students the fundamentals of metrology of geometrical quantities. The detailed views of the selected specialized measuring systems shown in Fig. I.38 and I.42-I.50.



Fig. I.38. Laboratory of metrology of geometrical quantities at Rzeszów University of Technology



Fig. I.39. Coordinate measuring technique laboratory at Kaunas University of Technology

Fig. I.39 presents the coordinate measuring machine enabling contact measurements and produced by the Mitutoyo company. The machine is available at Kaunas University of Technology and applied for presenting the fundamentals of the coordinate metrology to students, which can create CNC programs for a CMM in the on-line mode. The group of students should only consist of a few people during classes. This is due to the limited access to the machine and the need to ensure high accuracy of coordinate measurements during classes. Students obtain knowledge how to select the most appropriate measurement strategy in order to make a measurement process as accurate as possible.



Fig. I.40. Test-stand for surface quality analysis at Kaunas University of Technology

Performing measurements by using the system presented in Fig. 1.40 is not as difficult as in the case of coordinate measurements conducted by means of CMMs. However, students have to prepare a measurement program, select the right measurement parameters and analyse obtained results. They gain knowledge in the field of geometrical deviations of products based on measurements performed by using the above mentioned measuring system.



Fig. 1.41. Inspection laboratory at Estonian University of Life Sciences

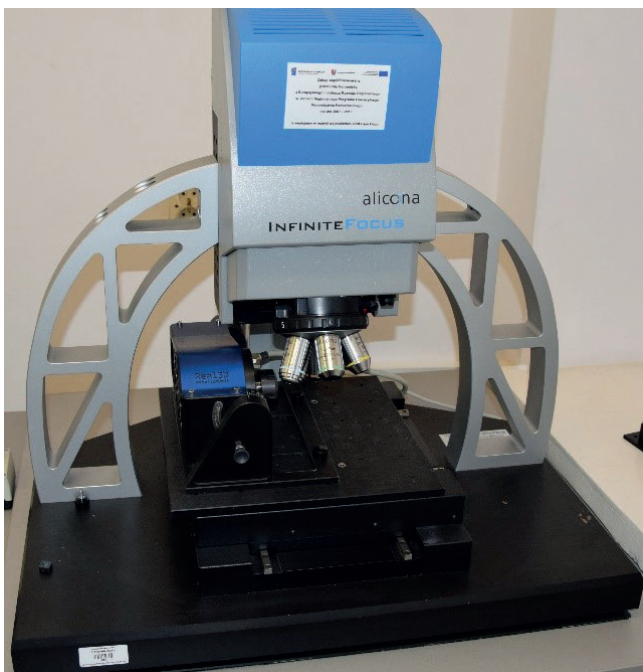


Fig. 1.42. Alicona measuring system applied for e.g., measurements of roughness



Fig. 1.43. Height measuring instrument produced by the Mahr company



Fig. I.44. iNEXIV measuring system mainly dedicated to 2D non-contact measurements

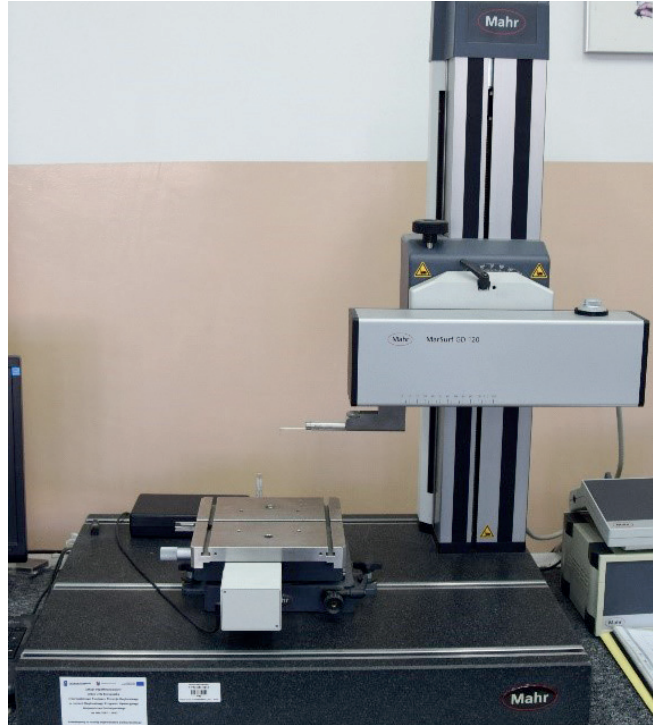


Fig. I.45. MarSurf GD 120 dedicated to measurements of roughness of an object

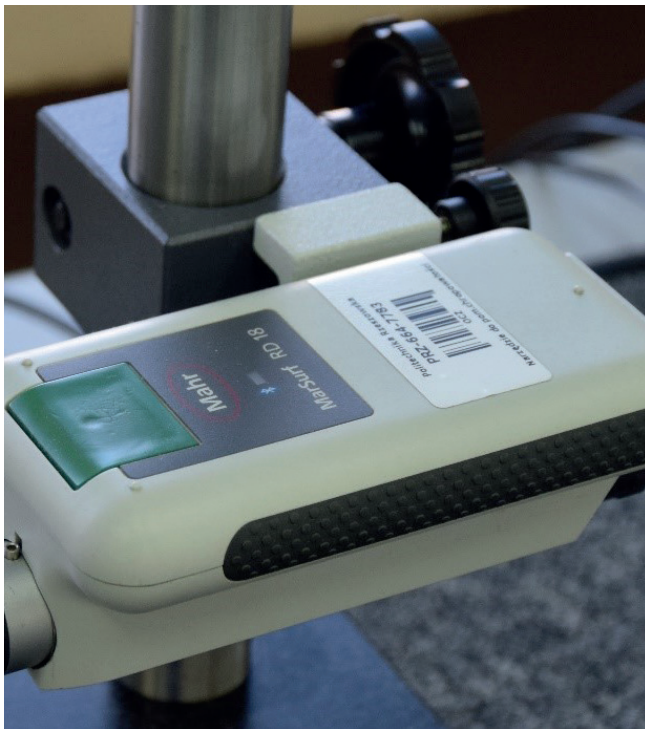


Fig. I.46. Measuring system dedicated to measurements of roughness mainly under industrial conditions



Fig. I.47. Measuring system applied for measurements of geometrical deviations



Fig. 1.48. Articulated measuring arm enabling contact and non-contact coordinate measurements and the reverse engineering process



Fig. 1.49. Form measuring system MMQ 400 of the Mahr company applied for measurements of geometrical deviations of products



Fig. 1.50. TalyScan 150 dedicated to measurements of roughness

Moreover, students of the Rzeszów University of Technology have the access to the advanced coordinate measuring machine produced by the Carl Zeiss company (Fig I.51, I.52). The machine is in the Department of Manufacturing Techniques and Automation of the Faculty of Mechanical Engineering and Aeronautics. The CMM is equipped with three measuring probes: two contact probes (VAST XT, VAST XXT – Fig I.53, I.54) and one non-contact probe (LineScan – Fig I.55). The presented coordinate measuring system enables coordinate measurements of free-form surfaces of products and objects characterized by regular geometric shapes. Moreover, the reverse engineering process of products can be performed with the use of the shown CMM. The digitalization process of objects is mainly conducted by using the LineScan probe, which enable to obtain a lot of data (measurement points) in a relatively short time. Moreover, the presented CMM is equipped with many inspection software packages e.g., Calypso (Fig. I.56), Holos, Blade Pro, Gear Pro and Zeiss Reverse Engineering. For example, the Blade Pro software enables to analyse results of coordinate measurements of turbine blades.

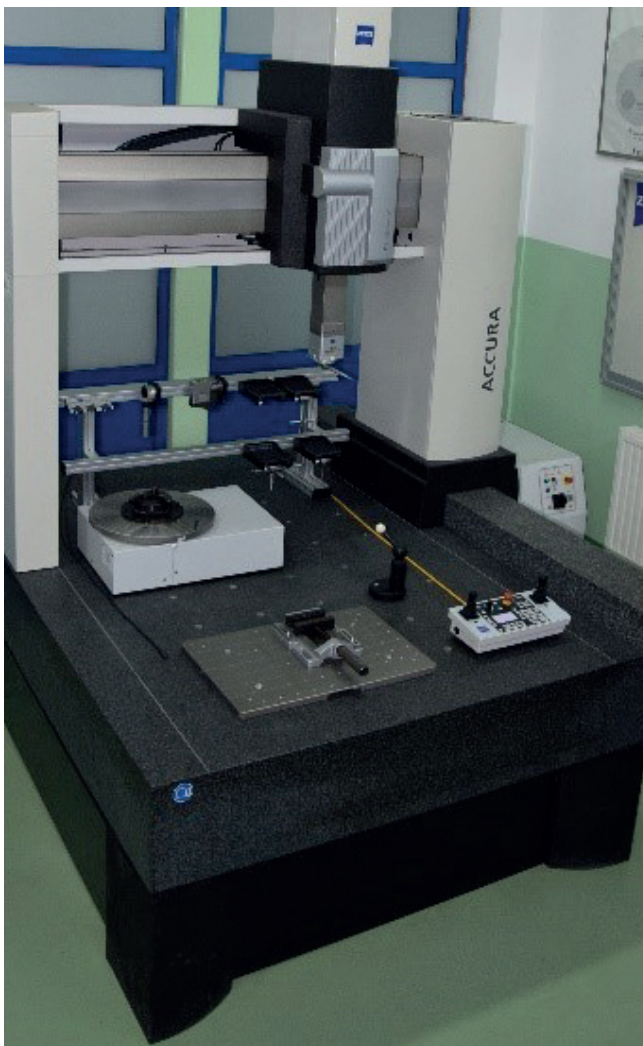


Fig. I.51. Coordinate measuring machine ACCURA II



Fig. I.52. Coordinate measuring machine ACCURA II equipped with three measuring probe and a rotary table



Fig. I.53. VAST XT contact measuring probe



Fig. 1.54. VAST XXT contact measuring probe

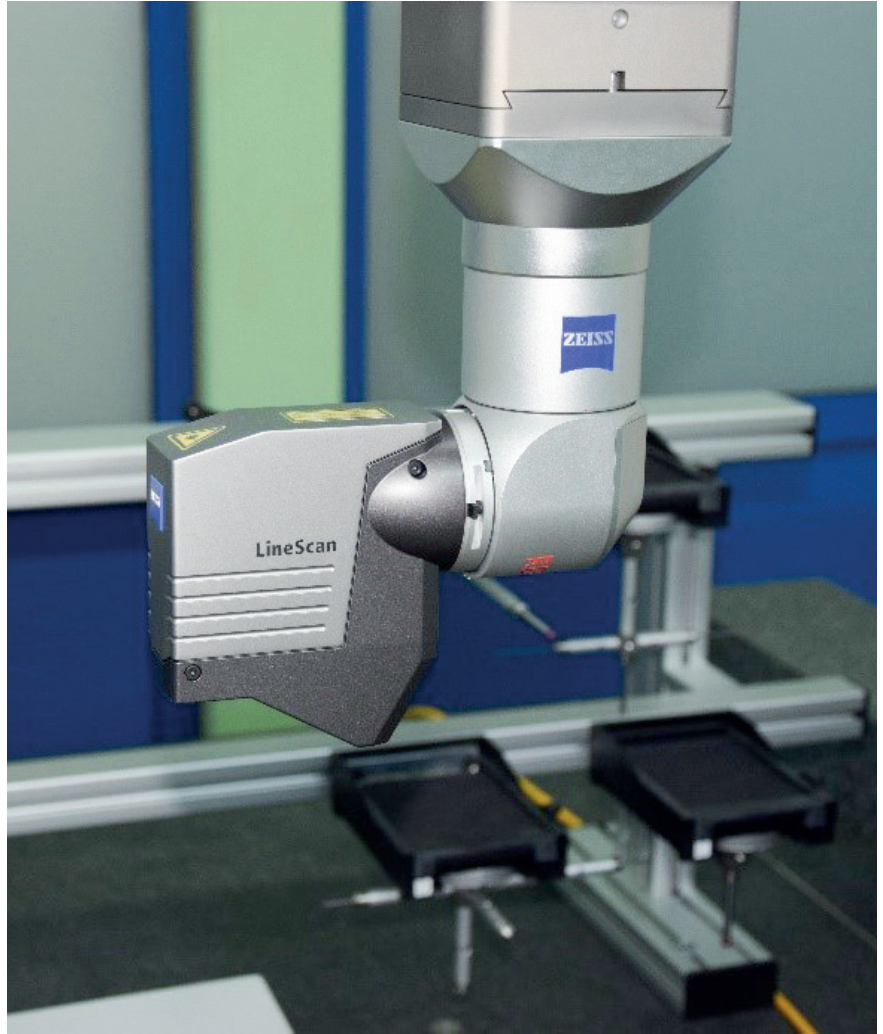


Fig. 1.55. LineScan non-contact measuring probe

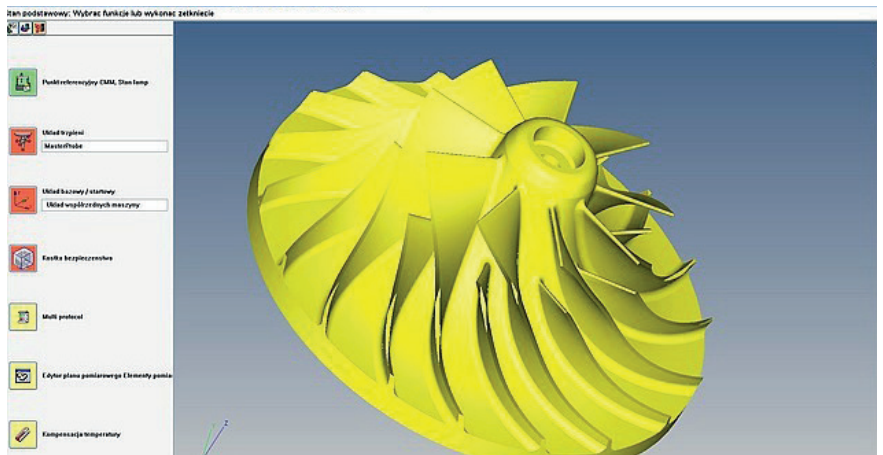


Fig. 1.56. The Calypso software enabling e.g., measurements of curvilinear surfaces of products

The use of the ACCURA II coordinate measuring machine is demonstrated in the following videos available on the website: <https://box.pionier.net.pl/d/a70f3064e7d746d69eab/>.

The first movie concerns the application of the LineScan non-contact measuring probe. The film presents, among others, the process of qualifying the laser probe and measurements of a curvilinear surface. Moreover, the method of determining a coordinate system of a measured product was presented.

The second video is the presentation of measurements of a blade at its individual cross-sections. The measurements were made with the VAST XT measuring probe. The beginning of the movie also shows the stages of qualifying the applied contact measuring probe.

The third video shows coordinate measurements of a product characterized by regular geometric shapes. Measurements were carried out in the scanning and single-point probing modes by using the VAST XT contact measuring probe of the ACCURA II coordinate measuring machine.

The last, fourth, video is the presentation of the qualification process of the VAST XXT measuring probe in the RDS-CAA mode. The applied mode enables the fast qualification of a measuring probe, which reduces the time of coordinate measurements performed with the VAST XXT probe.

To sum up, laboratories dedicated to the teaching different stages of a manufacturing process (based on machining) may be equipped with the objects listed in the following lists. The lists present model equipment for each laboratory.

Product development

- Computer stations available for each student,
- Networked computers to control student's work by a teacher and share materials with students,
- Controllers supporting 3D design (e.g., 3Dconnexion SpaceMouse),
- Virtual reality equipment,
- Multimedia projector,
- Media board.

Design

- CAD software,
- Computer stations available for each student,
- Networked computers to control student's work by a teacher and share materials with students,
- Controllers supporting 3D design (e.g., 3Dconnexion SpaceMouse),
- Virtual reality equipment supporting designing process,
- Multimedia projector,
- Media board,
- Up-to-date standards of technical documentation.

Manufacturing

- CAD/CAM software,
- Computer stations for each student,
- Networked computers to control student's work by a teacher and share materials with students,
- Controllers supporting 3D designing and manufacturing (e.g., 3Dconnexion SpaceMouse),
- Multimedia projector,
- Media board,
- CNC machine tools,
- Virtual CNC machine tools' simulators,
- Software enabling simulations of CNC programs created by manual programming,
- Cutting tools,
- Basic measuring instruments enabling e.g., measurements of surface roughness,
- Measuring systems for the diagnosis of the technical condition of CNC machines.

Inspection

- Manual measuring tools,
- Surface roughness measuring equipment for contact and non-contact measurements,
- Devices enabling contact and non-contact measurements for measuring form deviations,
- Coordinate measuring machine,
- Multimedia projector,
- Media board,
- CAI software enabling off-line programming of CMMs,
- Data collection and Statistical Process Control (SPC) software,
- Computer stations for all students,
- Networked computers to control students' work by a teacher and share materials with students,
- Up-to-date standards regarding the metrology of geometrical quantities,
- Up-to-date standards regarding the coordinate measuring technique.

In the case of CAD/CAM and inspection software (applied during classes regarding designing, manufacturing and inspection processes) students may use software packages presented in the following table 1.2. The table includes the information regarding, e.g. hardware requirements for each software package.

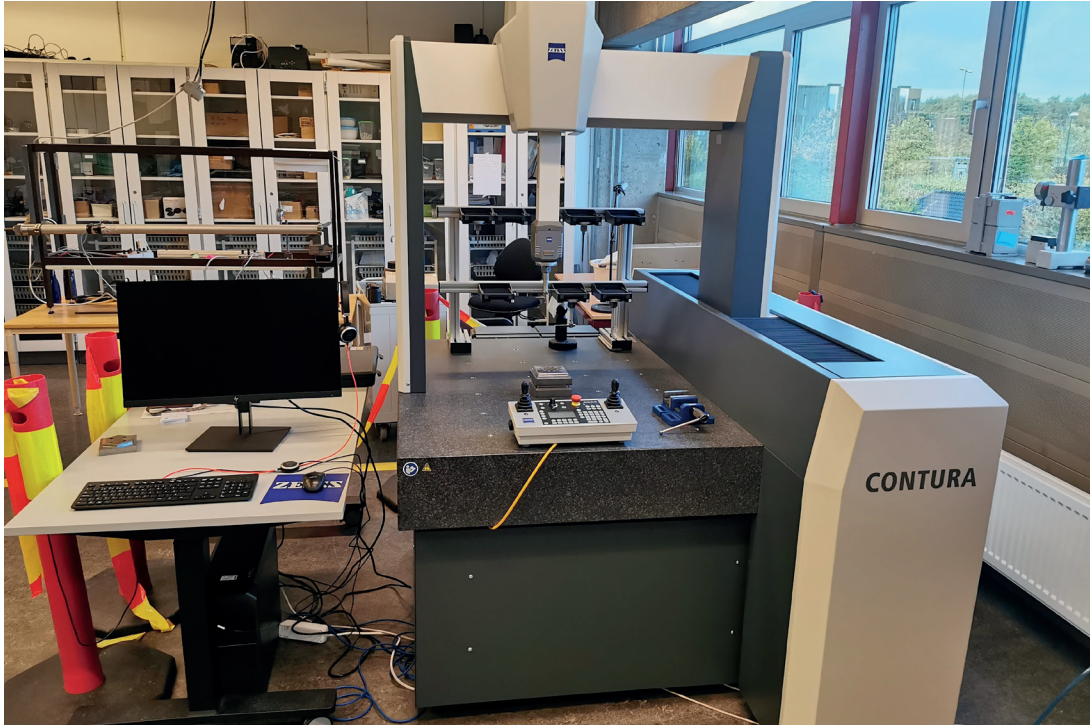


Fig. I.57. Zeiss Contura Coordinate Measuring Machine



Fig. I.58. Machine Workshop at UiS



Fig. I.59. Tensile Test and Charpy Impact Test Stations



Fig. I.60. Okuma Genos L3000-e Horizontal Lathe



Fig. I.61. Rapid prototyping laboratory



Fig. I.62. Materials science laboratory

Operating systems	SolidWorks 2020	Siemens NX (1899)
Windows 10, 64-bit	yes	yes
Windows 7 SPI, 64-bit	yes	yes, but not supported
Linux (64-bit)	no	SuSE & Red Hat
Mac OS X	no	no
Web browser	not specified	not specified
MS Office required	not specified	not specified

Table 1.2. Examples of required hardware configuration for selected digital tools

Hardware	SolidWorks 2020	Siemens NX (1899)
Processor	3.3 GHz or higher	Symmetric Multiprocessing (SMP) and Multi-core processors are supported
RAM	16 GB or more	12 GB or more
Graphics card	certified cards and drivers available on the website	the latest information on certified graphics cards and driver versions, can be found at the Customer Support (GTAC) Web site
Drives	SSD drives recommended	not specified
Source information	https://www.solidworks.com/sw/support/SystemRequirements.html	https://docs.plm.automation.siemens.com/tdoc/nx/1899/release_notes#uid:index_xid1753866:xid950624:id744501:id744509:id746462
Date	26.02.2020	26.02.2020

Table 1.2. Examples of required hardware configuration for selected digital tools

Operating systems	Solid Edge 2020	Autodesk Inventor 2021
Windows 10, 64-bit	yes	yes
Windows 7 SPI, 64-bit	yes, but not supported	not specified
Linux (64-bit)	no	not specified
Mac OS X	no	not specified
Web browser	Internet Explorer 11	Google Chrome™ or equivalent
MS Office required	Professional 2016 or 365 Business	Microsoft® Excel 2016 (build 16.0.4519.1000) or later

Tab I.2. Examples of required hardware configuration for selected digital tools

Hardware	Solid Edge 2020	Autodesk Inventor 2021
Processor		recommended: 3.0 GHz or greater, 4 or more cores
RAM	8 GB or more	32 GB RAM or more
Graphics card	65K Colors, Screen Resolution: 1920 x 1080	minimum: 1 GB GPU with 29 GB/S Bandwidth and DirectX 11 compliant
Drives	8 GB of disk space required for installation	installer plus full installation: 40 GB
Source information	https://solidedge.siemens.com/en/resources/system-requirements/	https://knowledge.autodesk.com/support/inventor-products/troubleshooting/caas/sfdcarticles/sfdcarticles/System-requirements-for-Autodesk-Inventor-2021.html
Date	26.02.2020	4.10.2020

Tab 1.2. Examples of required hardware configuration for selected digital tools

Operating systems	Calypso 2022	ZEISS Reverse Engineering 2.8
Windows 10, 64-bit	yes	yes
Windows 7 SPI, 64-bit	no	no
Linux (64-bit)	no	no
Mac OS X	no	no
Web browser	not specified	not specified
MS Office required	not specified	not specified

Tab I.2. Examples of required hardware configuration for selected digital tools

Hardware	Calypso 2022	ZEISS Reverse Engineering 2.8
Processor	Intel Core i3-I0320 3.8 GHz 4C65W	Intel Core i7, 64 bit ≥ 3.2 GHz
RAM	16 GB (2x8 GB) DDR4 3200 NECC	≥ 64 GB
Graphics card	NVIDIA Quadro P620 2 GB (4)mDP	NVIDIA graphics card Open GL 4.3 supported Graphics memory ≥ 8 GB
Drives	256 GB SSD M.2 HDD 500 GB 7200RPM SATA 3.5 in 2nd	(depends on the project size) Installation: 1.5 GB SSD or RAID disks
Source information	https://portal.zeiss.com/	https://portal.zeiss.com/
Date	26.08.2022	26.08.2022

Tab 1.2. Examples of required hardware configuration for selected digital tools

[1] Kawalec A., Magdziak M.: The selection of radius correction method in the case of coordinate measurements applicable for turbine blades. *Precision Engineering* **2017**, 49, 243-252.

[2] Magdziak M.: Selection of the Best Model of Distribution of Measurement Points in Contact Coordinate Measurements of Free-Form Surfaces of Products. *Sensors* **2019**, 19(24), 5346.

[3] Magdziak M.: A New Method of Distribution of Measurement Points on Curvilinear Surfaces of Products. *Sensors* **2019**, 19(12), 2667.

[4] Magdziak M., Ratnayake R.M.C.: Investigation of best parameters' combinations for coordinate measuring technique. *Procedia CIRP* **2018**, 78, 213-218.

[5] Turek P., Magdziak M.: The influence of the type of a filter on the results of non-contact measurements of the selected free-form surface. *Mechanik* **2018**, 11(91), 992-994.

2. TEACHING WITHIN PRODEM EDUCATION PHASES

2.1. Methodology of product development teaching process

Product development classes should introduce the fundamentals in the product development process. The product development focuses on the various processes that lead to the realization of a product. This includes idea and opportunity identification, identifying the customer needs and requirements for functionality and a systematic assessment of alternative solutions for the realization of the product. In below Fig. 2.1. is a suggestion of topics that can be presented during lectures.

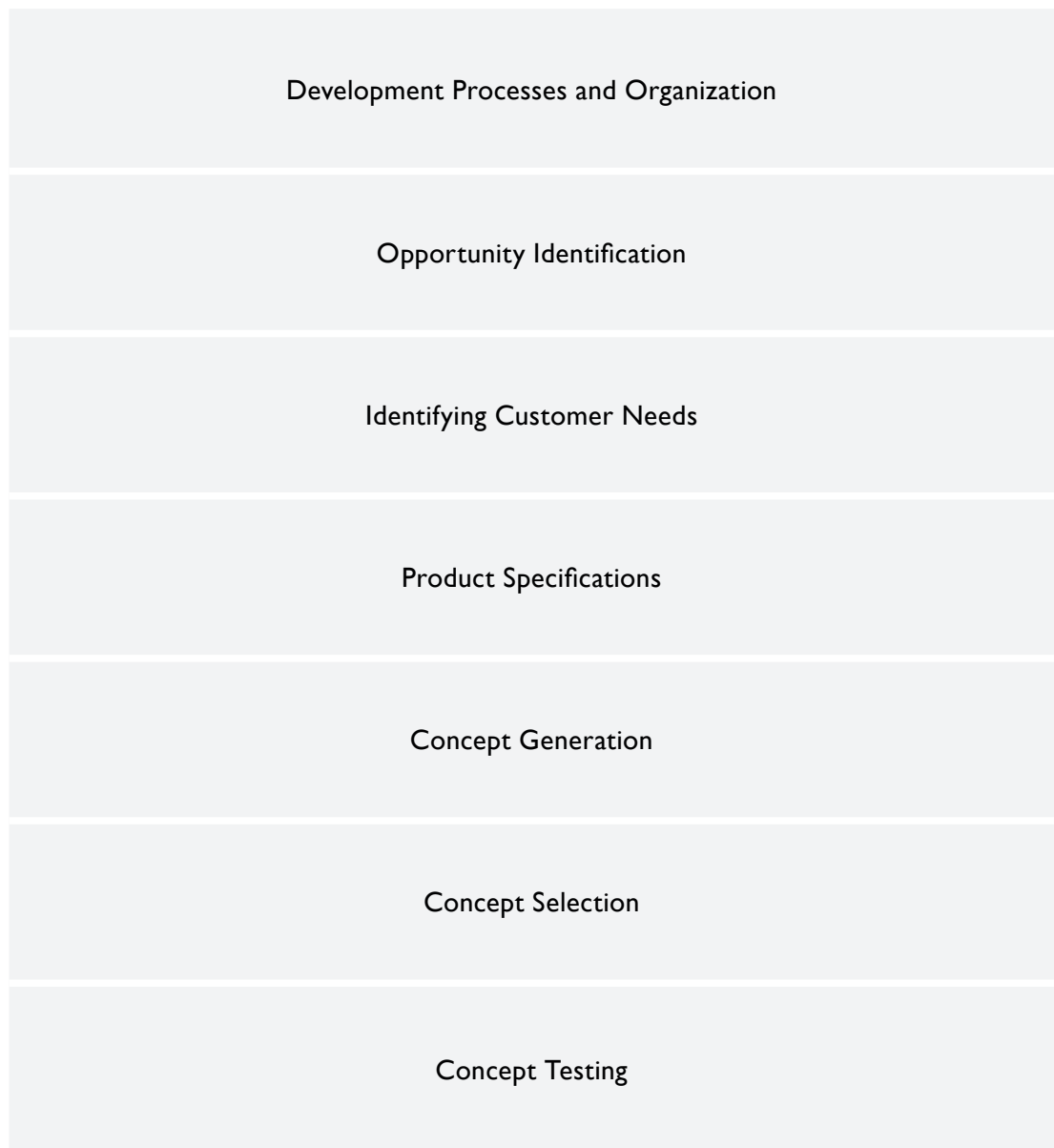


Fig. 2.1. Topics in product development

The production development subject has a widespread area of topics that should be presented to the student. Some of the topics in the curriculum can be introduced and overlapped in other subjects such as project management and planning, product prototyping, manufacturing methods and 3D design. Common for the subjects are they all can be summarized in these groups, CAE/CAD/CAM.

Theoretical classes in product development may be presented by lectures and multimedia presentation. The presentation should be made available for the student using their learning management system in-front of the lecture. Teaching using e-learning platforms or internet communicator is possible, especially tools like Zoom classroom meeting, where students can be divided into groups, having discussions about a specific topics or solving problems with the possibility for the teacher to access each group to monitor and provide feedback to the students. Micro-lectures can be recorded and made available online by the instructor to give the students access to part of the curriculum they may find more difficult or need to understand better. YouTube channels and other web-based sources can be used as well to give students access to information to help them advance in the subject.

Project work during the semester is possible and can be utilized by asking the class to come up with a list of ideas for a new product, improvement of an existing product or a business opportunity. From here on the idea screening process can be used to find the best product or opportunity to proceed with for each group. Furthermore, the product specifications should be decided using methods learned in lectures. Each group should develop four or more concepts using the best idea found earlier. Tools such as concept classification tree, concept scoring, and concept screening matrixes should be used to find the best concept or business opportunity for further developing. Concept testing and prototyping using digital tools, 3D printed models or CNC manufactured parts can be included in the product development class but can be more appropriate to introduce in other subjects. Project planning and management is also possible to include in the learning outcome by using Gantt charts and network diagrams during the project. Project can be finalized by a presentation in front of the class or presented using digital tools such as Zoom or Teams.

Product development assignments can be made with interactive content with presentation of topics with question covering the curriculum with drag and drop features, so students learn the basics concepts in this subject.

In order to minimize the lead time of product development, it is vital to exploit digitalization opportunities in product prototyping for testing in physical (e.g. subtractive and additive manufacturing) and immersive environments [e.g. augmented reality (AR) and virtual reality (VR)]. Introduction to AR and VR are during the product development classes are highly recommended.

2.1.1. Product development process knowledge dissemination

Below in Fig. 2.2 is an outline of phases that should be involved in the knowledge dissemination of the subject. After completing the product development course, students should understand the various processes that lead to the realization of a product and be able to use them during projects, thesis work or for developing new products.



Fig. 2.2. Phases involved in product developing process

A real-world example is presented below (Fig. 2.3) to show how an idea or need for a product is transformed to a finished product using the product development phases presented above.

Develop a Ergonomical Grinder to Grind Steel Rails on the Floor

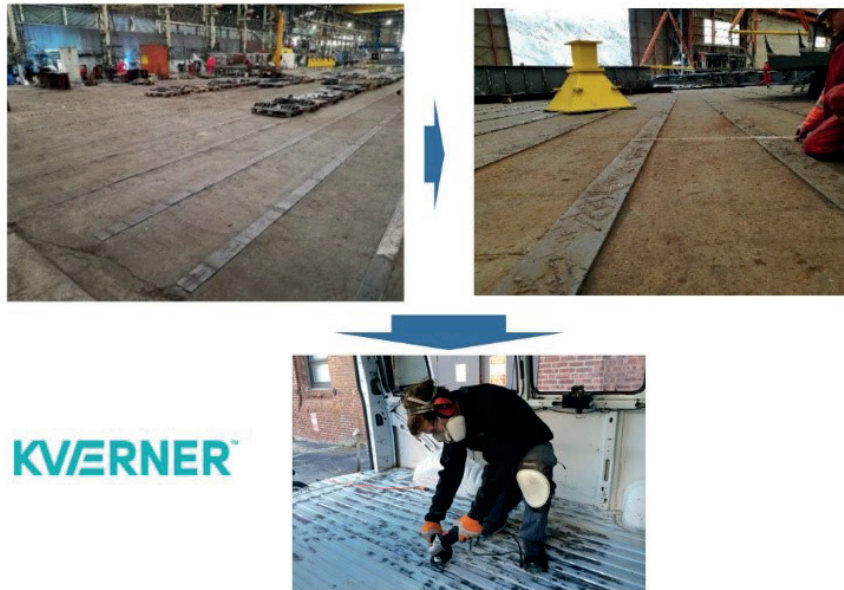


Fig. 2.3. Product idea/opportunity for PD and planning

Product Concept Generation

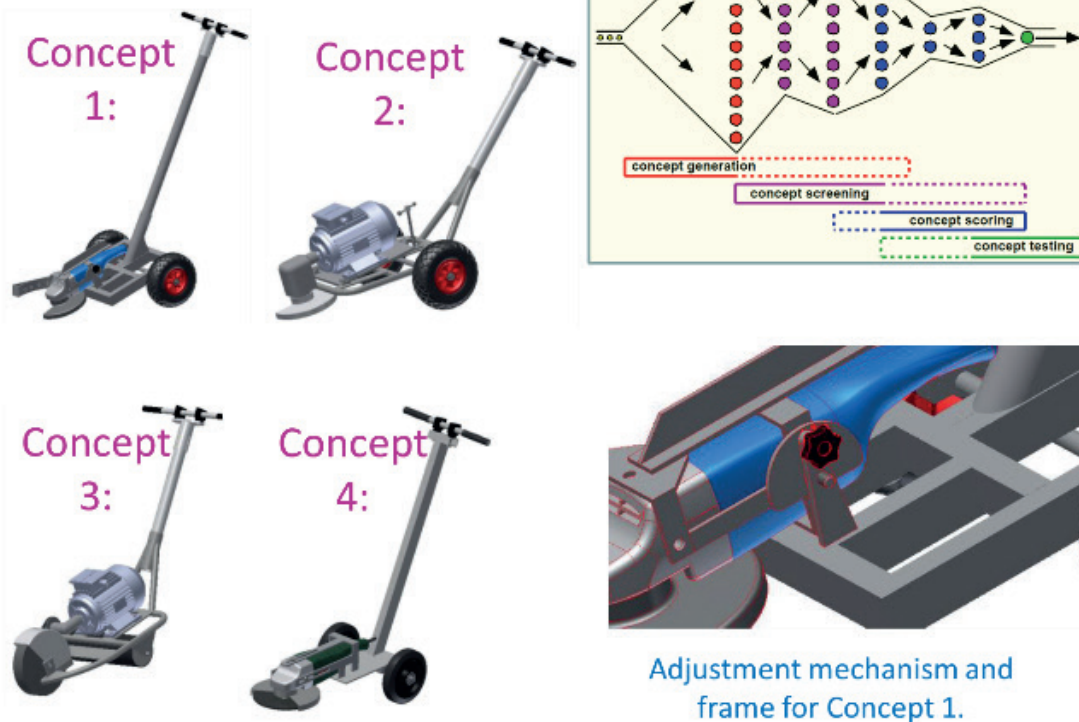


Fig. 2.4. Example of product concept generation

Basic design and engineering calculations performed

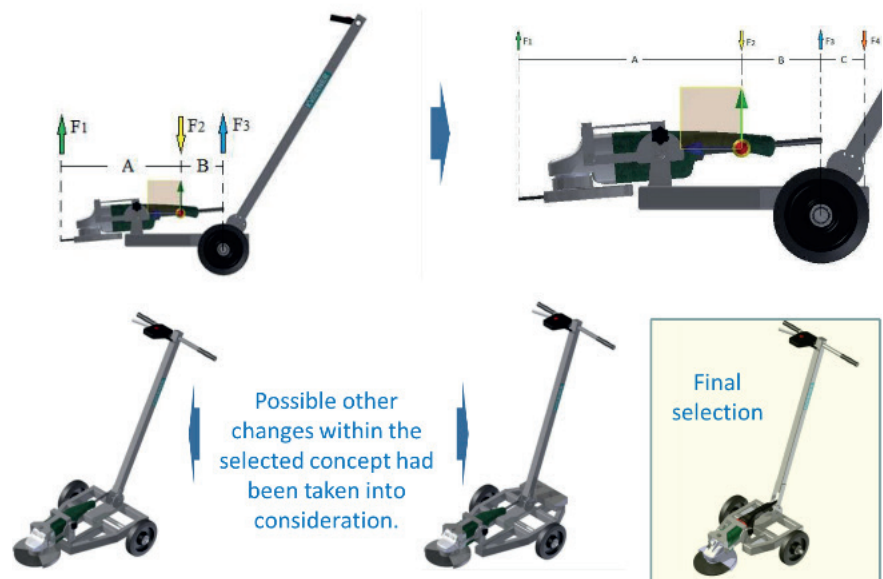


Fig. 2.5. Example of product system-level design

Further analysis and arrangements within the select product concept

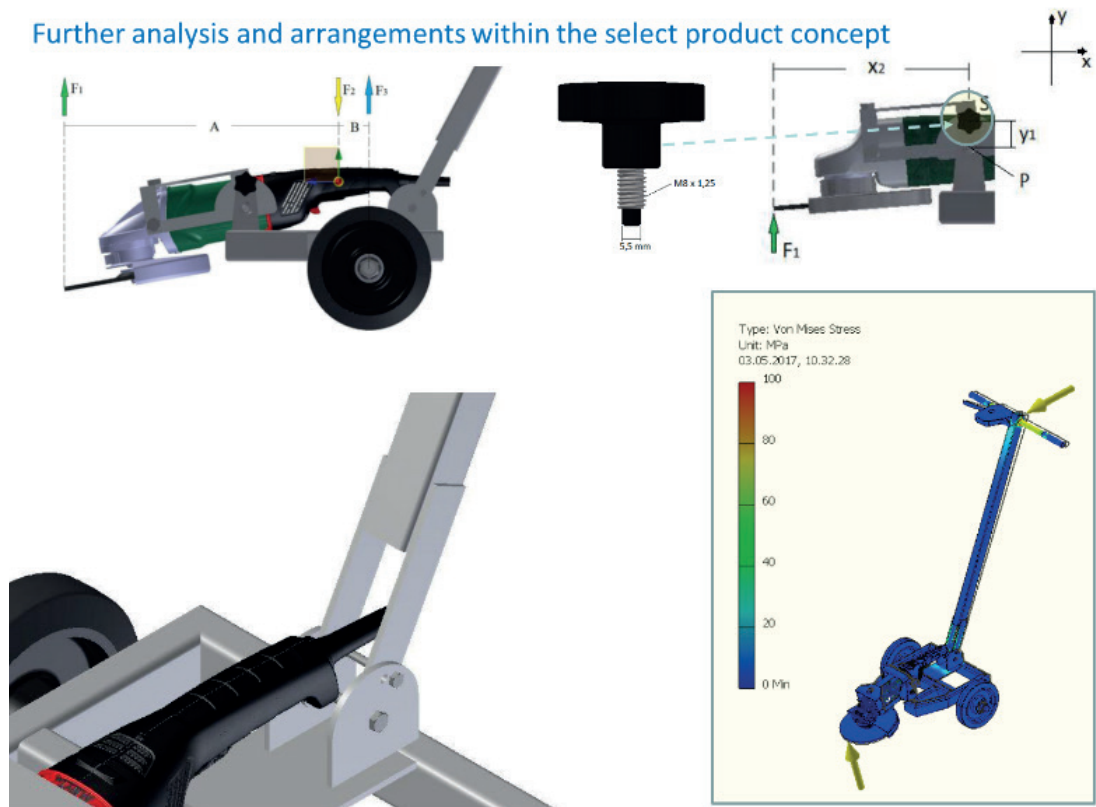
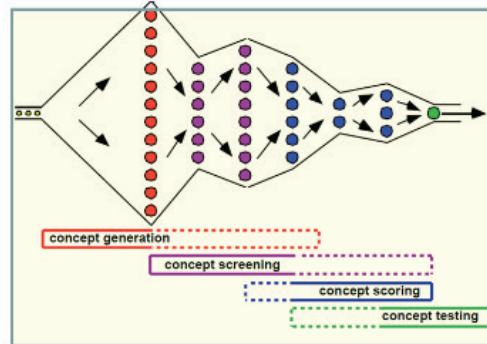
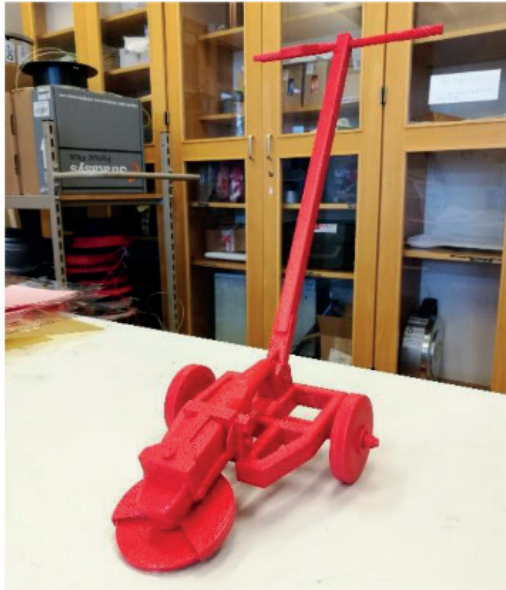


Fig. 2.6. Example of product detail design

Prototyping for Product Concept Testing:
3D Printing – Additive Layer Manufacturing



Material used in 3D printing



3D-printer Fortus 450mc in IMBM, University of Stavanger

Fig. 2.7. Example of product concept testing using additive manufacturing

Product Concept Revision and Improvement

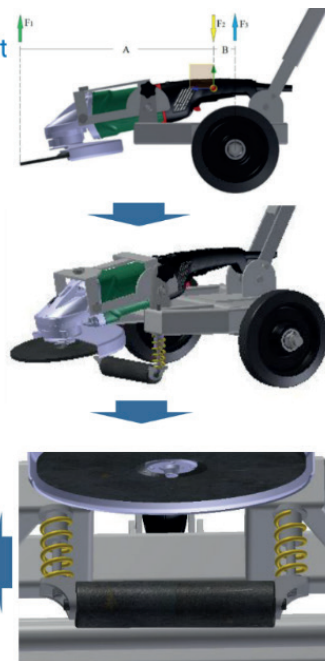
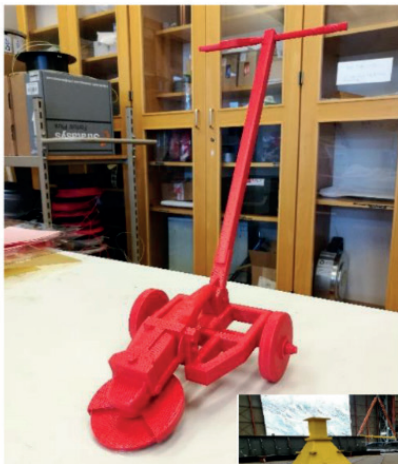


Fig. 2.8. Example of product concept testing and refining

Manufacturing of the Improved Product Concept



Fig. 2.9. Example of product manufacturing

Final Product and Product Performance Testing



Performance analysis

Grinding surface with a new disc

Slip surface with worn disc

Fig. 2.10. Example of product performance testing



Fig. 2.II. Example of final product ready for use or mass scale manufacturing

Source Fig 2.3 – Fig 2.II

Thesis: Product development for a weld grinder

Authors: Even Renolen Litlabø and Øyvind Malmanger

Supervisors:

R.M. Chandima Ratnayake (UIS) – university supervisor

Stig Magne Tveito (Kværner Stord) – company supervisor

University of Stavanger

Due date: 15.05.2017

2.1.2. Digital tools for product development

Examples of digitalization based subtractive and additive manufacturing as well as measurement tools, developments and systems that shall be used for product development work are as follows.

- Mazak 430A: <https://www.mazakeu.com/da/machines/vertical-center-smart-430a/>
- Okuma Genos L3000-e: <https://www.okuma.eu/products/by-technology/turning/genos-l-series/genos-l3000-e/>
- Zeiss Contura: <https://www.zeiss.no/metrology/products/systems/coordinate-measuring-machines/bridge-type-cmms/contura.html>
- Robot arm (Dobot Magician): <https://www.dobot.cc/dobot-magician/specification.html>
- Amazon has great pictures of the setup: <https://www.amazon.com/Dobot-Magician-Educational-Conveyor-Edu-Magician-Belt/dp/B07PPPDFST>
- Ultimaker S5 printer: <https://ultimaker.com/3d-printers/ultimaker-s5>
- Makerbot Replicator 2x (we have two of these, they are old but works): <https://www.komplett.no/product/805953>
- Stratasys Fortus 450mc (large printer): <https://www.protechnorge.no/produkter/stratasys-fdm/fortus-450mc>
- Markforged Mark 2 (composite printer): <https://markforged.com/mark-two/>
- Markforged Metal X: <https://markforged.com/metal-x/>
- Formlabs Form 2 (SLA printer): <https://formlabs.com/store/form-2/>
- Natubots Vit SLS printer (to arrive later this year): <https://natubots.com/vit-sls/?lang=en>

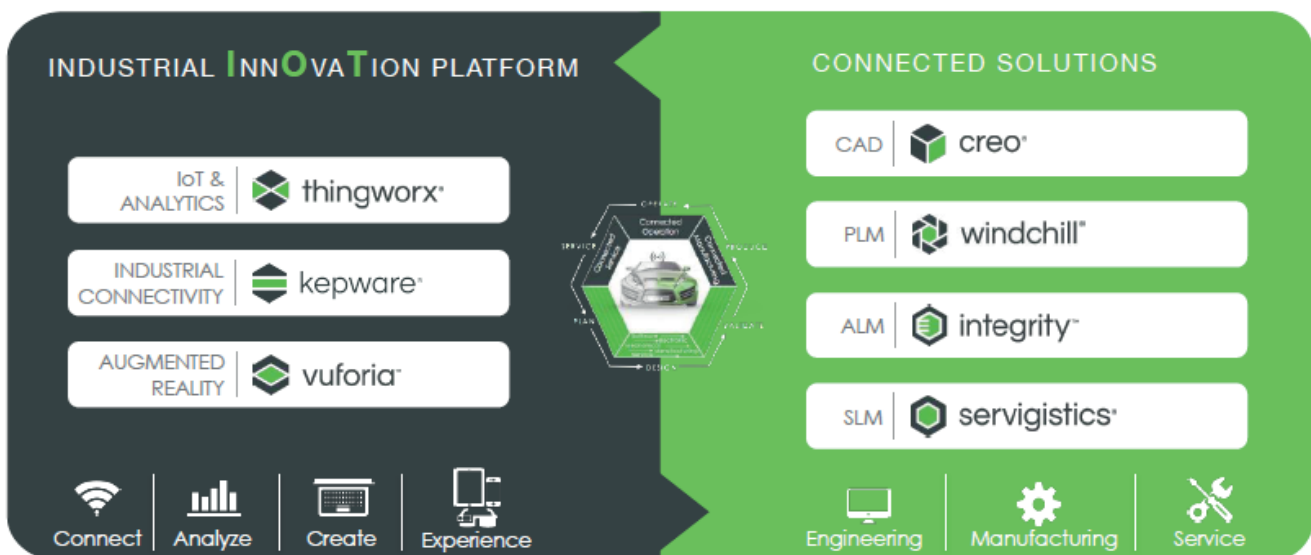


Fig. 2.12. Example connected platform & solutions to enable digital transformation in product development, source: PTC company (<https://www.ptc.com>).

-
- HTC Vive Pro Eye (VR setup): <https://www.atea.no/eshop/product/htc-vive-pro-full-kit/?prodid=4081725>

Apart from above typical 3D modelling tools and finite analysis software together with other Microsoft tools such as MS Excel, MS Words, MS Visio, etc. shall be used. Also, latest developments such as MS PTC platforms and tools shall be used to enhance product development process. Fig. 2.12 provides an example of a connected platform & solutions to enable digital transformation in product development.

Immersive learning concepts potential in PD. Use of Augmented Reality (AR):

Find below a list of free resources to help you get started with our software solutions. You can begin by exploring the courses available on our online training platforms:

1. Fundamentals of AR with Vuforia Studio: <https://www.ptcu.com/enrollment/student/fundamentals-of-ar-development-with-vuforia-studio>
2. Fundamentals of IoT with ThingWorx: https://trainingcentral.ptcu.com/learn/catalog/view/14?ctl0=t-_elearning, where there are the following 3 courses available for free:
 - ThingWorx: Basics of the Edge Connectivity Development Process
 - ThingWorx: Basics of the ThingWorx Development Process
 - ThingWorx: Basics of the ThingWorx Composer

For both Vuforia Studio (AR) and ThingWorx (IoT) solutions, there 2 trials available for free for a limited period:

- Vuforia Studio Trial: <https://trial.studio.vuforia.com/>
- Thingworx Trial: <https://developer.thingworx.com/resources/downloads>

Other interesting materials you may like to take a look at:

- the recently released MOOC about AR in busines
- our main educational solutions and Academic cases studies using Vuforia Studio & other PTC Academic licenses
- European Transformation Center video at RWTH Aachen (E4TC) <https://www.youtube.com/watch?v=ns9PnPL2Kig>
- short references featuring professors talking about technologies like IoT and AR: Teaching Vuforia in University Classrooms and Entertainment Technology to an Industrial Solution and a succes stuory in Austria FH Technikum Wien Case Study

The table 2.1 presents list of exemplary PRODUCT DEVELOPMENT tools available on the market.

Name	Producer	Additional information
Matmatch	Matmatch GmbH	Material Connection Platform. Find and compare materials and connect with suppliers. https://matmatch.com/
Ansys	Ansys, Inc	https://www.ansys.com/products
Inventor	Autodesk	https://www.autodesk.no/products/inventor/overview
SolidWorks	Dassault Systemes	https://www.solidworks.com/
SketchUp	Trimble, Inc	https://www.sketchup.com/
CATIA	Dassault Systemes	https://www.3ds.com/products-services/catia/
PTC Creo		https://www.ptc.com/
SimScale	Simscale	https://www.simscale.com/
LabView	National Instruments	https://www.ni.com/en-no/shop/labview.html

Table 2.1. List of exemplary PRODUCT DEVELOPMENT tools available on the market

Name	Producer	Additional information
WORKFRONT	Workfront, Inc.	https://www.workfront.com/products
TeamGantt		https://www.teamgantt.com/
SurveyMonkey	Bain & Company, Inc	Survey Software. Easy setup for gathering information from customers. https://www.surveymonkey.com/
TypeForm		Survey – Product research, customer survey etc. https://www.typeform.com/
Minitab	Minitab, LLC	https://www.minitab.com/en-us/
NPDsolutions		https://www.npd-solutions.com/npdsoftwaretools/pdtoolkit
Coursera.com		https://www.coursera.org/learn/design#about
Matlab	MathWorks	https://www.mathworks.com/products/matlab.html
Calfem	Lund University	http://www.byggmek.lth.se/english/resources/software/calfem/
Vive	HTC Corp.	https://www.vive.com/us/

Table 2.1. List of exemplary PRODUCT DEVELOPMENT tools available on the market

2.1.3. Literature, exemplary tests and guides for teachers

Literature – list for product development phase

Books

Bhise, Vivek D. *Automotive Product Development. A Systems Engineering Implementation*, 1st edition. CRC Press, Boca Raton, London, New York 2017, ISBN 978-1498706810.

Canuto, E.; Daum, B.; Rödel, M. *SAP PLM (Product Lifecycle Management) Product Development: PPM, VC, DMS, and Beyond*, 1st edition. SAP PRESS. Rheinwerk Publishing Inc., Boston 2017, ISBN 978-1493215201.

Jamnia A. *Introduction to Product Design and Development for Engineers*, 1st edition. CRC Press, Boca Raton 2018, ISBN 978-1315148939, <https://doi.org/10.1201/9781315148939>.

Lynch, M., *Product Development Essentials: Hands-on Help for Small Manufacturers and Smart Technical People*. Kindle Edition, 2014.

Mattson, Ch.A.; Sorensen C.D., *Fundamentals of Product Development: Creating Desirable and Transferable Designs*, 5th edition. Create Space Independent Publishing Platform 2017, ISBN 978-1974606320.

Mattson, Ch.A.; Sorensen, C. *Product Development. Principles and Tools for Creating Desirable and Transferable Designs*. Springer International Publishing, Switzerland 2020, ISBN 978-3-030-14898-0, DOI 10.1007/978-3-030-14899-7, <https://doi.org/10.1007/978-3-030-14899-7>.

Morgan, J.M.; Liker, J.K., *The Toyota Product Development System. Integrating People, Process And Technology*, 1st edition. Productivity Press, 2006, ISBN 9781563272820.

Rafinejad D. *Innovation, Product Development and Commercialization: Case Studies and Key Practices for Market Leadership*. Ross, J. Publishing, Incorporated, 2007, ISBN 9781932159707.

Trott, P. *Innovation Management and New Product Development*, 6th edition. Pearson, 2016, ISBN 978-1292133423.

Ulrich, K.T.; Eppinger S.D. *Product Design and Development*, 6th edition. McGraw-Hill, New York 2016, ISBN 978-0078029066.

Research papers

Isoherranen, V.; Ratnayake, R.M.C. Use of Pull Product Development for Enhancing Lean Startups. Proceedings of the IEEE International Conference on Industrial Engineering and Engineering Management (IEEM), IEEM 2019, 15–18 December, 2019, Macau.

Ratnayake, R.M.C. *Enabling RDM in Challenging Environments via Additive Layer Manufacturing. Enhancing Offshore Petroleum Asset Operations*. Production Planning & Control, accepted for publication, vol. 30, issue 7.

Ratnayake, R.M.C. *Hybridizing MJF Based Additive Layer and CNC Supported Subtractive Manufacturing for Enhancing Productivity in Design Iterations*. Proceedings of the IEEE International Conference on Industrial Engineering and Engineering Management (IEEM), IEEM 2018.

Ratnayake, R.M.C. *On the necessity for risk based product development: process digitalization*. Proceedings of the IEEE International Conference on Industrial Engineering and Engineering Management (IEEM), IEEM 2020.

Websites

<https://www.engineeringtoolbox.com/>

<https://www.leansixsigmadefinition.com/>

<http://www.matweb.com/index.aspx>

<https://mechanicalc.com/>

<https://www.oreilly.com/library/view/product-development2nd/9780127999456/xhtml/Cover.xhtml>

<https://productschool.com/blog/product-management-2/curated-list-tools-software-product-managers-2020/>

Issues that may be used during exams regarding a product development phase

1. Selection of materials for mechanical construction by the use of software.
2. Preparation of sketches and CAD modelling of prototypes.
3. Description of prototype manufacturing techniques and machines.
4. Description of materials used in rapid prototyping.
5. Calculation and prediction of construction elements strength, reliability, durability by the use of software.
6. Description of software digital tools used in product development phase.
7. Analysis of construction wear and comparison to alternatives.
8. Description of construction ergonomics.
9. Experimental methods of prototype testing.
10. Preparation of documentation regarding product development phase.

2.2. Design phase

2.2.1. Methodology of design teaching process

Classes regarding computer aided design (CAD) should concern, among others, 3D modelling of geometrically simple products and parts composed of curvilinear surfaces, preparing 2D construction documentation, creating assemblies and construction optimization. Models developed by students during their classes should be ready to be imported into, among others, the computer aided manufacturing and inspection software for automatic generation of paths of cutting tools and a program cooperating with advanced coordinate measuring machines.

CAD classes should be conducted in a laboratory equipped with computer workstations available for all students and a teacher. The detailed laboratory equipment is presented in Section I. The type of computer workstations depends on requirements of CAD software applied during classes. The sample requirements are presented in Section I. Laboratory classes should be based on specific product examples. The 2D documentation of analysed examples, based on which 3D models are created during CAD classes, should be available for all students.

Each example of modelled parts should be presented to students by a teacher by using a projector. Shown examples should be chosen so that they make it possible to present new functions of CAD software during each class. Moreover, presented examples should be available for students after classes in the form of electronic materials enabling students to consolidation their skills and knowledge obtained during CAD classes.

Students should have the possibility of applying alternative methods of solving problems. They should not just apply methods suggested by a teacher and learned during classes.

Computer workstations of students should be connected to the network which allows the teacher to remotely share materials with students and control their work. Laboratory equipment may also include virtual reality tools that could enable students to visualize 3D models in assemblies and understand problems posed during CAD classes.

The figure 2.13 presents the information flow between the individual stages of a manufacturing process and indicates the place of computer aided design in manufacturing.

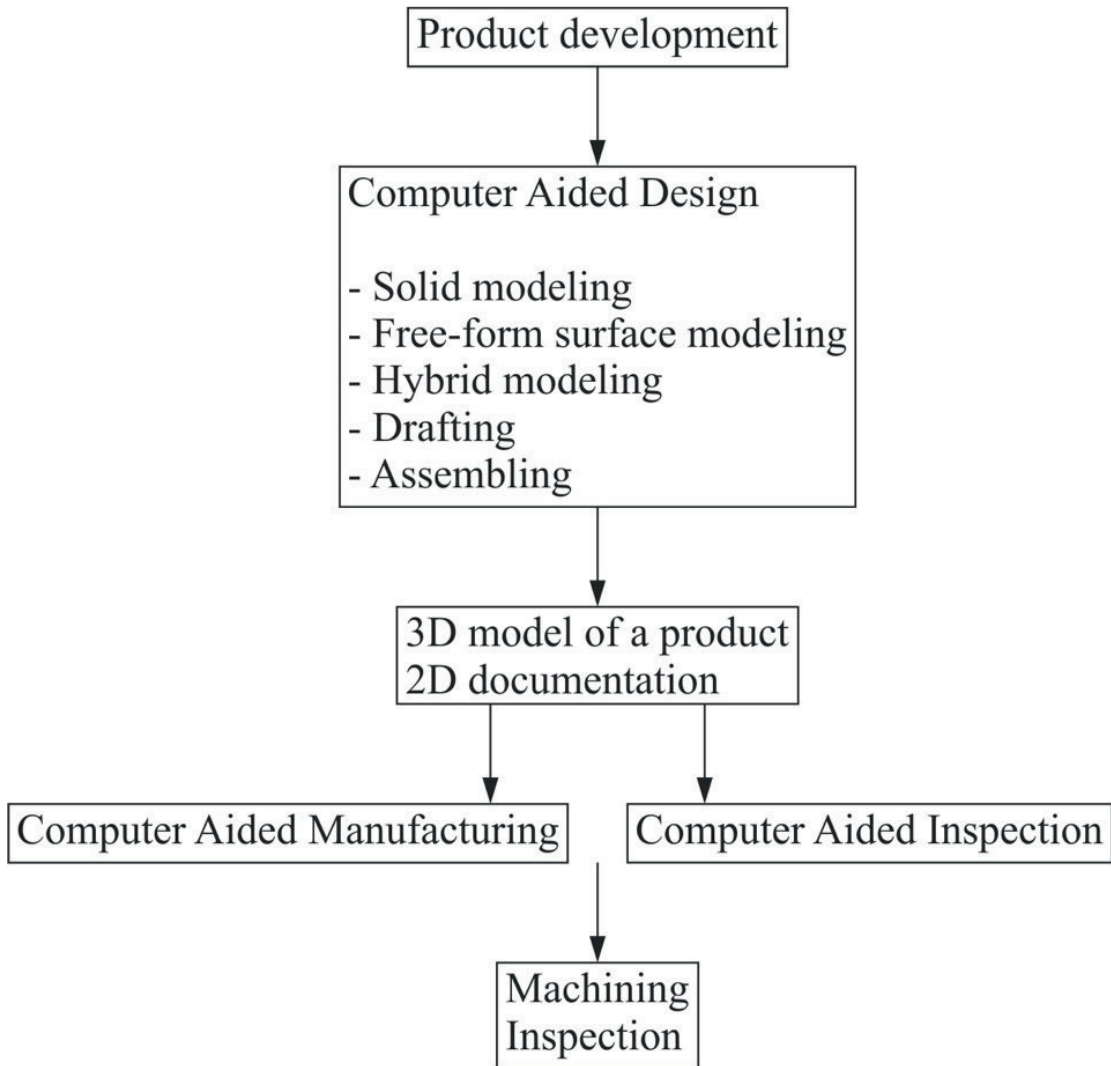


Fig. 2.13. The information flow between the individual stages of a manufacturing process and indicates the place of computer aided design in manufacturing

2.2.2. Digital tools for design

The table 2.2 presents list of exemplary DESIGN tools available on the market.

Name	Producer	Additional information
ACTCAD	Jytra Technology Solutions Private Limited	https://actcad.com/index.php
Alibre 3D CAD	Alibre	https://www.alibre.com/
AutoCAD	Autodesk	https://www.autodesk.com/products/autocad/overview
BricsCAD	Bricsys nv	https://www.bricsys.com/en-eu/bricscad/
CADPRO	Delta Software International LLC	https://www.cadpro.com/
Catia	Dessault Systemes	https://www.3ds.com/products-services/catia/?wockw=card_content_cta_l_url%3A%22https%3A%2F%2Fblogs.3ds.com%2Fcatia%2F%22
Creo	PTC	https://www.ptc.com/en/products/cad/creo
DesignSpark	RS Components Limited	https://www.rs-online.com/designspark/mechanical-software
DraftSight	Dessault Systemes	https://www.3ds.com/products-services/draftsight-cad-software/?wockw=Draftsight

Table 2.2. List of exemplary DESIGN tools available on the market

Name	Producer	Additional information
FreeCAD		https://www.freecadweb.org/
Inventor	Autodesk	https://www.autodesk.com/products/inventor/overview
IronCAD	IronCAD, LLC.	https://www.ironcad.com/design-collaboration-suite/ironcad
KOMPAS-3D	ASCON	http://ascon.net/solutions/kompas_3d
KUBOTEC3D	KUBOTEC3D	https://www.kubotek3d.com/
LibreCAD		https://librecad.org/
NX	Siemens	https://www.plm.automation.siemens.com/global/en/products/nx/nx-for-design.html
Onshape	Onshape inc.	https://www.onshape.com/
OpenSCAD		https://www.openscad.org

Table 2.2. List of exemplary DESIGN tools available on the market

Name	Producer	Additional information
Rhino	Robert McNeel & Associates	https://www.rhino3d.com/
Sharp3D	Shapr3D zrt	https://www.shapr3d.com/industry/engineering
SketchUp	Trimble Inc.	https://www.sketchup.com/
Solid Edge	Siemens	https://solidedge.siemens.com/en/
SOLIDWORKS	Dessault Systemes	https://discover.solidworks.com/solidworks-products?mktid=7745&gclid=CjwKCAiAx_DwBRAfEiwA3vwZYvZRbHRTByTO02b2VgBQcKi-Yv2TtgpiP32wVy3T8fwP___MY8S4ihoCBWgQAvD_BwE
SOLVESPACE	developed by Jonathan Westhues. maintained by whitequark and others.	http://solvespace.com/index.pl
SpaceClaim	SpaceClaim Corporation	http://www.spaceclaim.com/
TurboCAD	IMSI/Design	https://www.turbocad.com/
ZWCAD	ZWSOFT	https://www.zwsoft.com/zwcad/overview

Table 2.2. List of exemplary DESIGN tools available on the market

Name of a CAD system:

Fusion 360

Producer of a measuring system:

Autodesk

Contact information/ website:

<https://www.autodesk.com/products/fusion-360>

Technical specification:

System requirements for the optimal hardware configuration can be found from the manufacturer's website: <https://knowledge.autodesk.com/support/fusion-360/troubleshooting/caas/sfdcarticles/sfdcarticles/System-requirements-for-Autodesk-Fusion-360.html>

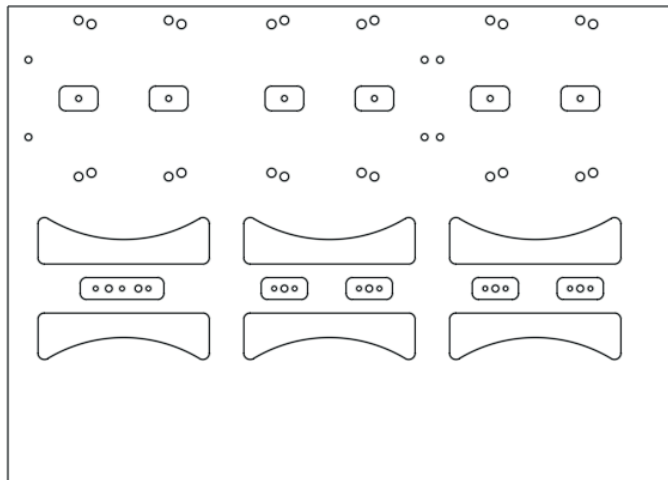
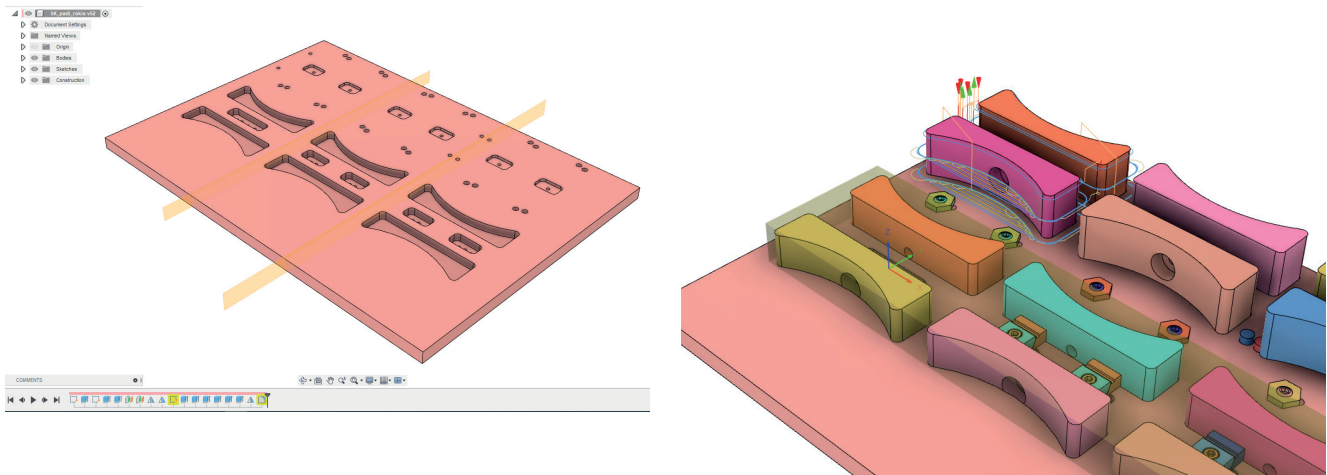
System description:

Fusion 360 is an integrated engineering software package for CAD, CAM, CAE, and PCB. It is offering a wide range of tools well integrated into one package. The tools are grouped into different workspaces like Design and Manufacturing to name a couple. Other workspaces are dedicated to the simulations, rendering, animation and others. Depending on the intent of the process it can be used for design process only. Or activities can be extended to the creation of the technical drawings, photorealistic renderings and so on. Fusion 360 gives access to a wide range of modelling tools for parametric approach, direct modelling, usage of surfaces and forms. All general CAD formats are supported. Also Fusion 360 is capable of working with file formats directly from some of the other CAD systems. On the CAM side of things there is possible to generate toolpaths and NC-code for simple 3-axis CNC milling machines up to 5-axis equipment. In addition to milling CNC turning is available in the same package. A specialized sub-module is available for handling 3D printing related tasks. From simple model preparation tasks up to cumbersome generative design possibilities. In all cases the cloud based platform makes it easy to collaborate on the design with the coworkers etc.

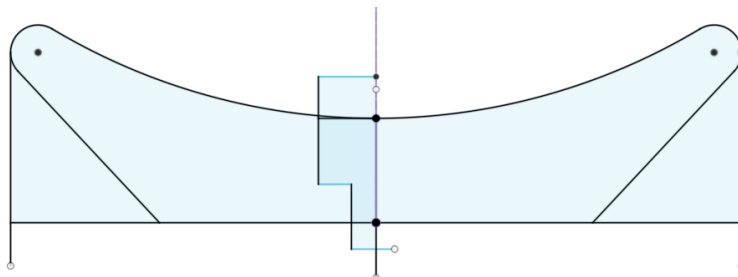
Learning how to use the software has been made easy and accessible. Several high quality self-paced courses are published on the product webpage. Additional support can be found from the social media where dedicated users are sharing their experience with the software.

The software has a friendly pricing policy for business users and academic licenses are available for students and educators.

Photos:
from authors creation



	Materjal: Teras S355	Nähtavate pühitsete: ISO 2678 - f
	Teadis: Anri Siemsonov	Nimetus:
	Kontrollis: Tõnu Leemet	
	Kirjutas: Tõnu Leemet	
 <small>Eesti Maasüsi</small> <small>Estonian University of Life Sciences</small> <small>Tartu</small>		Leht: Täht:



Name of a CAD system:

Ansys SpaceClaim (former SpaceClaim)

Producer of a measuring system:

ANSYS, Inc.

Contact information/ website:

<https://www.ansys.com/products/3d-design/ansys-spaceclaim>

Technical specification:

System requirements for the optimal hardware configuration can be found from the manufacturer's website.

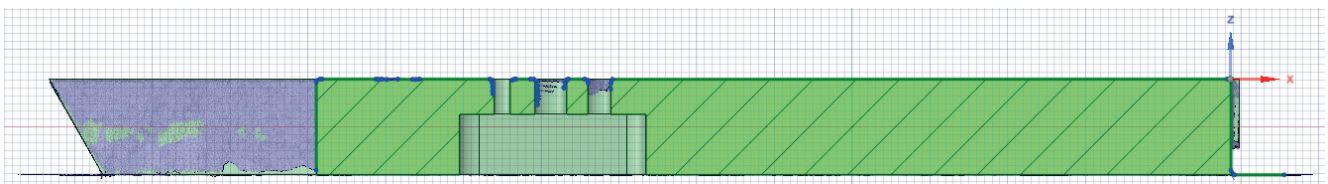
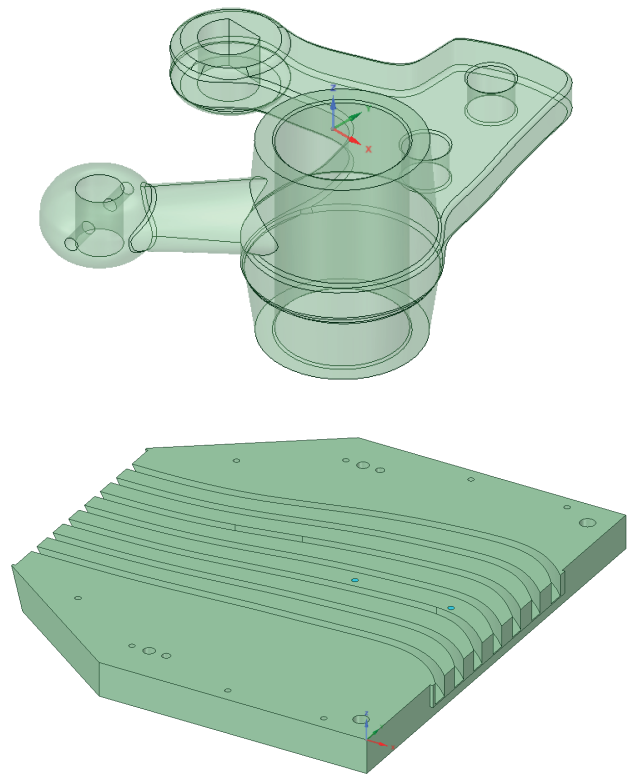
System description:

SpaceClaim is a direct modelling software. Direct modelling is a technique where modelling actions tend to leave no footprint behind. Meaning there is no modelling timeline as such where parameters can be changed iteratively.

Direct geometry alteration is relatively quick and easy. This way lending itself conveniently to conceptual design activities. Majority of the modelling operations are done via the utilization of four main modelling tools Pull, Move, Combine and Blend. Tool guides give rise to different means of utilization of the particular modeling tool.

SpaceClaim is suitable for handling specialized tasks like model de-features, preparation for manufacturing, reverse engineering, 3D printing etc. An additional Facets module gives excellent tools for editing STL models. De-features is a crucial step in preparation for the simulations and analyses. Also it is a must do activity when designing work holding for example. In essence it means that some part of the geometry can be removed from the model as it plays no significance in the foreseen application. When it comes to the complex chain of fillets it might not be a straight forward task to remove them with the conventional CAD package.

Photos:
by authors



Name of a CAD system:

SolidWorks

Producer of a measuring system:

Dassault Systemes

Contact information/ website:

<https://www.solidworks.com/3dexperience-works>

Technical specification:

System requirements for the optimal hardware configuration can be found from the manufacturer's website.

System description:

SOLIDWORKS is an engineering software where you have an opportunity to create your own product lifecycle. This program has its own packages for CAD, CAE, CAM, FEM and PDM software making designing and manufacturing different kind of products very easy. It is mainly known for 3D modelling and simulation but can be used to write codes for part manufacturing or even create a collaboration between workgroups with their own libraries.

SOLIDWORKS consists of three different environments: part, assembly and drawing. Part environment is used to make individual solid parts. There is a wide range of modeling tools such as surfaces, forms and sheet metal to make 3D body creation with various properties very simple. Assembly environment is used for part assemblies, simulations, code writing and also has availability to make parts. In drawing environment different kinds of technical drawings can be made. Each part of the program work together and separately. SOLIDWORKS supports various kinds of file extensions therefore it is possible working with parts or assemblies made in other CAD software.

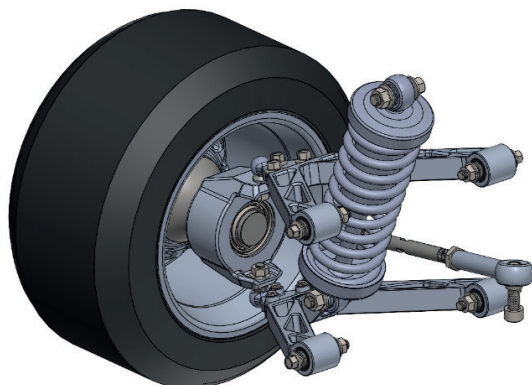
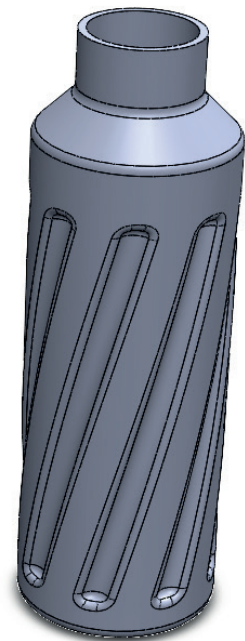
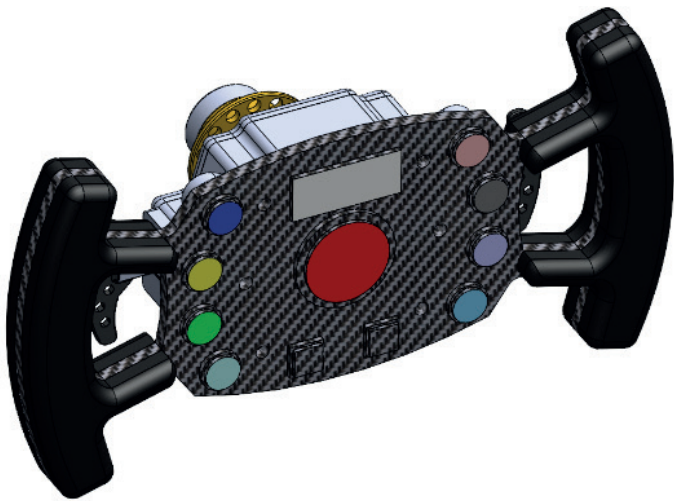
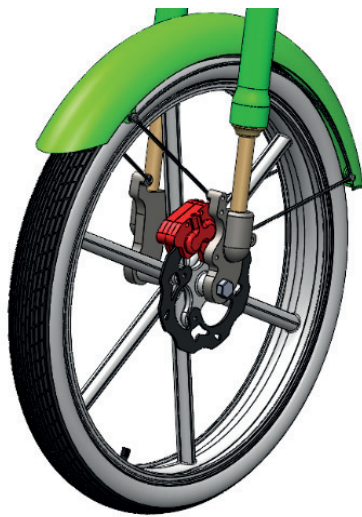
SOLIDWORKS Corporation has made program learning very easy. There are tutorials and online support of 3D community which are accessible from the software and online. Additional support can be found from the social media where dedicated users are sharing their experience with the software.

The software has a friendly pricing policy for students and educators.

Photos:

<https://my.solidworks.com/cadmodels/explore>

Date 02 Feb 2021



2.2.3. Literature, exemplary tests and guides for teachers

Literature – list for design phase

Books

Abbasov, I.B. *Computer Modeling in the Aerospace Industry*. 1st edition, kindle edition. John Wiley & Sons Ltd. and Scrivener Publishing, USA 2019, ISBN 978-1-119-66131-3.

Kumar, G.S. *Geometric Modeling Methods using Point Cloud Data. Computing Techniques for Recognition and Fitting of Free-form Curves and Surfaces*. Lambert Academic Publishing, 2010, ISBN 978-3-843-35912-2.

Mastercam – modelowanie krawędziowe, powierzchniowe i bryłowe. ZALCO Sp. z o.o, Warszawa 2007, <https://www.mastercam.pl/?q=podreczniki>.

Mazur, D.; Rudy, M. *Modelowanie w systemie NX CAD*. Oficyna Wydawnicza Politechniki Rzeszowskiej, Rzeszów 2016, <https://oficyna.prz.edu.pl/otwarty-dostep/monografie/2016/mazur-damian--rudy-marek>.

Michaud, M. *CATIA. Narzędzia i moduły*. Helion, Gliwice 2014, ISBN 978-83-246-8789-3.

Piegl, L.; Tiller, W. *The Nurbs Book*, 2nd edition. Springer-Verlag, Berlin, Heidelberg, New York 1997, ISBN 978-3540615453.

Shih, R. *Parametric Modeling with Siemens NX*. SDC Publications, Mission, KS, USA 2019, ISBN 978-1630572808.

Tickoo, S. *CATIA V5-6R2019 for Designers*. Purdue University Northwest, CAD/CIM Technologies, USA 2020, ISBN 978-1640570863.

Ulrich, K; Eppinger, S.; Yang, M.C. *Product Design & Development*, 7th edition. McGraw Hill Education, 2020, ISBN 978-1260043655 (dostęp wkrótce).

Valentino, J.; DiZinno, N. *SolidWorks for Technology and Engineering*, 2nd edition. Industrial Press, Inc., New York 2012, ISBN 978-0-831-13451-8.

Vukašinović, N; Duhovnik, J. *Advanced CAD Modeling. Explicit, Parametric, Free-Form CAD and Re-engineering*. Springer, Switzerland 2019, ISBN 978-3-030-02398-0, <https://doi.org/10.1007/978-3-030-02399-7>.

Zhuming, B.; Xiaoqin, W. *Computer Aided Design and Manufacturing*, 1st edition, kindle edition. John Wiley & Sons Ltd. and ASME Press, 2020, ISBN 978-1119534211.

State of the art papers

Li, L.; Zheng, Y.; Yang, M.; Leng, J.; Cheng, Z.; Xie, Y.; Jiang, P.; Ma, Y. *A survey of feature modeling methods. Historical evolution and new development*. Robotics and Computer-Integrated Manufacturing 2020, vol. 61, ISSN 0736-5845, <https://doi.org/10.1016/j.jclepro.2017.06.204>.

Pernot, J.P.; Falcidieno, B.; Giannini, F.; Leon, J.C. *Incorporating free-form features in aesthetic and engineering product design: State-of-the-art report*. Computers in Industry 2008, vol. 59, issue 6, pp. 626-637, ISSN 0166-3615, <https://doi.org/10.1016/j.compind.2008.03.004>.

Research papers

Di Angelo, L.; Di Stefano, P.; Morabito, A.E. Fillets, rounds, grooves and sharp edges segmentation from 3D scanned surfaces. Computer-Aided Design 2019, vol. 110, pp. 78-91, ISSN 0010-4485, <https://doi.org/10.1016/j.cad.2019.01.003>.

Hong, y.; Park, Y.; Kim, M.S.; Elber, G. *Trimming offset surface self-intersections around near-singular regions*. Computers & Graphics 2019, vol. 82, pp. 84-94, ISSN 0097-8493, <https://doi.org/10.1016/j.cag.2019.05.016>.

Kutin, A.; Dolgov, V.; Sedykh, M.; Ivashin, S. *Integration of different computer-aided systems in product designing and process planning on digital manufacturing*. Procedia CIRP 2018, vol. 67, pp. 476-481, ISSN: 2212-8271, <https://doi.org/10.1016/j.procir.2017.12.247>.

Li, Z.; Wang, J.; Anwar, M.S.; Zheng, Z. *An efficient method for generating assembly precedence constraints on 3D models based on a block sequence structure*. Computer-Aided Design 2020, vol. 118, ISSN 0010-4485, <https://doi.org/10.1016/j.jclepro.2017.06.204>.

Webpages

<https://b2b.partcommunity.com/community/>

<https://cad.pl/>

<https://gallery.autodesk.com/>

<https://grabcad.com/>

<https://www.3dcontentcentral.com/>

Issues that may be used during exams regarding a designing process

1. Modelling methods by using computer aided designing software.
2. Idea of the reverse engineering process.
3. Stages of the reverse engineering process.
4. Mathematical description of free-form curves and curvilinear surfaces.
5. Parametric modeling.
6. Direct modelling.
7. Designing by using the virtual reality.
8. 2D and 3D documentation. Advantages and disadvantages.
9. Integration of 3D documentation with computer aided inspection software.
10. Review of standards regarding technical documentation of a product.

2.3. Manufacturing phase

2.3.1. Methodology of manufacturing teaching process

Manufacturing classes concern many areas such as: manufacturing techniques, technological process planning, CAD/CAM programming, technological databases, machines and technological equipment design and exploitation, etc. (Fig 2.14). The classes are performed mainly as lectures, projects and laboratories. Theoretical issues can be presented during presentations in dedicated lecture rooms. However, practical issues should be addressed to laboratories and projects. Manufacturing is one of the most challenging phases of production process and teaching of it requires practical experience of students. However, safety issues must be strongly taken into consideration. The student's access to equipment is on the one hand important and on the other may cause the need of supervision from a teacher because of safety. In the case of laboratories students are usually familiarized with the use of machines, fixtures, tools or conduct the tasks in computer laboratories which are necessary in CAD/CAM classes.

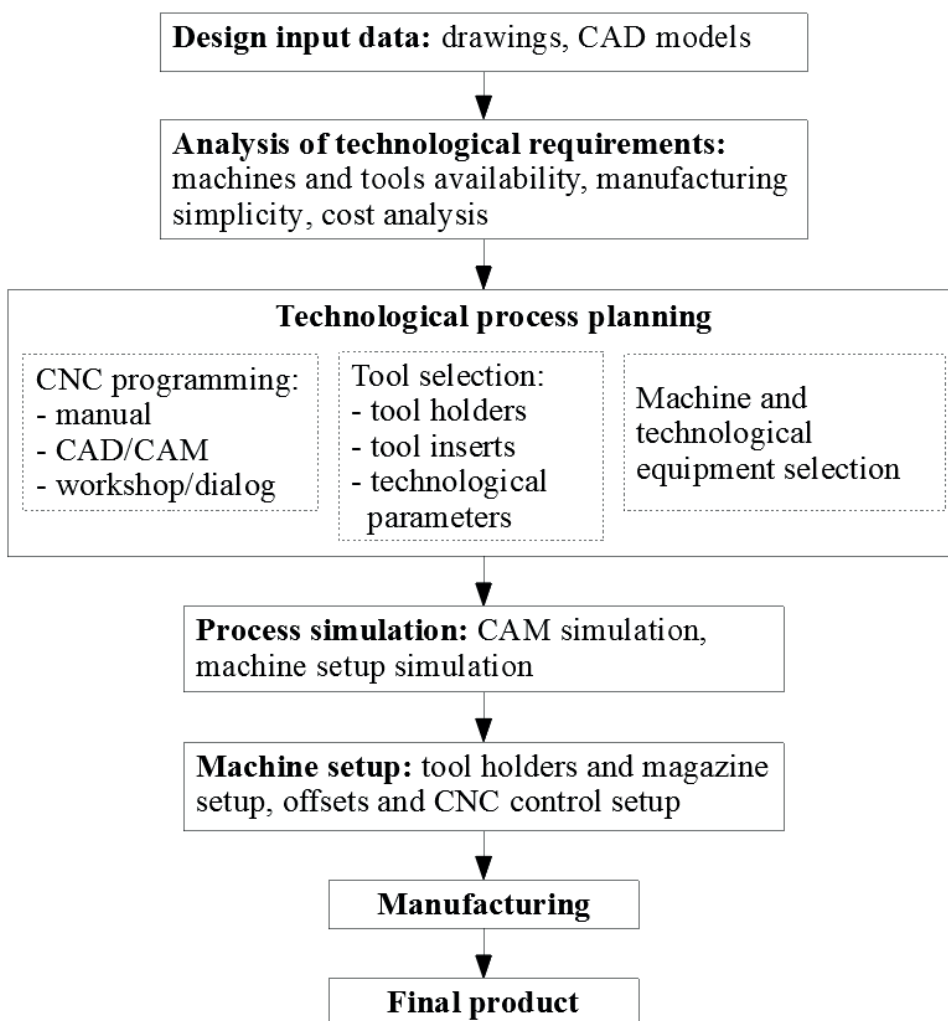


Fig. 2.14. General steps being taught within manufacturing phase

2.3.2. Digital tools for manufacturing

The table 2.3 presents list of exemplary CAM (MANUFACTURING) tools.

Name	Producer	Additional information
NX CAM	Siemens	https://www.plm.automation.siemens.com/global/en/products/nx/
Edgecam SURFCAM ALPHACAM RADAN VISI	Hexagon	http://www.edgcam.com
Mastercam	CNC Software, Inc.	https://www.mastercam.com
SolidCAM	SolidCAM GmbH	https://www.solidcam.com
SOLIDWORKS CAM	Dassault Systèmes	https://www.3ds.com/products-services/solidworks

Table 2.3. List of exemplary CAM (MANUFACTURING) tools available on the market

Name	Producer	Additional information
Autodesk HSM Fusion 360 FeatureCAM PowerMill	Autodesk Inc.	https://www.autodesk.com/solutions/manufacturing/cam
ESPRIT	DP Technology Corp.	http://www.espritcam.com
HSMXpress	Autodesk Inc.	https://www.autodesk.com/campaigns/hsm-free-solidworks
TopSolid'CAM	Missler Software	https://www.topsolid.com/products/topsolidcam.htm
Space E	NTT Data Engineering Systems Corporation (NDES)	http://www.nttd-es.co.jp/en/products
SprutCAM	SPRUT Technology	https://www.sprutcam.com/sprutcam-and-solutions/sprutcam

Table 2.3. List of exemplary CAM (MANUFACTURING) tools available on the market

Name	Producer	Additional information
GibbsCAM Cimatron	3D Systems, Inc.	https://www.3dsystems.com/software/gibbscam
Adem	ADEM Group of Companies	https://adem.ru/products/cam
SmartCAM	SmartCAMcnc	http://www.smartcamcnc.com/index.php
ZW3D	ZWSOFT CO., LTD.	https://www.zwsoft.com/zw3d/capabilities/cam
BobCAD-CAM BobCAM for SOLIDWORKS	BobCAD- CAM, Inc.	https://bobcad.com/?source=LOGO
HyperMILL	Open Mind Technologies AG	https://www.openmind-tech.com

Table 2.3. List of exemplary CAM (MANUFACTURING) tools available on the market

Name	Producer	Additional information
Lantek Expert	Lantek	https://www.lanteksms.com
CamBam	HexRay LTD	http://www.hexray.com
Plug-ins	MecSoft Corporation	https://mecsoft.com/all-products
GO2cam	GO2cam International	http://www.go2cam.net
PEPS CAD/ CAM SYSTEM V8	Camtek GmbH	https://en.camtek.de
Plug-ins	SolutionWare Corporation	https://www.solution-ware.com

Table 2.3. List of exemplary CAM (MANUFACTURING) tools available on the market

Name of a machine:

Pinacho Rayo 165

Producer of a machine:

Pinacho

Contact information / website of a machine producer:

Metalúrgica Torrent S.A.

Partida de la Sierra, s/n.

22310 Castejón del Puente.

Huesca (España)

+34 974 40 16 50

info@metosagroup.com



Technical specifications of a machine:

Centre Height 165 mm
Distance Between Centers 750–1000 mm
Swing Over Bed 335 mm
Swing Over Carriage 310 mm
Swing Over Cross Slide 168 mm
Bed Width 250 mm
Main Spindle Bore 42 mm
Tailstock Shank Diameter 58 mm
Spindle Speed Range 0–4000 rpm
Power Capacity 5.5 kW
Feedrate (Z, X) 0–10000 mm/min
Rapid Traverse (Z, X) 15 m/min
Dimensions LxBxH 2380x1510x1550 mm
Weight 1400 kg

Software cooperating with a machine:

Fanuc Manual Guide i

Manufacturing capabilities of a machine:

CNC lathe Pinacho RAYO 165 for the machining of small and medium-sized parts in single and serial production. The lathe can machine parts at a spindle speed that varies from 0 to 4000 rpm. By using a variety of tools and gadgets, the machine can perform various turning, drilling, threading, boring and other machining works. The lathe has an 8-seat automatic horizontal tool turret and can automatically change the tools specified in the program. The tool can be cooled by the coolant through the side cooler, and can also be operated without using it. The machine is controlled by the Fanuc 21i-TC controller. The machine can be connected to a PC by using the RS232 connection, and the process can be controlled directly from it, or else the program can be manually entered by using the keyboard.

Possibilities of using a machine in education:

The CNC Pinacho RAYO 165 may be used to present fundamentals of the CNC programming with simulation software or universal programming language G-codes. A lecturer may present the stages of CNC programming using different types of manufacturing processes, basics of CNC program set up, subprograms and machining cycles. Moreover, the CNC Pinacho RAYO 165 may be used to present the digitalization process. Students may also gain knowledge in the field of operation, programming subjects.

Name of a machine:

LEADWELL V-20

Producer of a machine:

LEADWELL

Contact information / website of a machine producer:

LEADWELL CNC MACHINES MFG.,CORP.

No.8, Xingke Road, Houli District, Taichung City 421007, Taiwan

886-4-25589008

sales@leadwell.com.tw



Technical specifications of a machine:

X-Travel 510 mm

Y-Travel 350 mm

Z-Travel 400 mm

Turning Speed Range 80-8000 rpm

Max Torque 35 Nm

Power Capacity 5.5/7.4 kW

Table Surface Area 600x350 mm

Max. Table Load 200 kg

Feedrate Speeds (X, Y, Z) 10000 mm/min

Rapid Traverse (X, Y, Z) 24 m/min

Dimensions LxBxH 2983x1745x2504 mm

Weight 3000 kg

Software cooperating with a machine:

Fanuc Manual Guide i

Manufacturing capabilities of a machine:

The CNC Universal Vertical Machining Center Leadwell V-20 with automatically changeable tools for machining small and medium-sized parts in single and serial production. The machining center can machine parts at a spindle speed that varies from 80 to 8000 rpm. The large machine power (5.5/ 7.4 kW) and torque (35 Nm) allow machining at high cutting speeds. By using a variety of tools and gadgets, the machine can perform various milling, drilling, threading, boring and other types of machining work.

Possibilities of using a machine in education:

The CNC Leadwell V-20 may be used to present fundamentals of the CNC programming with simulation software or universal programming language G-codes. A lecturer may present the stages of cnc programming using different types of manufacturing processes, basics of cnc program set up, subprograms and machining cycles. Moreover, the CNC Leadwell V-20 may be used to present the digitalization process. Students may also gain knowledge in the field of operation, programming subjects.

Name of a machine:

Deckel Maho DMU 35M

Producer of a machine:

Deckel & Maho

Contact information / website of a machine producer:

Gildemeister straÙe 60 D-33689 Bielefeld, Germany

Phone : +49(0)5205/74-0



Technical specifications of a machine:

X-Travel, 350 mm

Y-Travel, 240 mm

Z-Travel, 340 mm

Turning Speed Range 20-6300 rpm

Max Torque 80 Nm

Power Capacity 6.3/10 kW

Table Surface Area 400x280 mm

Max. Table Load 100 kg

Feedrate Speeds (X, Y, Z) 5000 mm/min

Rapid Traverse (X, Y, Z) 5 m/min

Dimensions LxBxH 1700x2100x2100 mm

Weight 1600 kg

Software cooperating with a machine:

Siemens Sinumerik Shopmill

Manufacturing capabilities of a machine:

The CNC Universal Vertical Milling Machine Deckel Maho DMU 35M (3+2 axis) with manually changeable tools for machining small and medium-sized parts in single and serial production. The machining center can machine parts at a spindle speed varying from 20 to 6300 rpm. The extensive machine power (6.3/ 10 kW) and torque (80 Nm) allow machining at high cutting speeds. By using a variety of tools and gadgets, the machine can perform various milling, drilling, threading, boring and other machining types of work. The operator by using the pneumatic clamping device can manually replace the tool on the machine. The tool can be cooled by the coolant through the axle and the side cooler, and can also be operated without using it. The machine is controlled by the Siemens Sinumerik 840D controller. The machine can be connected to a PC, and the machining process can be controlled directly from it or the program can be manually entered by using the keyboard.

Possibilities of using a machine in education:

The CNC Universal Vertical Milling Machine Deckel Maho DMU 35M may be used to present fundamentals of the CNC programming with simulation software or universal programming language G-codes. A lecturer may present the stages of cnc programming using different types of manufacturing processes, basics of cnc program set up, subprograms and machining cycles. Moreover, the Deckel Maho DMU 35M may be used to present the digitalization process. Students may also gain knowledge in the field of operation, programming subjects.

Name of internet-based tool	Provider	Information
Cutting speed calculator	Sandvik Coromant	https://www.sandvik.coromant.com/pl-pl/products/Pages/toolguide.aspx
Tool Guide	Sandvik Coromant	https://www.sandvik.coromant.com/pl-pl/products/Pages/toolguide.aspx
Smart Tool Recommendation		http://www.ygl.co.kr/finder/main/index.asp?LangSelect=ENG
Iscar Tool Advisor	Iscar	https://www.iscar.com/ita/MainPage.aspx

Table 2.4. Exemplary Internet-based digital tools for manufacturing

Additional sources of digital tools for manufacturing phase:

<https://www.emco-world.com/en/products/industrial-training/softwarecontrols.html>

<https://www.dormerpramet.com/pl-pl/news-media/media-library>

2.3.3. Literature, exemplary exam tests and guides for teachers

Literature – list for manufacturing phase

Books

Bowman, M. *CNC Milling in the Workshop (Crowood Metalworking Guides)*. Illustrated edition. Crowood Press, Marlborough, UK 2014, ISBN 978-1847975126.

Evans, K. *Programming of CNC Machines*, 4th edition. Industrial Press Inc., New York 2016, ISBN 978-0831135249.

Feld, M. *Podstawy projektowania procesów technologicznych typowych części maszyn*. Wydawnictwo Naukowe PWN, WNT, Warszawa 2018, ISBN 978-8-30119-761-2.

Fitzpatrick, M. *Machining and CNC Technology*, 4th edition, kindle edition. McGraw-Hill Higher Education, New York 2018, ISBN 978-1259827440.

Geng, H. *Manufacturing Engineering Handbook*, 2nd edition. McGraw Hill, New York 2015, ISBN 978-0-07183-977-8.

Habrat, W. *Obsługa i programowanie obrabiarek CNC. Podręcznik operatora*. Wydawnictwo KaBe, Krosno 2015, ISBN 978-83-627606-2-6.

Harvey, J. *CNC Trade Secrets. A Guide to CNC Machine Shop Practices*. Industrial Press, Inc., 2014, ISBN 978-0831135027.

Harvey, J. *Machine Shop Trade Secrets*, 2nd edition. Industrial Press, Inc., 2013, ISBN 978-0831134778.

Hoffman, P.J.; Hopewell E.S. et al. *Precision Machining Technology*. Cengage Learning, New York 2019, ISBN 978-1285444543.

Honczarenko, J. *Obrabiarki sterowane numerycznie*. PWN, Warszawa 2017, ISBN 978-8-30119-728-5.

Kalpakjian, S.; Schmid, S. *Manufacturing Engineering & Technology*, 7th edition. Pearson, Illinois Institute of Technology 2014. ISBN 978-9-33258-790-8.

Kibbe, R.R.; Meyer R.O.; White W.; Neely J.; Stenerson J.; Curran, K. *Machine Tool Practices*, 10th edition. Pearson, 2014, ISBN 978-0132912655.

Krar, S.; Gill, A.; Smid, P.; Gerritsen, R.J. *Technology Of Machine Tools*, 9th edition. McGraw Hill Education, New York 2020, ISBN 978-1-26008-793-2.

Mastercam X2 Komputerowe wspomaganie projektowania i wytwarzania, wyd. I. ZALCO Sp. z o. o., Warszawa 2007, ISBN 987-83-923687-3-1, https://www.mastercam.pl/dload/podreczniki/Komputerowe_wspomaganie-Mastercam_X2.pdf.

Niesłony, P. *Podstawy programowania maszyn CNC w systemie CAD/CAM Mastercam*. BTC, Legionowo 2012, ISBN 978-83-60233-89-4.

NX CAM Virtual Machine Podręcznik Programisty, e-book. CAMdivision, Wrocław 2018, <https://www.camdivision.pl/pl/produkty/nx-cam>.

Qasim, R. *Tool Path Planning for Free-Form Surfaces of CNC Milling Machine. Investigation of Tool Path Generation*. Lambert Academic Publishing, 2016, ISBN 978-36-593483-5-8.

Rausa, L. *CNC 50 Hour Programming Course*, 2nd edition. CreateSpace Independent Publishing Platform, New York 2018, ISBN 978-1493713578.

Scheer A.W. *CIM Computer Integrated Manufacturing Towards the Factory of the Future*. Springer-Verlag, Berlin Heidelberg 1994, ISBN 978-3-642-78990-8, <https://doi.org/10.1007/978-3-642-78988-5>.

Smid, P. *CNC Control Setup for Milling and Turning*. Industrial Press Inc., New York 2010, ISBN 978-0831133504.

Smid, P. *CNC Programming Handbook*, 3rd edition. Industrial Press Inc., New York 2007, ISBN 978-0831133474.

Smid P. *CNC Programming Techniques*. Industrial Press Inc., New York 2005, ISBN 978-0831131852.

Smid, P. *CNC Tips and Techniques. A Reader for Programmers*. Industrial Press Inc., 2013, ISBN 978-0-83113-472-3.

Smid, P. *Fanuc CNC Custom Macros. Programming Resources for Fanuc Custom Macro B Users*. Industrial Press Inc., New York 2005.

Suk-Hwan Suh, S.H.; Kang, S.K. et al. *Theory and Design of CNC Systems*. Springer Series in Advanced Manufacturing. Springer-Verlag, London 2008, ISBN 978-1-84800-335-4, <https://doi.org/10.1007/978-1-84800-336-1>.

Thompson, R. *Manufacturing Processes for Design Professionals*. Thames & Hudson, London 2007, ISBN 978-0-50051-375-0.

Xu, X.; Nee, A.Y.C. (eds.). *Advanced Design and Manufacturing Based on STEP*. Springer-Verlag, London 2009, ISBN 978-1-84882-738-7, <https://doi.org/10.1007/978-1-84882-739-4>.

State of the art papers

Chryssolouris, G.; Mavrikios, D.; Papakostas, N.; Mourtzis, D.; Michalos, G.; Georgoulas, K. Digital manufacturing: history, perspectives, and outlook 2009, vol. 223, issue 5, pp. 451-462, <https://journals.sagepub.com/doi/10.1243/09544054JEM1241>.

Habrat W.; Wdowik R. *Ustawianie maszyny sterowanej numerycznie*. Przemysłowy Instytut Automatyki i Pomiarów, Warszawa., *Pomiary Automatyka Robotyka* 2012, z. 2, t. 16, 2012, s. 52-57.

Lan H. *Web-based rapid prototyping and manufacturing systems: A review*. *Computers in Industry* 2009, vol. 60, issue 9, pp. 643-656, <https://doi.org/10.1016/j.compind.2009.05.003>.

Research papers

Andersson, O.; Semerea, D.; Melandera, A.; Arvidsson, M.; Lindberg, B. *Digitalization of process planning of spot welding in body-in-white*. Procedia CIRP 2016, vol. 50, pp. 618-623, <https://doi.org/10.1016/j.procir.2016.05.082>.

Mashinini, P.M., Soni, H.; Gupta, K. Investigation on dry machining of stainless steel 316 using textured tungsten carbide tools. *Materials Research Express* 2019, vol. 7, no. 1, <https://iopscience.iop.org/article/10.1088/2053-1591/ab5630>.

Wdowik, R.; Ratnayake, R.M.C: *Open Access Digital Tool's Application Potential in Technological Process Planning: SMMEs Perspective*. IFIP Advances in Information and Communication Technology (AICT). *Advances in Production Management Systems. Towards Smart Production Management Systems*, Springer, 312-319, 2019, https://link.springer.com/chapter/10.1007%2F978-3-030-29996-5_36.

Webpages

<https://academy.titansofcnc.com/>

www.haascnc.com

<https://www.sandvik.coromant.com/en-gb/knowledge/pages/default.aspx>

<https://www.cnc-academy.com/>

<https://www.iscar.pl/newarticles.aspx/countryid/11/newarticleid/2393>

http://www.mitsubishicarbide.com/en/technical_information#section-2

<https://www.sandvik.coromant.com/en-gb/knowledge/pages/default.aspx>

Issues that may be used during exams regarding a manufacturing phase

1. Technological process planning.
2. Definition of machining/manufacturing tasks in CAM software.
3. Configuration of machine tools.
4. Description of different CAM software tools.
5. Machine tool setup supported by the digital tools.
6. Selection of tools by the use of software and internet tools.
7. Design and setup of fixtures.
8. Process simulation in CAM software.
9. CNC programming – direct, dialog, CAD/CAM.
10. NC code verification, CAM postprocessing and program testing.

2.4. Inspection phase

2.4.1. Methodology of inspection teaching process

Proposed methodology of conducting classes regarding the modern inspection techniques on the example of the subject *Coordinate measuring technique*

The subject regarding the modern inspection methods of geometrical quantities should include both theoretical and practical classes with students. Theoretical classes should be conducted in the form of lectures, while practical ones may be performed as laboratories. In the case of the subject *Coordinate measuring technique*, the minimum number of hours of lectures should be equal to 15, just like in the case of laboratories.

Theoretical classes should be realized by using multimedia presentations, visualizing e.g., the fundamentals of the coordinate measuring technique and materials shared by producers of e.g., coordinate measuring systems. Producers of advanced measuring systems share information concerning their measuring gages via e.g., their YouTube channels and websites. The example of the manufacturer of measuring systems that publishes extensive educational materials is the Carl Zeiss company.

The lectures on the subject *Coordinate measuring technique* may include: the stages of contact and non-contact coordinate measurements, the explanation of the probe radius correction process, the methods of calculating corrected measurement points based on their indicated counterparts, the types of associated elements applied in the coordinate measuring technique, the algorithms of the distribution of measurement points on measured surfaces of investigated parts, the fundamentals of coordinate measurements of free-form surfaces and the review of the elements having the influence on the accuracy of coordinate measurements and results of measurements.

Lecture content should be constantly supplemented with new results of investigations (regarding e.g., the metrology of geometrical quantities, reverse engineering process and coordinate measuring technique) included in articles published by well-known worldwide publishers (e.g., Elsevier, Springer and MDPI). Moreover, lectures may be also supported by educational materials available to students in the form of e-learning courses, which may include control questions verifying students' knowledge gained during theoretical classes. Additionally, electronic materials available as e-learning courses may consolidate students' knowledge in the field of e.g., the coordinate measuring technique.

In addition, lectures regarding e.g., the subject *Coordinate measuring technique* may be enriched by the presentation of stages of programming of measuring systems. Programming process may be conducted by means of metrological software working in the off-line mode. The example of the off-line software cooperating with coordinate measuring machines (CMMs) is the Calypso software produced by the Carl Zeiss company. In the case of the Renishaw company, the Productivity + is the off-line software, supporting the on-machine measurements, which may be used during lectures. Both software packages may be easily presented to students during classes.

Students after lectures (regarding e.g., the coordinate measuring technique) should be aware of factors influencing the accuracy of coordinate measurements. This knowledge will enable them to plan the correct strategy of coordinate measurements characterized by the highest possible accuracy.

The consultations with a teacher regarding a content presented during lectures should also be conducted remotely by using e.g., the Microsoft Teams software package.

Practical classes should be carried out in the form of laboratory classes. In the case of the subject Coordinate measuring technique, a measurement laboratory should be equipped with at least one coordinate measuring machine, which would be used to present measurement programs created during laboratory classes. Practical classes should concern measurements of products characterized by regular geometric shapes and parts composed of curvilinear surfaces e.g., turbine blades. Additionally, students should have the access to metrological software available in the off-line version. The number of licenses of off-line measurement software should correspond to the number of students of a laboratory group.

The first laboratory class should concern the explanation of the fundamentals of operation of e.g., a coordinate measuring machine and the basic steps of programming of measuring systems. The next practical class may regard e.g., coordinate measurements of turbine blades and measurements of different types of gears. Measurement programs should be prepared in the off-line mode by using software packages enabling simulations of measurements. Inspection programs should be prepared by all students based on the detailed analysis of technical documentation of a product, which may be available in the form of 2D drawings and 3D CAD models with measurement characteristics. Documentation of a measured product should be provided by a teacher. Created measurement programs should be compatible with up-to-date standards concerning the metrology of geometrical quantities (e.g., ISO 1101).

Off-line software packages of coordinate measuring machines enable simulations of coordinate measurements by using 3D models of a coordinate measuring machine, a measuring probe and a probing system. The simulation of coordinate measurements, conducted by means of a CMM, is aimed at e.g., verifying the existence of collisions which may occur between a measured part and an applied stylus of a measuring probe.

The best measurement program / programs, prepared in the off-line mode by students during laboratory classes, should be run on a coordinate measuring machine. The results of real coordinate measurements enable students to prepare reports regarding completed exercises.

Laboratory classes, just like lectures, may also be supported by educational materials available in the form of e-learning courses. These materials may include e.g., movies visualizing real coordinate measurements conducted during practical classes. These movies may help students in drawing conclusions from conducted research.

Reports should be prepared by students after laboratory classes. Students' reports may include a purpose and a scope of a class, a description of an applied measuring system, its technical specifications and stages of an exercise. Each report should include results of measurements and conclusions drawn based on conducted investigations.

The proposed methodology of conducting laboratory classes regarding the subject Coordinate measuring technique is presented in the following figure.

Model of laboratory classes regarding the coordinate measuring technique

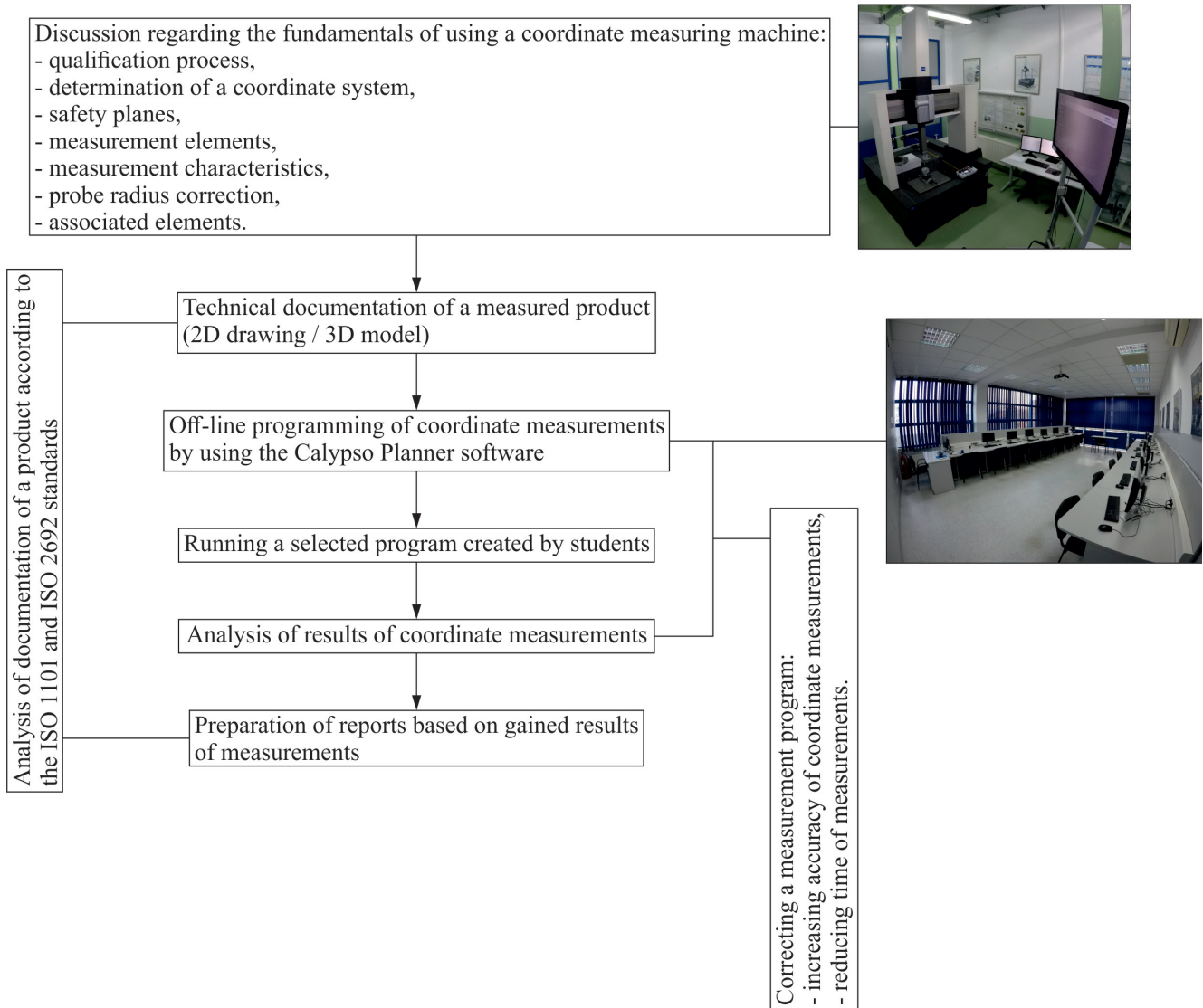


Fig. 2.15. Model of laboratory classes regarding the coordinate measuring technique

2.4.2. Digital tools for inspection

Name	Producer	Additional information
Zeiss Calypso	Carl Zeiss	https://www.zeiss.com/metrology/products/software/calypso-overview.html
Gear Pro	Carl Zeiss	https://www.zeiss.com/metrology/products/software/calypso-overview/gear-pro.html
Blade Pro	Carl Zeiss	
Zeiss Caligo	Carl Zeiss	https://www.zeiss.com/metrology/products/software/caligo.html
Zeiss Reverse Engineering	Carl Zeiss	https://www.zeiss.com/metrology/products/software/reverse-engineering.html
Zeiss colin3D	Carl Zeiss	https://www.zeiss.com/metrology/products/software/colin3d.html
MiCAT Planner	Mitutoyo	https://shop.mitutoyo.pl/web/mitutoyo/en_PL/mitutoyo/1343028164341/MiCAT%20Planner/\$catalogue/mitutoyoData/PG/CMM%20Software/index.xhtml
MCOSMOS	Mitutoyo	https://shop.mitutoyo.pl/web/mitutoyo/en_PL/mitutoyo/1343028164341/MCOSMOS%20-%20The%20Modular%20Software%20for%20all%20Kinds%20of%20Measurement/\$catalogue/mitutoyoData/PG/SOFT%20MCOSMOS/index.xhtml

Table 2.5. List of exemplary INSPECTION tools available on the market

Name	Producer	Additional information
MAFIS-Express	Mitutoyo	https://shop.mitutoyo.pl/web/mitutoyo/en_PL/mitutoyo/1343028164341/MAFIS%20Express%20-%20Rapid%20Air%20Foil%20Inspection%20Software/\$catalogue/mitutoyoData/PG/MAFISExpress/index.xhtml
MSURF	Mitutoyo	https://shop.mitutoyo.pl/web/mitutoyo/en_PL/mitutoyo/1343028164341/Point%20Cloud%20Processing%20Software%20for%20Coordinate%20Measuring%20Machines%20MSURF/\$catalogue/mitutoyoData/PG/MSURF-S%252FI/index.xhtml
MSURF-G	Mitutoyo	https://shop.mitutoyo.pl/web/mitutoyo/en_PL/mitutoyo/1343028164341/MSURF-G/\$catalogue/mitutoyoData/PG/MSURF-G/index.xhtml
PC-DMIS	HEXAGON Manufacturing Intelligence	https://www.hexagonmi.com/products/software/pc-dmis/pc-dmis-2021-2
QUINDOS	HEXAGON Manufacturing Intelligence	https://www.hexagonmi.com/en-GB/products/software/quindos
I++ Simulator	HEXAGON Manufacturing Intelligence	https://www.hexagonmi.com/en-GB/products/software/i-simulator
SpatialAnalyzer	HEXAGON Manufacturing Intelligence	https://www.hexagonmi.com/en-GB/products/software/spatialanalyzer

Table 2.5. List of exemplary INSPECTION tools available on the market

Name	Producer	Additional information
Inspire	HEXAGON Manufacturing Intelligence	https://www.hexagonmi.com/en-GB/products/metrology-software/inspire
CMM-Manager	Nikon	https://www.nikon.com/products/industrial-metrology/lineup/3d_metrology/software/cmm/
Inspect-X	Nikon	https://www.nikonmetrology.com/en-us/x-ray-ct/x-ray-core-products-and-services-inspect-x-for-2d-inspection
Focus Scan	Nikon	https://www.nikon.com/products/industrial-metrology/lineup/3d_metrology/software/focus_scan/
Focus Handheld	Nikon	https://www.nikon.com/products/industrial-metrology/lineup/3d_metrology/software/mca/

Table 2.5. List of exemplary INSPECTION tools available on the market

Name	Producer	Additional information
Focus Inspection	Nikon	https://industry.nikon.com/en-gb/products/3d-laser-scanners/automated-3d-scanning/focus-inspection/
GOM Inspect Professional	GOM	https://www.gom.com/3d-software/gom-inspect-professional.html
GOM Correlate	GOM	https://www.gom.com/3d-software/gom-correlate.html
Blade Analyzer	WENZEL	https://www.wenzel-group.com/en/products/wm-blade-analyzer/
Gear & Gear Analyzer	WENZEL	https://www.wenzel-group.com/en/products/wm-gear/
Quartis	WENZEL	https://www.wenzel-group.com/en/products/measuring-software-metrosoft-quartis/
PointMaster	WENZEL	https://www.wenzel-group.com/en/products/pointmaster/

Table 2.5. List of exemplary INSPECTION tools available on the market

Name	Producer	Additional information
Generator	WENZEL	https://www.wenzel-group.com/en/products/wm-generator/
MODUS 2	Renishaw	https://www.renishaw.com/en/modus-2--32079
MODUS	Renishaw	https://www.renishaw.com/en/modus--10495
Blade Toolkit	Renishaw	https://www.renishaw.com/en/toolkit-for-blade-engineering-and-manufacturing--16410
Inspection Plus	Renishaw	https://www.renishaw.com/en/inspection-plus-software-for-machining-centres--6094
Productivity+	Renishaw	https://www.renishaw.com/en/productivity-pc-based-probe-software-for-machining-centres--6252
Powerinspect	Autodesk	https://www.autodesk.co.uk/products/powerinspect/overview

Table 2.5. List of exemplary INSPECTION tools available on the market



Name of a measuring system:

ACCURA II coordinate measuring machine

Producer of a measuring system:

Carl Zeiss

Contact information / website of a measuring system's producer:

Carl-Zeiss-Straße 22

73447 Oberkochen

Germany

www.zeiss.com/metrology

Technical specifications of a measuring system:

$E_MPE = (1,6 + L/333) \mu\text{m}$

$P_MPE = 1,7 \mu\text{m}$

$T_MPE = 2,5 \mu\text{m}$

Metrological software cooperating with a measuring system:

Calypso, Zeiss Reverse Engineering, Blade Pro, Gear Pro, Holos

Measurement capabilities of a measuring system:

The ACCURA II machine is a bridge-type coordinate measuring machine (CMM). The coordinate measuring machine enables measurements of products characterized by regular geometric shapes and curvilinear surfaces of investigated objects. The machine can be equipped with several measuring probes and inspection software packages. The CMM cooperates with e.g., the VAST XT, VAST XXT contact measuring probes, the LineScan non-contact measuring probe and a rotary table. The ACCURA II machine must be used in a separate measurement laboratory. The CMM may be applied for digitalization i.e., the first stage of the reverse engineering process and the final inspection of a measured part. The machine is produced in various measuring ranges.

Possibilities of using a measuring system in education:

The ACCURA II machine may be used to present fundamentals of the coordinate measuring technique. A lecturer may present the stages of contact and non-contact coordinate measurements, the idea of the probe radius correction process, the influence of different measurement strategies on results of coordinate measurements and analyse various factors having the impact on the accuracy of measurements. Moreover, the CMM ACCURA II may be used to present the first stage of the reverse engineering process i.e., digitalization. Students may also gain knowledge in the field of on-line and off-line programming of CMMs.



Name of a measuring system:

MCAx measuring arm

Producer of a measuring system:

Nikon

Contact information / website of a measuring system's producer:

industry.nikon.com

Technical specifications of a measuring system:

Lengths between 2 m and 4.5 m

MMDx:

accuracy up to 10 μm

stripe widths available from 50 mm to 200 mm

Metrological software cooperating with a measuring system:

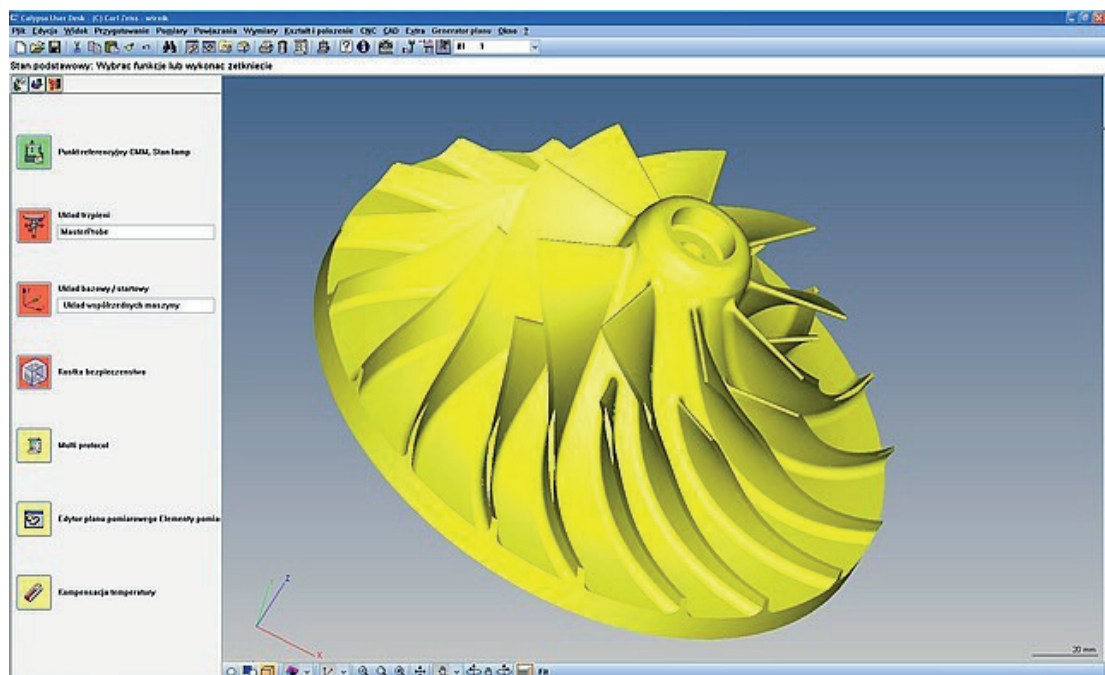
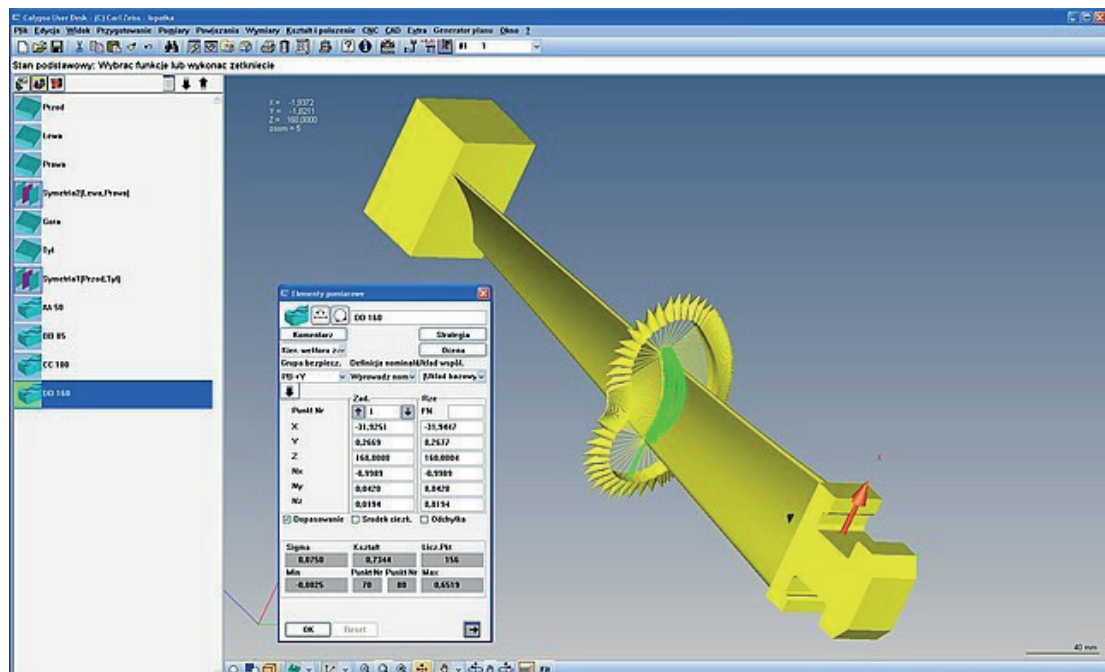
CMM-Manager, Focus Inspection

Measurement capabilities of a measuring system:

The MCAx measuring arm may be applied for both contact and non-contact coordinate measurements of products. Both types of measurements can be used due to two measuring probes cooperating with the measuring arm. The considered coordinate measuring system may be located nearby machine tools in a production hall. The measuring arm may be used for final inspection processes of products and during their digitalization when the reverse engineering process is conducted. The measuring instrument has different measuring ranges.

Possibilities of using a measuring system in education:

The MCAx measuring arm is a manual coordinate measuring system. The user of the arm has a big influence on final results of measurements. An analysis of measurement accuracy of the measuring arm by using the R&R (Repeatability & Reproducibility) methods may be performed with students. The R&R tests may verify the impact of the operator of the arm on the accuracy of coordinate measurements. Moreover, the measuring arm may be used to present the reverse engineering process and coordinate measurements of free-form surfaces of measured objects.



Name of inspection software:

Calypso

Producer of inspection software:

Carl Zeiss

Contact information / website of a producer of inspection software:

Carl-Zeiss-Straße 22

73447 Oberkochen

Germany

www.zeiss.com/metrology

Measurement capabilities of inspection software:

The main inspection software of the Carl Zeiss company cooperating with coordinate measuring machines (CMMs) and computed tomography (CT). The inspection software enables programming of CMMs in two main modes: on-line and off-line. The off-line programming allows the software to be used at various stages of a manufacturing process of a product. The considered metrological software enables measurements of, among others, products composed of curvilinear surfaces by using e.g., the following measurement elements: 2D and 3D curves. The software has large possibilities of reporting results of contact and non-contact coordinate measurements. Programming of measurements can be carried out based on 3D CAD nominal models including measurement characteristics.

Possibilities of using inspection software in education:

The software can be used in the off-line mode, so it can be applied by students without having the access to e.g., a coordinate measuring machine. Students may conduct simulations of contact and non-contact coordinate measurements by using 3D CAD models of CMMs, measuring probes and probing systems. Students can verify the correctness of measurement programs in terms of collisions and measurement time. Moreover, there is a possibility of analysis of a strategy of coordinate measurements by using the off-line version of the Calypso software. Students may also gain knowledge in the field of parametric programming of coordinate measurements. It is possible by using the PCM (Parameter Coded Measurements) module of the Calypso inspection software.



Name of a measuring system:

Line Scan measuring probe

Producer of a measuring system:

Carl Zeiss

Contact information / website of a measuring system's producer:

Carl-Zeiss-Straße 22

73447 Oberkochen

Germany

www.zeiss.com/metrology

Technical specifications of a measuring system:

LineScan 2-50

Measuring range in Z 50 mm

Working distance 94 mm

Measuring range in X (line width) 50 mm (middle)

Measuring rate max. 256 000 points/s

Probing error 20 µm

Metrological software cooperating with a measuring system:

Calypso, Zeiss Reverse Engineering

Measurement capabilities of a measuring system:

The non-contact measuring probe cooperating with coordinate measuring machines (CMMs). The probe orientation is controlled by the RDS (Articulating Probe Holder) module. The LineScan probe is based on triangulation. The probe enables obtaining many measurement points in a short time. The measuring probe may be applied for digitalization, which is the first stage of the reverse engineering process. Due to the lower accuracy of the LineScan probe, compared to contact measuring probes, the considered non-contact probe may be used in the case of final inspection for products characterized by large tolerances. In the case of coordinate measurements conducted by using the LineScan probe, filtration of points clouds has a great influence on results of measurements.

Possibilities of using a measuring system in education:

The LineScan non-contact measuring probe may be used to present the first stage of the reverse engineering process i.e., digitalization. Moreover, students may analyse the influence of different methods of filtration of measurement points on results of coordinate measurements. Additionally, results of contact and non-contact measurements may be compared to show advantages and disadvantages of both ways of conducting coordinate measurements.



Name of a measuring system:
Mitutoyo 570-312, HDS Digimatic Height Gage

Producer of a measuring system:
Mitutoyo

Contact information / website of a measuring system's producer:
Mitutoyo Europe GmbH
Borsigstr. 8 - 10
41469 Neuss
Fax: +49 (0) 2137 102 351
info@mitutoyo.eu

Technical specifications of a measuring system:

Measurement range of 0" - 12"/0 - 300 mm

Digital step: 0,01 mm

Scale: ABSOLUTE electrostatic linear encoder

Max. response speed: Unlimited

Battery life: approx. 20000 hours

Display: LCD, Character Height 10 mm

ORIGIN: Yes

ZERO/ABS: Yes

ON/OFF: Yes

DATA/HOLD: Yes

Low voltage alarm: Yes

Data output: Yes

Digital/Analog: Digital

Inch-Metric: Inch/Metric

Metrological software cooperating with a measuring system:

Mitutoyo MeasureReport, Mitutoyo MeasurLINK SPC-Light, Lotus 1-2-3, Excel

Measurement capabilities of a measuring system:

The Mitutoyo Digital Height Gauge is one of the most popular precision gages, because it is perfect for measuring distance between two points of an object, quickly and accurately. The machine can be equipped with several measuring claspers and Scribes. For CNC tools (milling, drilling, etc. tools) measurement very precise and reliable Mitutoyo Digimatic Height Gauge is used. LCD digital readout displays figures in inches or metric units for viewing ease. The data from digital height gauge Statistical Process Control (SPC) output can be transmitted to the computer's (PC) programs, for example Mitutoyo MeasurLINK SPC-Light or Excel program. It has built-in ABSOLUTE electrostatic linear encoder which means that it is not necessary to set the reference point at every power-on, improving reliability as over-speed errors cannot occur.

Possibilities of using a measuring system in education:

The Mitutoyo Digital Height Gauge may be used to present fundamentals of the CNC tool measuring technique. A lecturer may present the stages of height coordinate measurements of milling, drilling tools, the idea of the tool set-up process, the influence of different measurement strategies on results of tool height measurements and analyse various factors having the impact on the accuracy of measurements. Moreover, the Mitutoyo Digital Height Gauge may be used to present the digitalization process. Students may also gain knowledge in the field of measurement accuracy subjects.

Height measurement of tool is very important for CNC machining, especially for vertical CNC milling machines and machining centers. The height measurement is very important production case, since it involves the machined tolerances for the manufacturing parts, because the tool should be measured precisely. There are manual measurement devices, which precise is not very accurate and for some very high precision parts it's not suitable.

Name of inspection software:

Blade Pro

Producer of inspection software:

Carl Zeiss

Contact information / website of a producer of inspection software:

Carl-Zeiss-Straße 22

73447 Oberkochen

Germany

www.zeiss.com/metrology

Measurement capabilities of inspection software:

The Blade Pro inspection software enables checking accuracy of turbine blades. The software may be used in the off-line mode and it is based on data generated by the Calypso software. The examples of measurement characteristics, analysed by the Blade Pro software, of a turbine blade are as follows: the lengths of a profile chord and a mean camber line, the maximum length and thickness, the form deviation of an investigated profile of a blade, the radius of a leading edge and the radius of a trailing edge. A measurement program, prepared by means of the Blade Pro software package, is created for individual cross-sections of a blade. The considered software has large possibilities of reporting results of contact coordinate measurements of blades. The cooperation between the Calypso and Blade Pro software packages is conducted by using the Turbine blade macro available in the Calypso inspection software.

Possibilities of using inspection software in education:

Students, by using the Blade Pro software, may gain knowledge regarding programming of coordinate measurements of blades, different measurement characteristics of a turbine blade and coordinate measurements of curvilinear surfaces. The Blade Pro software may be used in the off-line mode, without having the access to a coordinate measuring machine, to analyse results of coordinate measurements. Therefore, it can be used by all students of a lab group.

2.4.3. Literature, exemplary exam tests and guides for teachers

Literature – list for inspection phase

Books

Dotson, C.L. *Fundamentals of Dimensional Metrology*, 6th edition. Cengage Learning, Boston 2014, ISBN 978-1133600893.

ElKott, D. *Coordinate Metrology of Free-form Surfaces. A CAD-based, Practical Approach*. VDM Verlag Dr. Müller GmbH & Co. KG, Saarbrücken 2011, ISBN-13 978-3639226713.

Henzold, G. *A Handbook for Geometrical Product Specification Using ISO and ASME Standards*, 2nd edition. Butterworth-Heinemann, Elsevier Ltd., Oxford, UK 2006, ISBN 978-0750667388.

Hocken, R.J.; Pereira, P.H. *Coordinate Measuring Machines and Systems*, 2nd ed. CRC Press, Boca Raton 2012, <https://doi.org/10.1201/b11022>.

Krulikowski, A. *Fundamentals of Geometric Dimensioning and Tolerancing*, 3rd edition. Cengage Learning, New York 2012, ISBN 978-111129828.

Mino, M.J. *CMM. Beginners Understanding: Understanding the Basics*, vol. 1. Createspace Independent Publishing Platform, Scotts Valley, USA 2012, ISBN 978-1475190953.

Pfeifer, T.; Imkamp D. *Koordinatenmesstechnik und CAX-Anwendungen in der Produktion*. Hanser, 2004, ISBN 978-3446227330.

Pfeifer, T.; Imkamp, D.; Schmitt, R. *Coordinate Metrology and CAX-Application in Industrial Production. Basics, Interfaces and Integration*. Hanser, Munich 2006, ISBN 978-3446401341.

Productive Measurement CMM. Function and Production Oriented Coordinate Technology, ISBN 978-3-9811422-6-6.

Puncochar, E.D.; Evans, K. *Interpretation of Geometric Dimensioning and Tolerancing*, 3rd edition. Industrial Press, Inc., New York 2011, ISBN 978-0-8311-3421-1.

Roithmeier, R. *Measurement Strategies in Tactile Coordinated Metrology*, No. 600060-7002-002, english edition. ZEISS Metrology Academy, Oberkochen, Germany 2015, ISBN 978-3-945380-04-8.

Stadek, J.A. *Coordinate Metrology. Accuracy of Systems and Measurements*. Springer-Verlag, Berlin Heidelberg 2016, ISBN 978-3-662-48463-0, <https://doi.org/10.1007/978-3-662-48465-4>.

Smith, G.T. *Industrial Metrology. Surfaces and Roundness*. Springer-Verlag, London 2002, ISBN 978-1-85233-507-6, <https://doi.org/10.1007/978-1-4471-3814-3>.

Suga, N.; Rollings, P. I *Metrology Handbook: The Science of Measurement*. Mitutoyo, West Point Business Park, UK 2007, ISBN 978-0955613302.

Weckenmann, A. *Koordinatenmesstechnik. Flexible Strategien für funktions- und fertigungsgerechtes Prüfen*. Carl Hanser Verlag GmbH & Co, Hanser, Munich 2012, ISBN 978-3-446-42947-5

ZEISS *Measuring Strategies Cookbook*. No. 600033-0200-812, english edition. ZEISS Metrology Academy, 2015, https://world.probes.zeiss.com/en/Training-Material/Books/ZEISS-Measuring-Strategies-Cookbook/category-1012/product-ARTIKEL_3984.html.

ZEISS *Sensor Cookbook*, No. 600033-0200-805, english edition. ZEISS Metrology Academy, USA 2017, https://world.probes.zeiss.com/en/Training-Material/Books/ZEISS-Sensor-Cookbook/category-1012/product-ARTIKEL_4481.html.

State of the art papers

Ali, S. State-of-the-Art of CMM-Coordinate Metrology in Automotive Industry. *SAE Technical Paper* 2017-01-0397 2017, <https://doi.org/10.4271/2017-01-0397>

Humienny, S. Geometrical Product Specification. *Course for Technical Universities Journal of Manufacturing Science and Technology* 2 (2009), 1–7, <https://doi.org/10.1016/j.cirpj.2009.06.007>.

Li, Y.; Gu, P. Free-form Surface Inspection Techniques State of the Art Review. *Comput. Aided Des.* 2004, 36, 1395–1417, <https://doi.org/10.1016/j.cad.2004.02.009>.

Singh, H.; Motwani, J.; Kumar, A. A Review and Analysis of the State-of-the-art Research on Productivity Measurement. *Industrial Management & Data Systems* 2000, 100, 5, 234–241, <https://doi.org/10.1108/02635570010335271>.

Thalmann, R.; Meli, F.; Küng, A. State of the Art of Tactile Micro Coordinate Metrology. *Appl. Sci.* 2016, 6, 150. <https://doi.org/10.3390/app6050150>.

X-ray Computed Tomography: from Medical Imaging to Dimensional Metrology 2019, <https://doi.org/10.1016/j.precisioneng.2019.06.007>.

Research papers

Li, T.; Gao, L.; Pan, Q.; Li, P. *Free-form Surface Parts Quality Inspection Optimization with a Novel Sampling Method*. *Appl. Soft Comput.* 2018, 62, 550–570, <https://doi.org/10.1016/j.asoc.2017.11.010>.

Kawalec, A.; Magdziak, M. *The Selection of Radius Correction Method in the Case of Coordinate Measurements Applicable for Turbine Blades*. *Precis. Eng.* 2017, 49, 243–252. <https://doi.org/10.1016/j.precisioneng.2017.02.012>.

Magdziak, M. *A New Method of Distribution of Measurement Points on Curvilinear Surfaces of Products*. *Sensors* 2019, 19, 2667, <https://doi.org/10.3390/s19122667>.

Magdziak, M. *Selection of the Best Model of Distribution of Measurement Points in Contact Coordinate Measurements of Free-form Surfaces of Products*. *Sensors* 2019, 19, 5346, <https://doi.org/10.3390/s19245346>.

Moroni, G.; Petrò, S. *Optimal Inspection Strategy Planning for Geometric Tolerance Verification*. *Precis. Eng.* 2014, 38, 71–81, <https://doi.org/10.1016/j.precisioneng.2013.07.006>.

Wang, X.; Xian, J.; Yang, Y.; Zhang, Y.; Fu, X.; Kang, M. *Use of Coordinate Measuring Machine to Measure Circular Aperture Complex Optical Surface*. *Measurement* 2017, 100, 1–6, <https://doi.org/10.1016/j.measurement.2016.12.038>.

Zapico, P.; Patiño, H.; Valiño, G.; Fernández, P.; Rico, J.C. *CNC Centralized Control for Digitizing Free-form Surfaces by Means of a Conoscopic Holography Sensor Integrated in a Machining Centre*. *Precis. Eng.* 2019, 55, 474–483, <https://doi.org/10.1016/j.precisioneng.2018.11.001>.

Webpages

GOM Metrology, <https://www.youtube.com/user/GOMMetrology/playlists>
Hexagon Manufacturing Intelligence, <https://www.youtube.com/user/hexmeteu>
<https://www.mitutoyo.co.uk/education>
Mitutoyo, <https://www.youtube.com/user/MitutoyoAmerica>
Renishaw, <https://www.youtube.com/user/RenishawEngineering/featured>
WenzelGroup, <https://www.youtube.com/user/WENZELGroup/videos>
ZEISS Software & digital Solutions, https://www.youtube.com/playlist?list=PLMjGCcUyqpjxRI_MwEqR6AApe83_NLMCD

Issues that may be used during exams regarding an inspection process

1. Geometric dimensioning and tolerancing (GD&T).
2. Parameters of surface roughness.
3. Uncertainty of measurements.
4. Coordinate measuring technique.
5. Contact and non-contact measurements. Advantages and disadvantages.
6. Uncertainty of coordinate measurements.
7. Factors influencing final results of measurements.
8. Probe radius correction in the coordinate measuring technique.
9. Measurements of curvilinear surfaces of products.
10. Repeatability & Reproducibility (R&R).

3. SURVEYS

The surveys concern the application of digital tools in education and the usage of those tools by companies specialized in the field of manufacturing. The surveys were conducted to e.g., determine the types of digital tools applied by manufacturing companies, universities and indicate software used at different stages of a manufacturing process of a product. Moreover, the purpose of the surveys was to e.g., obtain information on the expectations of manufacturing companies regarding student education in the field of the application of digital tools.

3.1. Survey template for manufacturing firms

SURVEY OI/AI

DIG-MAN: Integration of digital tools into product development and manufacturing education

The preliminary list of questions for MANUFACTURING FIRMS

1. Please indicate which groups (software, internet tools, machines and technological equipment, devices) of the digital tools are used in your organization.
 - Software** – S (e.g. PC software, software for mobile devices such as smartphones, tablets, laptops).
 - Internet tools** – IT (e.g. Internet-based tools such as WEB pages, electronic catalogues).
 - Machines and technological equipment** – MTE (e.g. CNC machine tools, measuring instruments, furnaces, assembly stations).
 - Devices** – D (e.g. smartphones, smartwatches, tablets, laptops, virtual reality/augmented reality devices).
2. Please indicate up to 10 relevant examples (**the names proposed by producers or resellers**) of digital tools for your organization in the case groups presented in a table.

	Software (S)	Internet tools (IT)	Machines and technological equipment (MTE)	Devices (D)
1				
2				
3				
4				

5				
6				
7				
8				
9				
10				

3. Please indicate up to 10 examples of the most relevant digital tools, from groups presented in a table, which your organization uses in the product development / design / manufacturing / inspection phases.

	Product development	Design	Manufacturing	Inspection
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				

-
4. How important is digitalization for your organization within the next 5 years? Please indicate from 1 to 5; 1 (it is not important), 5 (it is very important).

Answer:

5. What is your general opinion regarding the use of digital tools in your organization?
We use a lot of them and we plan to use more.
The usage of digital tools is not sufficient for now, but we have plans to increase the usage of digital tools.
The usage of digital tools is not sufficient and we do not know how to increase the usage of digital tools.

Other:

6. Academic teachers of bachelor students at universities should be more focused on:
teaching/learning the basics of **various** digital tools,
teaching/learning how to use **selected** digital tools relevant for local industry,
teaching/learning how to use **selected** digital tools relevant for European or national market,

other:

7. Academic teachers of master students at universities should be more focused on:
teaching/learning how to use the basics of various digital tools,
teaching/learning how to develop and adapt/customise digital tools,
teaching/learning how to use selected digital tools relevant for local industry,
teaching/learning how to use selected digital tools relevant for European or national market,

other:

8. What is **the main** limitation to increase the efficiency of the digital tools usage in your firm? Please indicate **one** of the following:
skills of users,
approach of managers,
lack of investments,
lack of internal training,

other:

9. What do you expect as a representative of industrial firm from higher education institutions in terms of teaching in the area of digital tools? Please choose **max. 2** most important expectations from the following:

- more practical exercises with the use of digital tools,
- more industrial internships of students focused on the usage of digital tools,
- availability of free software licences for students,
- self-made innovations of students (e.g. students' projects focused on digital tools development, customisation),

other:

10. What type of software is the most important for the development of your organization? Please indicate one of the following:

- CAD/CAM software,
- FEM (CAE) software,
- office software (e.g. Excel),
- calculators and other engineering software,
- all abovementioned,
- we do not use software.

11. Where have you learnt (as the person who is answering the question) how to use the most important type of software for your organization? Please indicate **at least one** of the following:

- in primary/secondary/high school,
- at university,
- individually at home,
- at workplace where I am employed now,
- at workplace where I used to be employed,
- all mentioned places.

12. Please indicate your country and a type/name of your organization (e.g. NORWAY, LARGE FIRM/NCX SOLUTIONS).

Answer:

3.2. Survey template for universities

Survey OI/AI

DIG-MAN: Integration of digital tools into product development and manufacturing education

The preliminary list of questions for PARTNER UNIVERSITIES

1. Please indicate which groups (software, internet tools, machines and technological equipment, devices) of the digital tools are used in your organization for teaching?
 - Software** – S (PC software, software for mobile devices such as smartphones, tablets, laptops).
 - Internet tools** – IT (Internet-based tools such as WEB pages, electronic catalogues).
 - Machines and technological equipment** – MTE (CNC machine tools, measuring instruments, furnaces, assembly stations).
 - Devices** – D (smartphones, smartwatches, tablets, laptops, virtual reality/augmented reality devices).

2. Please indicate up to 10 relevant examples of currently used digital tools which are used for teaching at your organization in the case of presented groups of digital tools. Please also indicate the form of classes (**L** – lecture, **LAB** – laboratory, **S** – seminar, **O** – other form) in which your organization uses the defined digital tool.

	Software (S)	Form of classes	Internet tools (IT)	Form of classes	Machines and technological equipment (MTE)	Form of classes	Devices (D)	Form of classes
1								
2								
3								
4								
5								
6								
7								
8								
9								
10								

3. Please indicate up to 10 examples of the most relevant digital tools, from groups presented in a table, which your organization uses to teach the product development/design/manufacturing/inspection phases.

	Product development	Design	Manufacturing	Inspection
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				

4. Which digital tools would you mostly like to use in your organization in the future? Please choose **two**, the most relevant, of the presented below:

VR/AR (virtual reality/augmented reality) tools,
 5G mobile networking (e.g. for e-learning),
 Free of charge or open-access CAD/CAM/CAE software,
 laptops, tablets and smartphones (e.g. for rent at library),

other:

5. How important will digitalization be for your organization within the next 5 years? Please indicate from 1 to 5. 1 (it is not important), 5 (it is very important)

Answer:; Justification: (1 paragraph, at least 3 sentences)

6. Which types of software do you expect to obtain from software suppliers for teaching at your organization in the next 5 years? Please indicate from the following:
 stand-alone licenses,
 software rent,
 internet-based solutions and cloud based software,
 free software.

other:

7. What is your general opinion regarding the use of digital tools in your organization? I think that:
 we use a lot of them and we plan to use more,
 the usage of digital tools is not sufficient for now, but we have plans to increase the usage of digital tools,
 the usage of digital tools is not sufficient and we do not know how to increase the usage of digital tools,

other:

8. Please indicate up to 5 names of important digital tools suppliers (e.g. names of firms) for ProDem (Product Development and Manufacturing) education in your organization taking into account 4 groups (Software, Internet-tools, Machines and technological equipment, Devices) of digital tools.

	Software (S)	Internet tools (IT)	Machines and technological equipment (MTE)	Devices (D)
1				
2				
3				
4				
5				

9. Academic teachers of bachelor students at your university are mostly focused on:
teaching how to use the basics of various digital tools,
teaching how to use selected digital tools relevant for local industry,
teaching how to use selected digital tools relevant for European or national market,

other:

10. Academic teachers of master students at your university are mostly focused on:
teaching how to use the basics of various digital tools,
teaching how to develop and adapt/customise digital tools,
teaching how to use selected digital tools relevant for local industry,
teaching how to use selected digital tools relevant for European or national market,

other:

11. What is **the main** limitation to increase the efficiency of the digital tools usage in your organization? Please indicate **one** of the following:
skills of users,
approach of managers,
approach of administration,
lack of money,
lack of internal training,

other:

12. Please indicate your country and name of university.
Answer:

3.3. Survey analysis

3.3.1. Introduction

This chapter presents the results of both surveys conducted for manufacturing firms and universities. Each of them has a separate chapter containing the answers, followed by their description and the most important conclusions.

3.3.2. Survey results for manufacturing firms

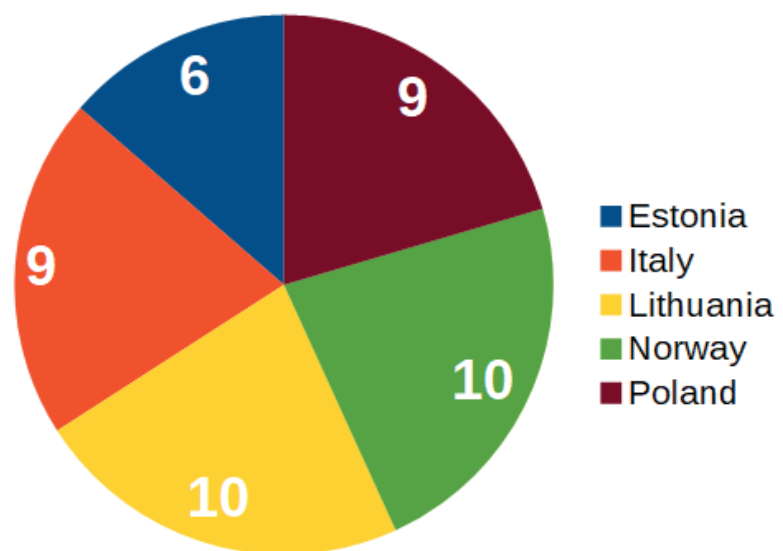


Fig. 3.1. Country of the surveyed companies

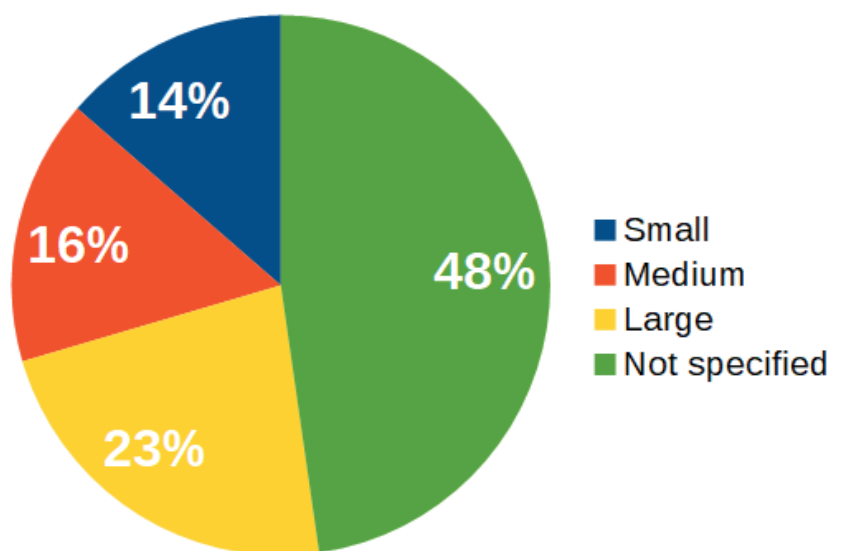


Fig. 3.2. Size of the organization

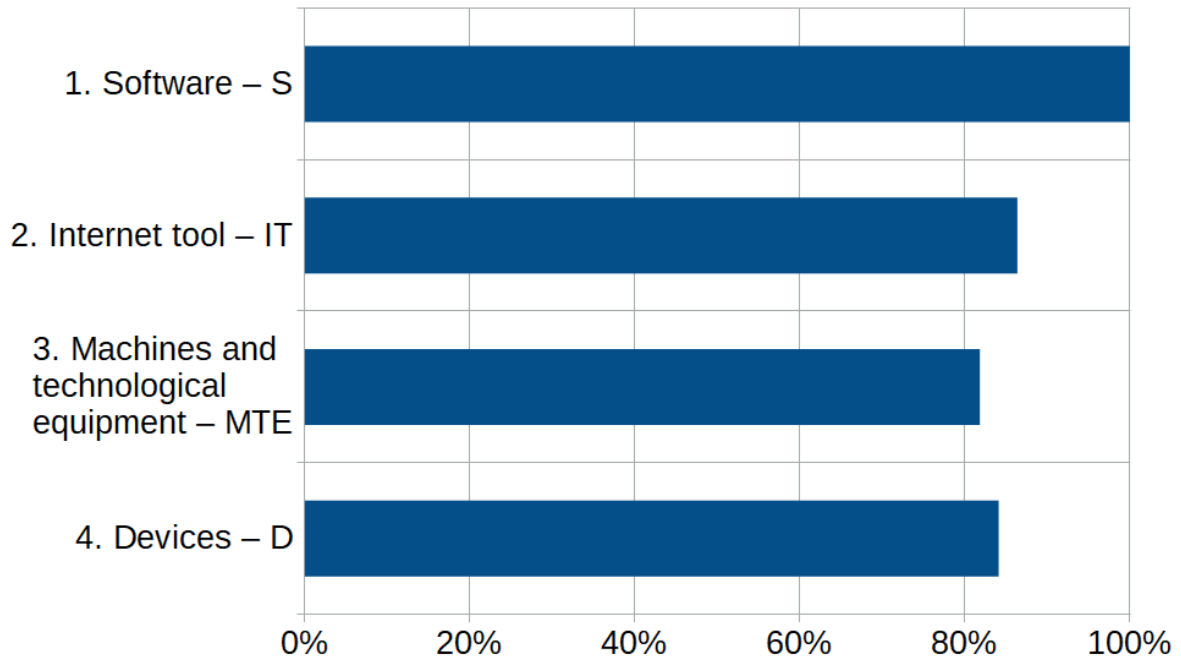


Fig. 3.3. Groups of the digital tools used in organizations

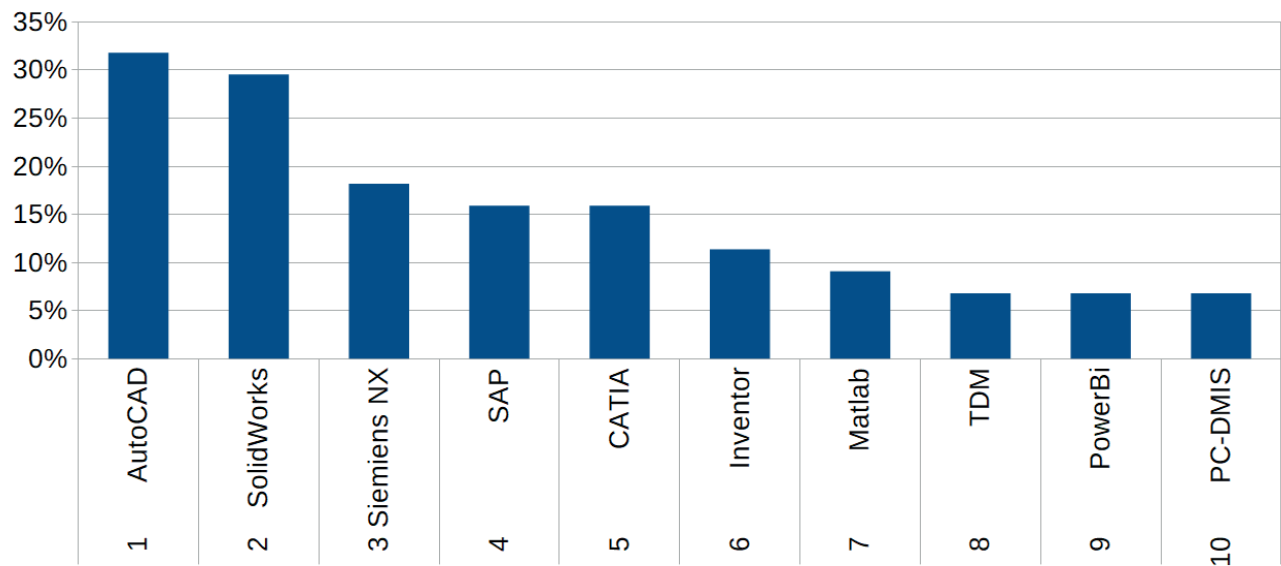


Fig. 3.4. Ten relevant examples of the SOFTWARE (S) used by companies

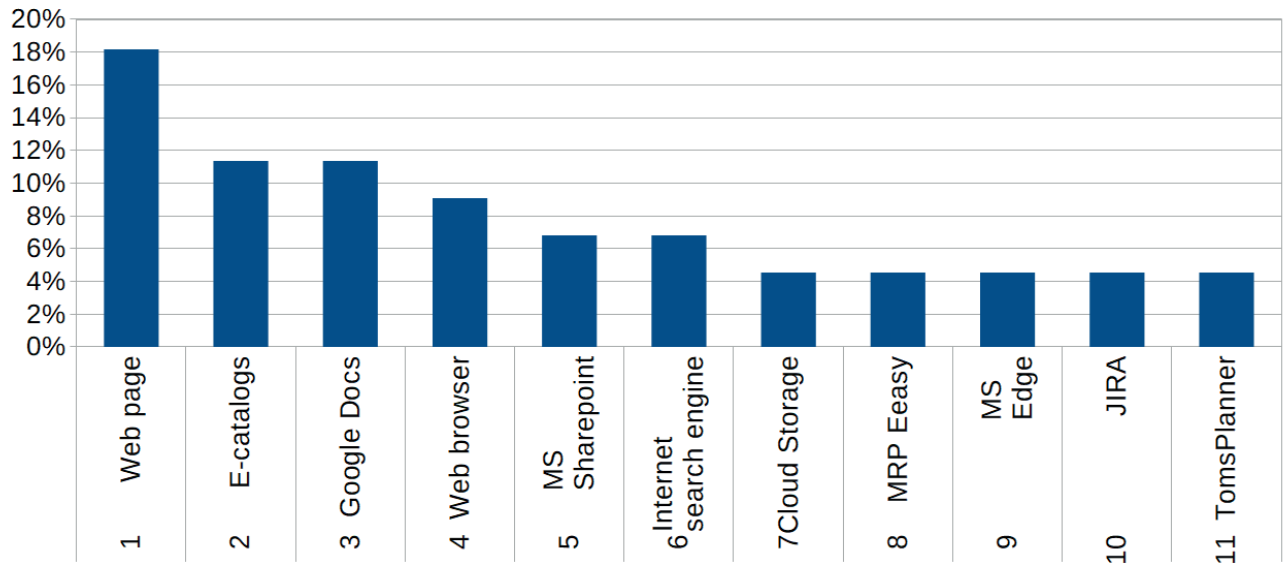


Fig. 3.5. Ten relevant examples of INTERNET TOOLS (IT) used by companies

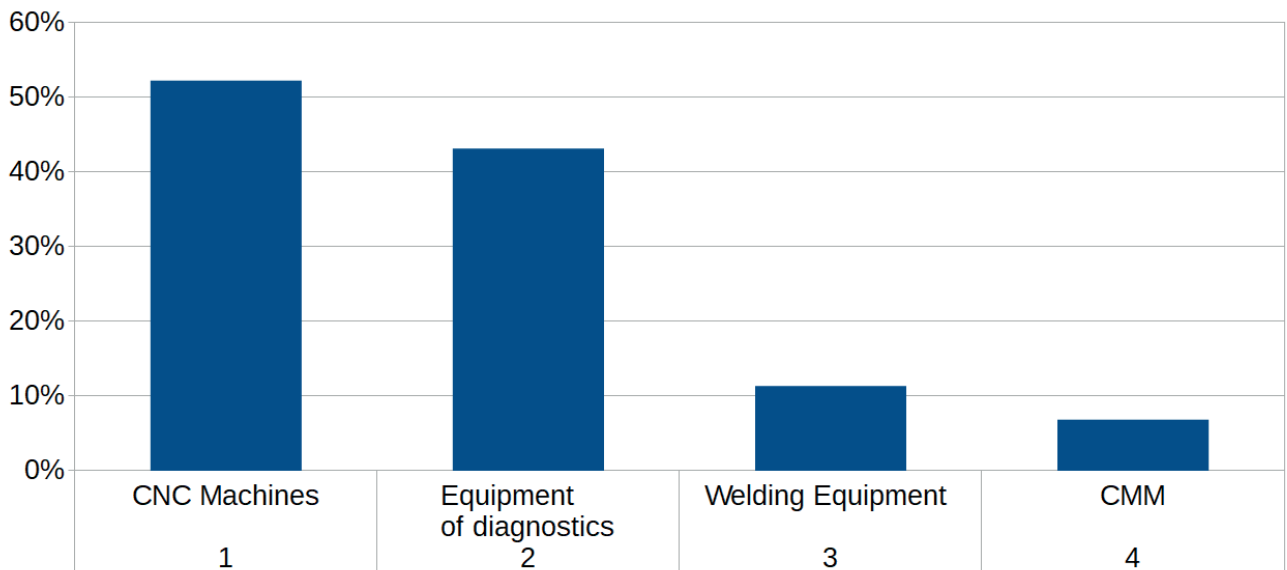


Fig. 3.6. Examples of MACH. AND TECH. EQUIPMENT (MTE) used by companies

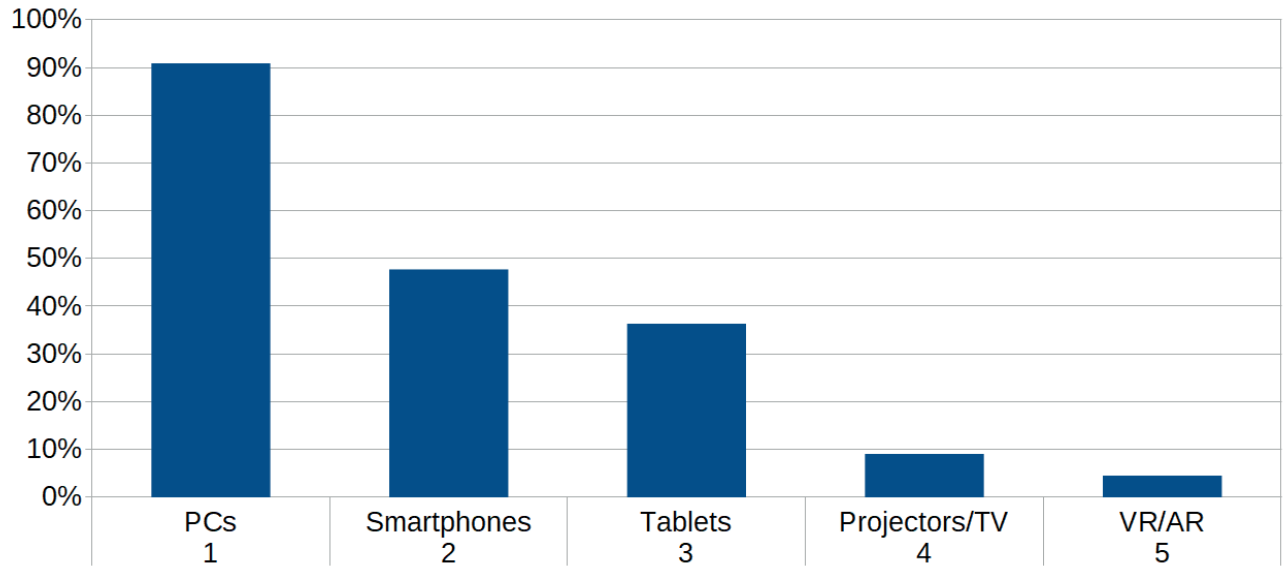


Fig. 3.7. Examples of DEVICES (D) used by companies

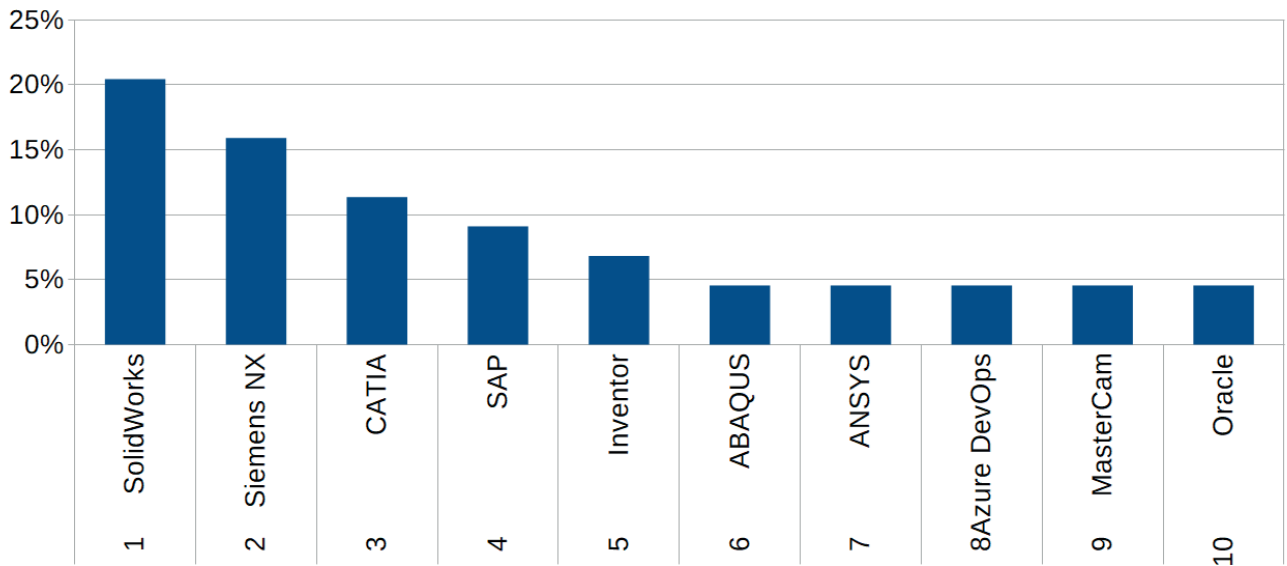


Fig. 3.8. Digital tools used in the product DEVELOPMENT

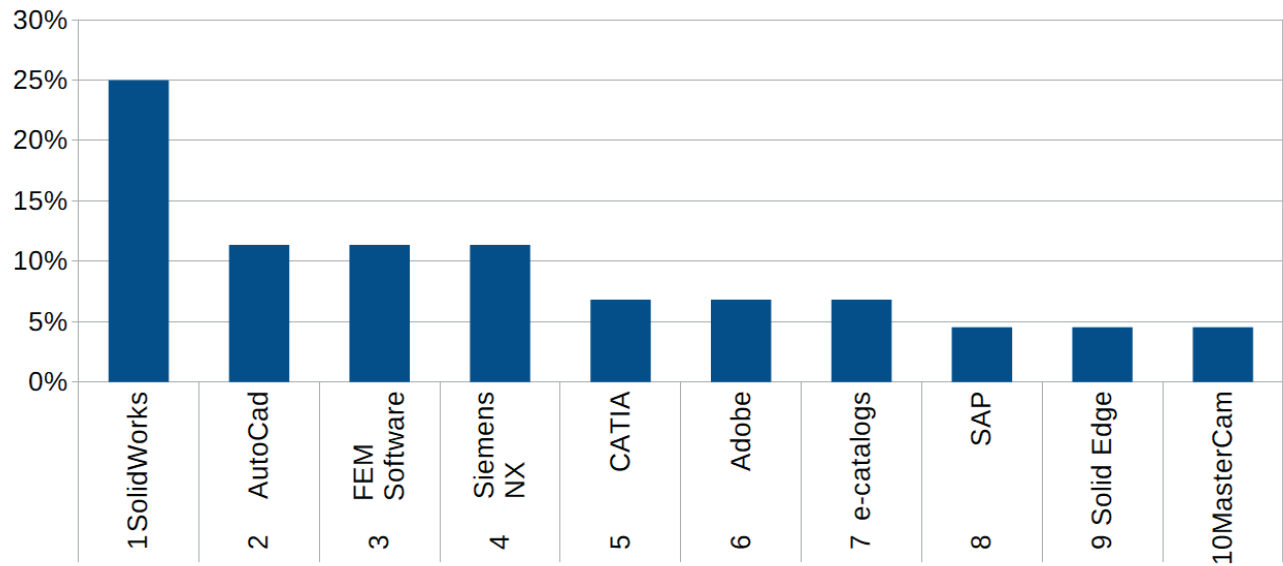


Fig. 3.9. Digital tools used in the product DESIGN

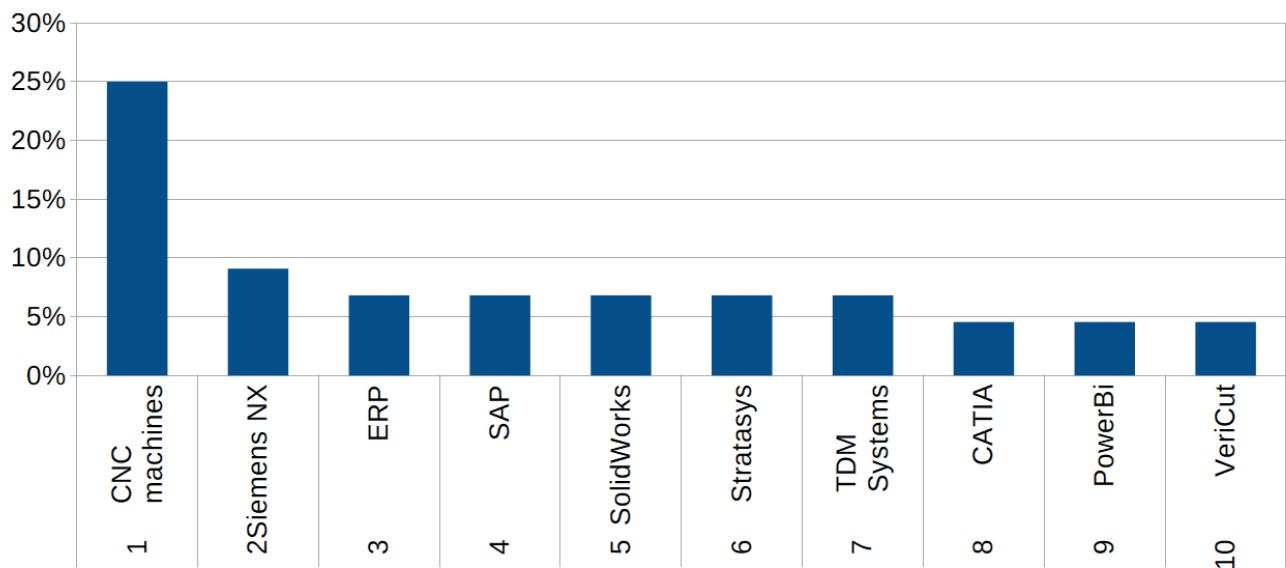


Fig. 3.10. Digital tools used in the product MANUFACTURING

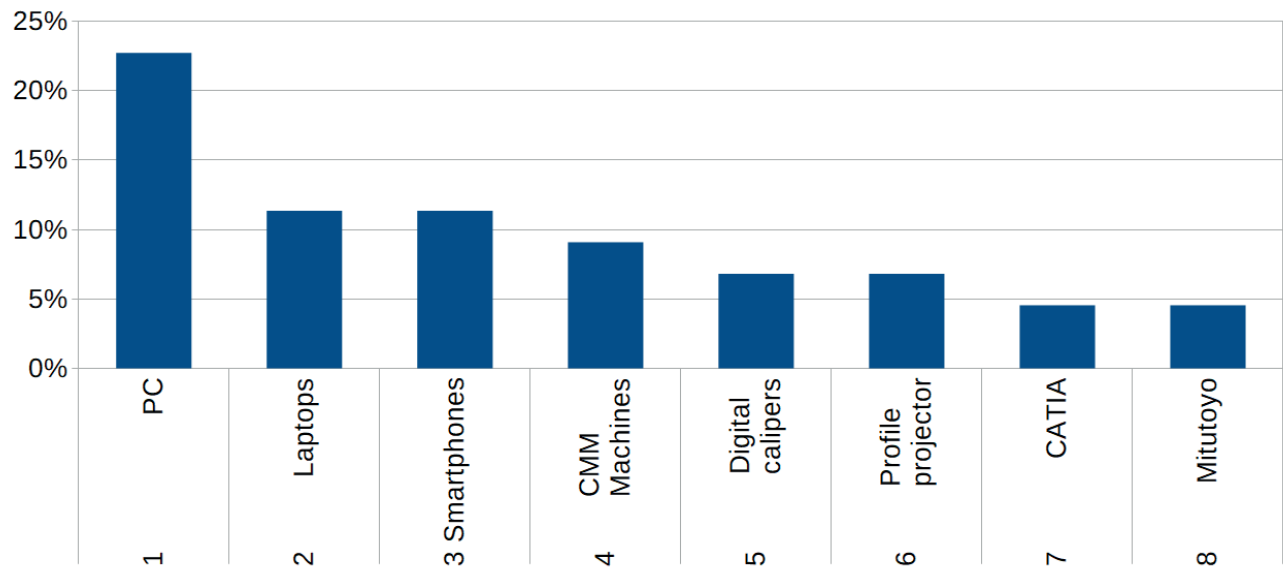


Fig. 3.11. Digital tools used in the product INSPECTION PHASE

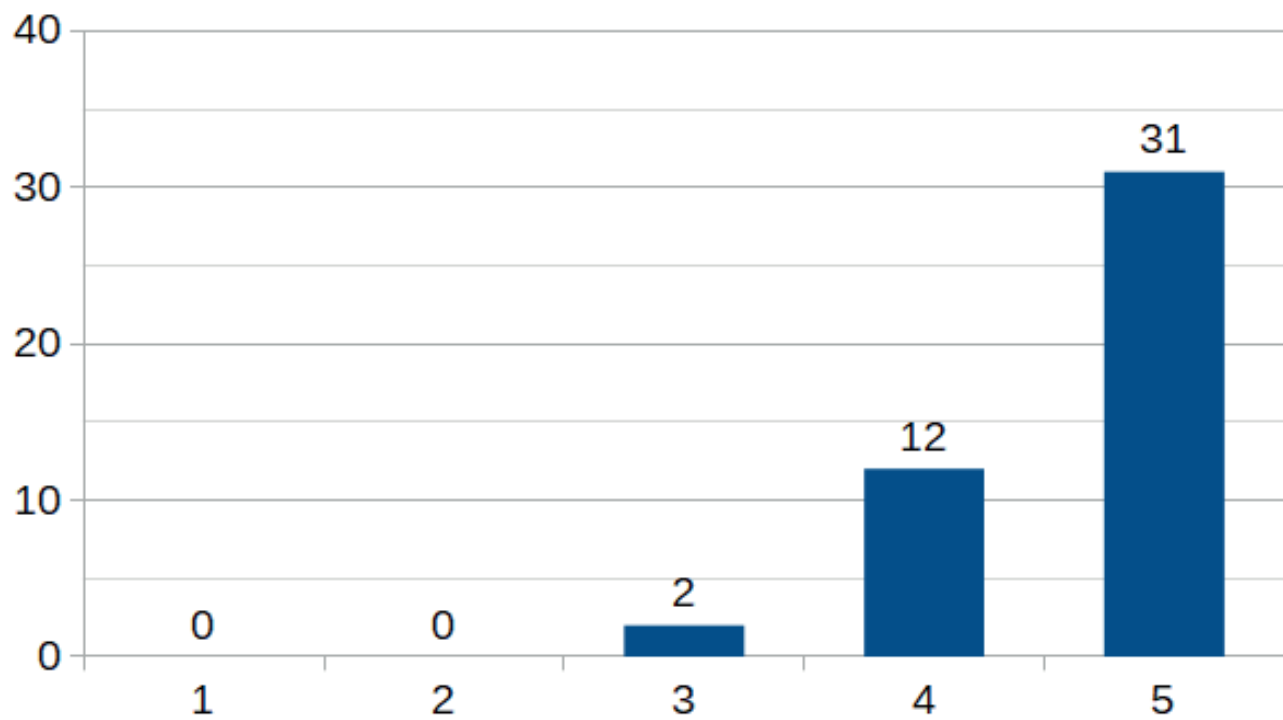


Fig. 3.12. Importance of the companies digitalization within the next 5 years (1 – it is not important, 5 – it is very important)

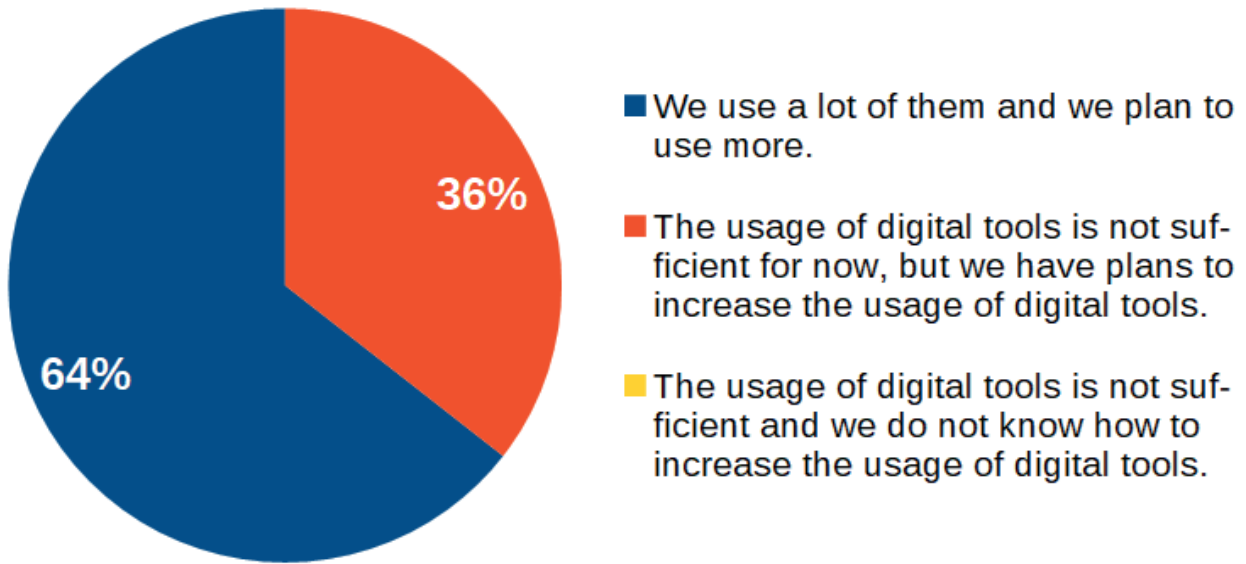


Fig. 3.13. General opinion regarding the use of digital tools in organizations

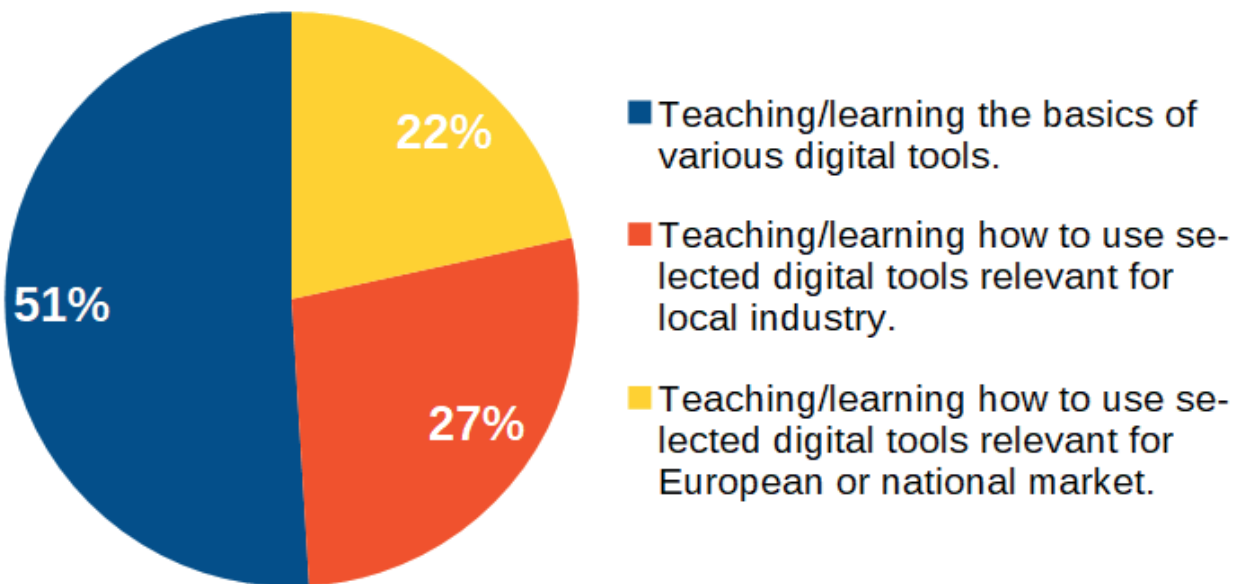


Fig. 3.14. Most important issues in teaching of bachelor students

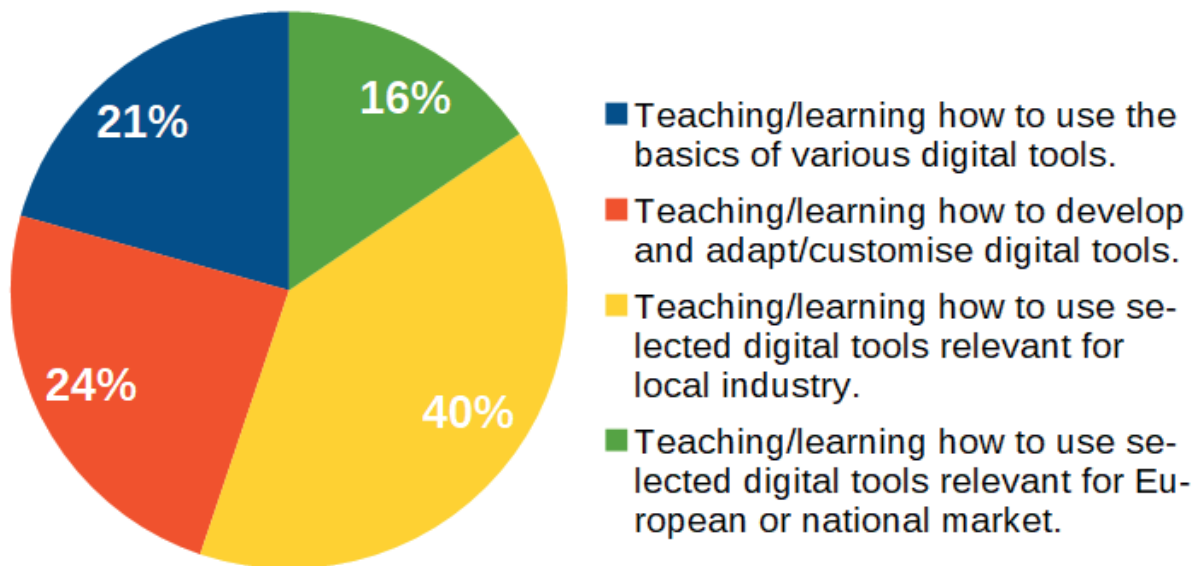


Fig. 3.15. Most important issues in teaching of master students

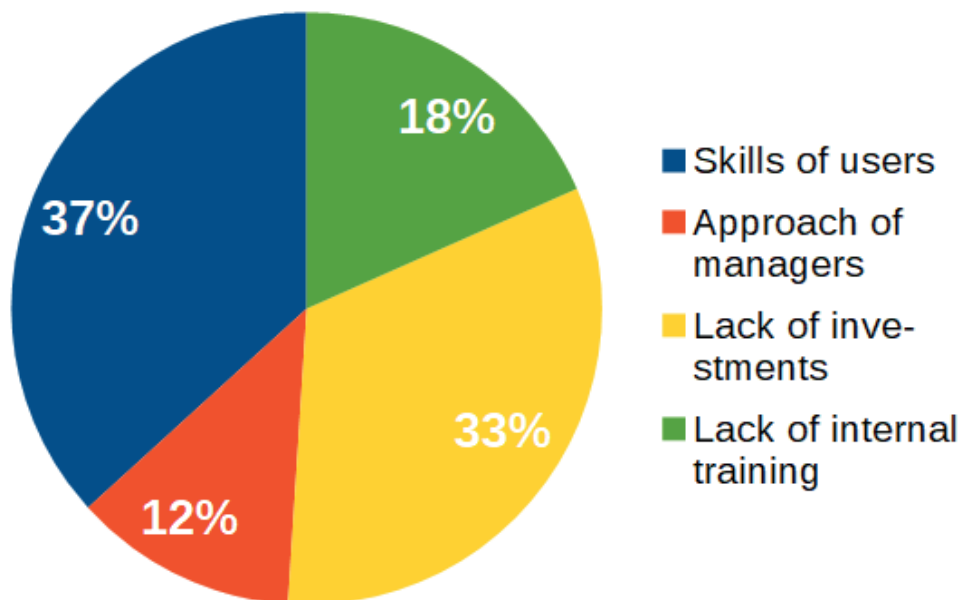


Fig. 3.16. Main limitation of increasing the efficiency of the digital tools usage in companies

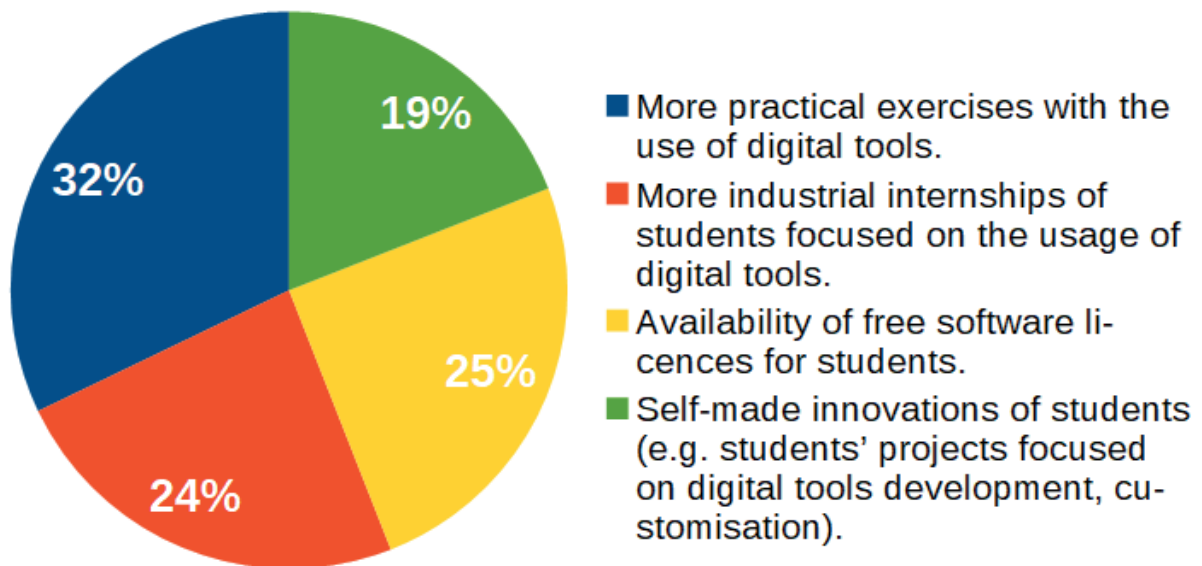


Fig. 3.17. Expectations of industrial firm from higher education institutions in terms of teaching in the area of digital tools

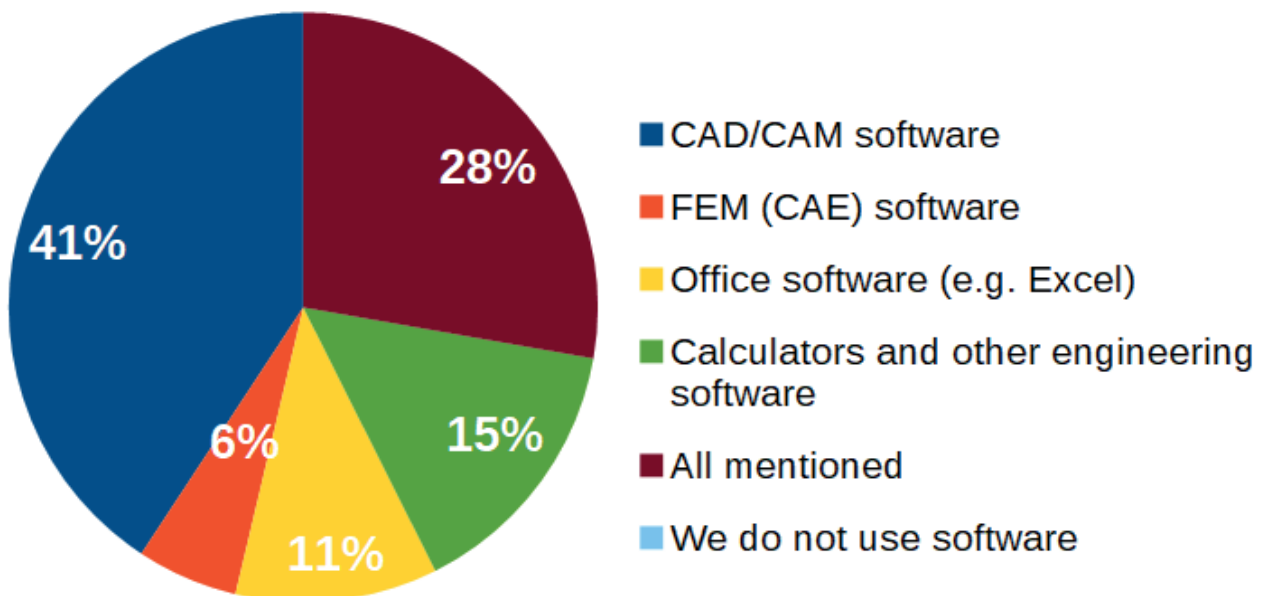


Fig. 3.18. The most important software for the development of organizations

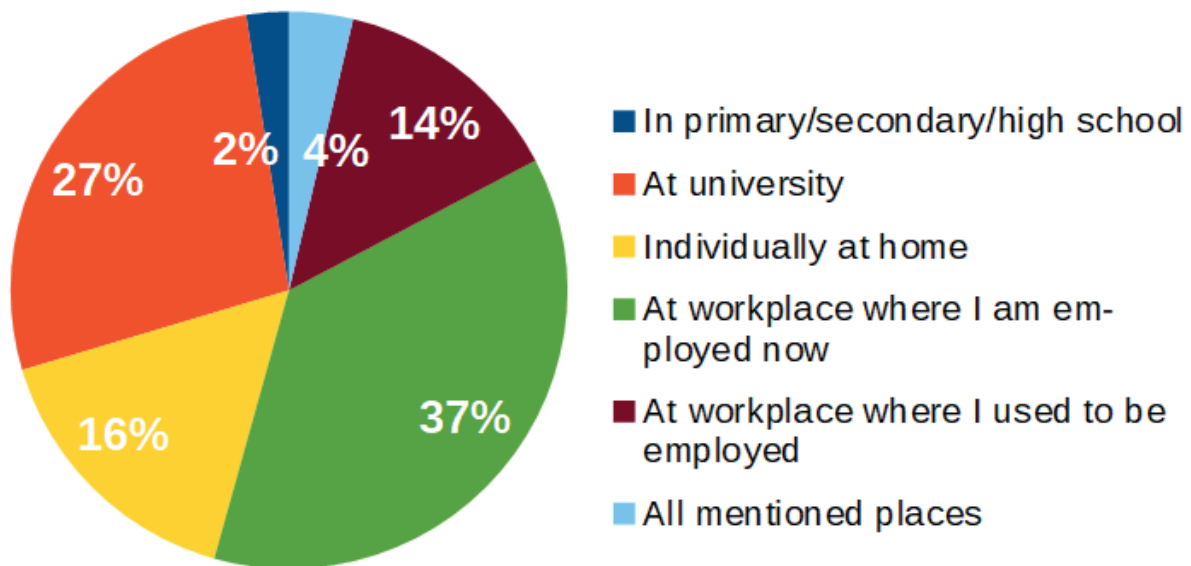


Fig. 3.19. The ways how respondent have learnt how to use software the most important for the organization

The surveyed companies come from five European countries related to the origin of the DIGMAN project partners. The number of respondents and their country of origin are presented in Fig. 3.1. Most of the respondents did not specify the size of their enterprise (Fig. 3.2), although it can be assumed that large and medium-sized companies have a dominant influence on the survey results. A software is indicated as one of the most frequently used digital tools by the respondents, although the use of Internet tools and various types of technological equipment and devices is also very high (more than 80%, see Fig. 3.3). In each of the groups of digital tools, the most frequently used are:

- **Software (S):** Autodesk AutoCad, SolidWorks, Siemens NX (Fig. 3.4),
- **Internet tools (IT):** websites related to manufacturers of tools and devices, e-catalogs and platforms enabling group work, i.e. Google Docs, MS Sharepoint, Cloud Storage (Fig. 3.5),
- **Machines and technological equipment (MTE):** CNC Machines, diagnostic and welding equipment (Fig. 3.6),
- **Devices (D):** personal computers, smartphones and tablets (Fig. 3.7).

The next group of questions concerned the use of digital tools in subsequent product life cycles. For the respondents, the most relevant digital tools are:

- in the **Product development:** SolidWorks, Siemens NX and CATIA (Fig. 3.8),
- in the **Design:** SolidWorks, CAD software (AutoCad, CATIA) and FEM Software (Fig. 3.9),
- in the **Manufacturing:** CNC machines, Siemens NX, ERP/SAP (Fig. 3.10),
- in the **Inspection:** personal computers, laptops and smartphones (Fig. 3.11).

Digitalization for the companies is very important for 66% of respondents (Fig. 3.12). Generally speaking, organizations use a lot of digital tools and they plan to use more (64%), but sometimes its usage is not sufficient (36%, see Fig. 3.13).

Academic teachers of **bachelor students** should be more focused on teaching/learning the basics of various digital tools (51%, see Fig. 3.14). According to the respondents, the following are less important: how to use selected digital tools relevant for European or national market (22%), how to use selected digital tools relevant for local industry (27%). Academic teachers of master students should be more focused on teaching/learning how to use selected digital tools relevant for local industry (40%, see Fig. 3.15). Less important are teaching the basics of various digital tools (21%) and how to use selected digital tools relevant for European or national market (24%).

The main limitations to increase the efficiency of the digital tools usage are (Fig. 3.16):

- (37%) skills of users,
- (33%) lack of investments,
- (18%) lack of internal training.

Expectations of industrial firm from higher education institutions in terms of teaching in the area of digital tools are (Fig. 3.17):

- (32%) more practical exercises with the use of digital tools,
- (25%) availability of free software licences for students,
- (24%) more industrial internships of students focused on the usage of digital tools.

The most important software for the organization development are (Fig. 3.18):

- (41%) CAD/CAM software,
- (28%) all mentioned tools (CAD/CAM/FEM/Office software, calculators and other engineering software),
- (15%) calculators and other engineering software.

The respondents have learnt how to use the most important types of software (Fig. 3.19) at workplace where they are employed now (37%), at university (27%) and individually at home (16%).

3.3.3. Survey results for universities

- Estonian University of Life Sciences, Estonia
- Kaunas University of Technology, Lithuania
- Rzeszow University of Technology, Poland
- Stavanger University, Norway

Fig. 3.20. Countries and names of the organizations participating in the survey.

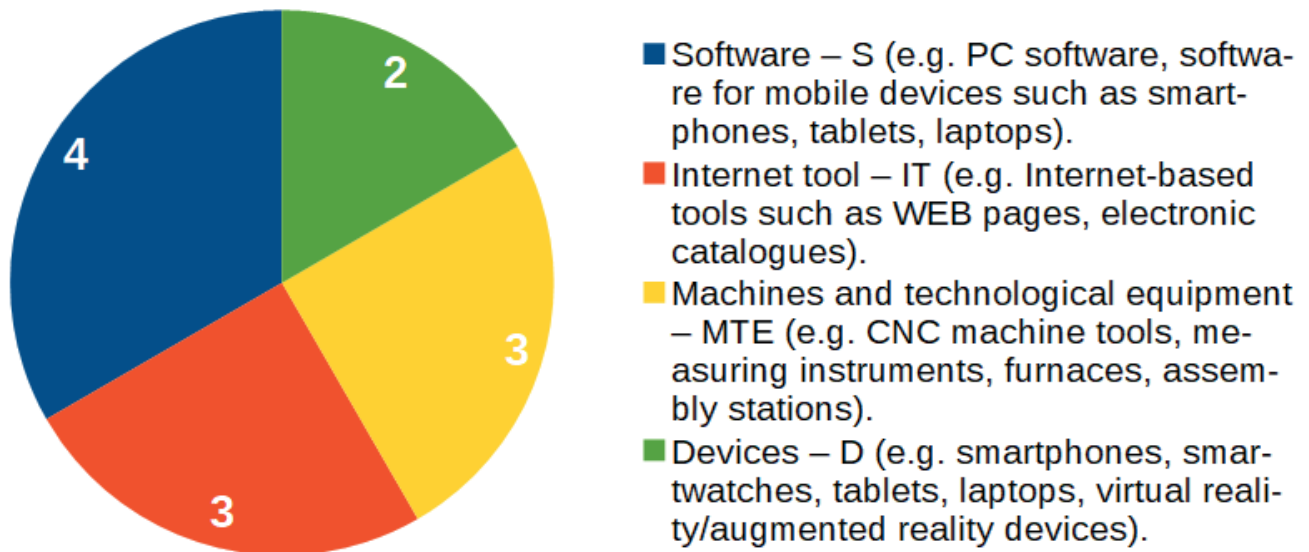


Fig. 3.21. Groups (software, internet tools, machines and technological equipment, devices) of the digital tools used for teaching.

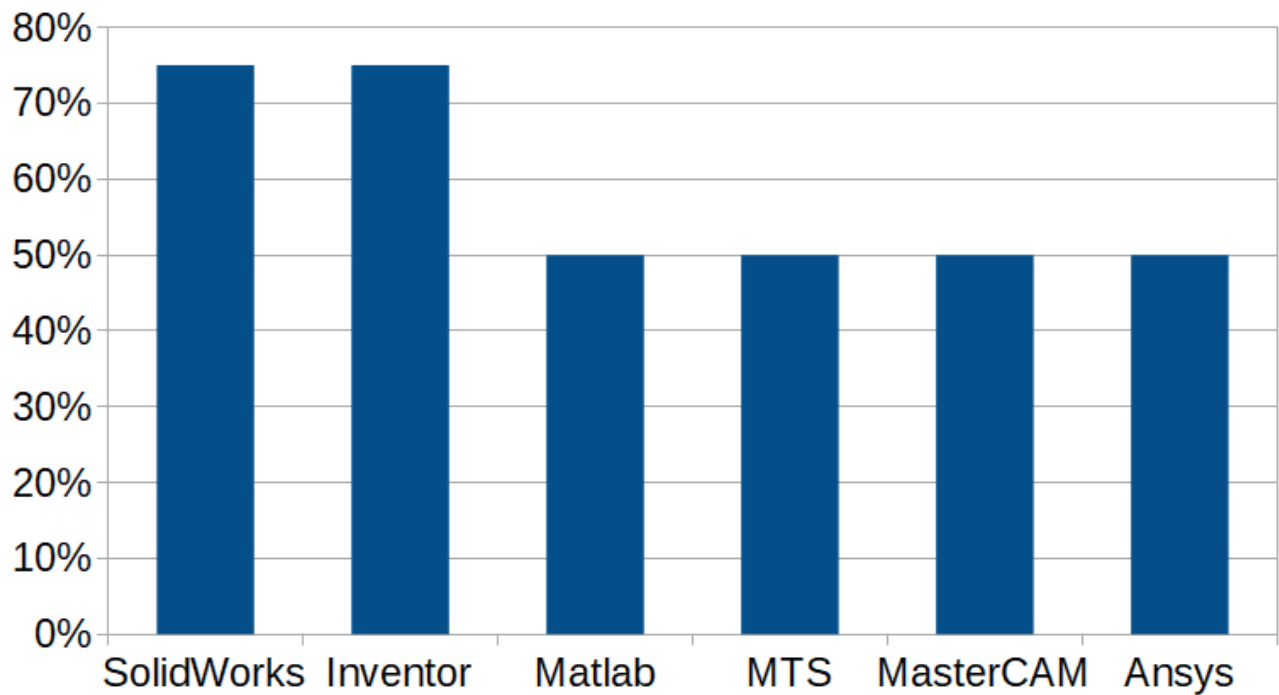


Fig. 3.22. Relevant examples of SOFTWARE (S) currently used for teaching.

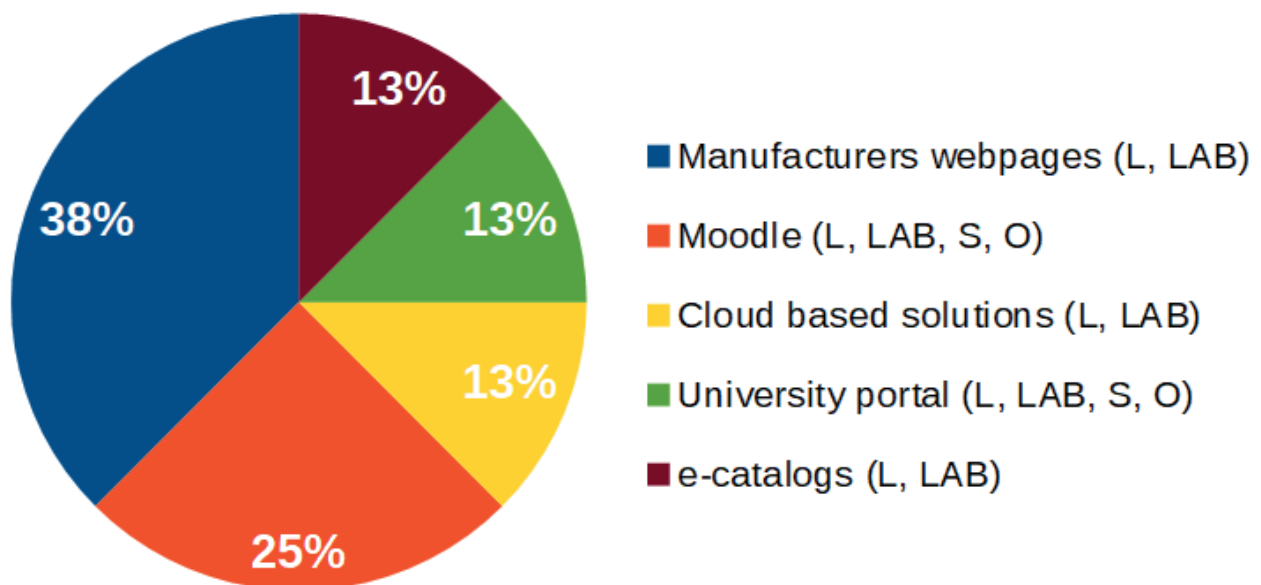


Fig. 3.23. Relevant examples of INTERNET TOOLS (IT) currently used for teaching.

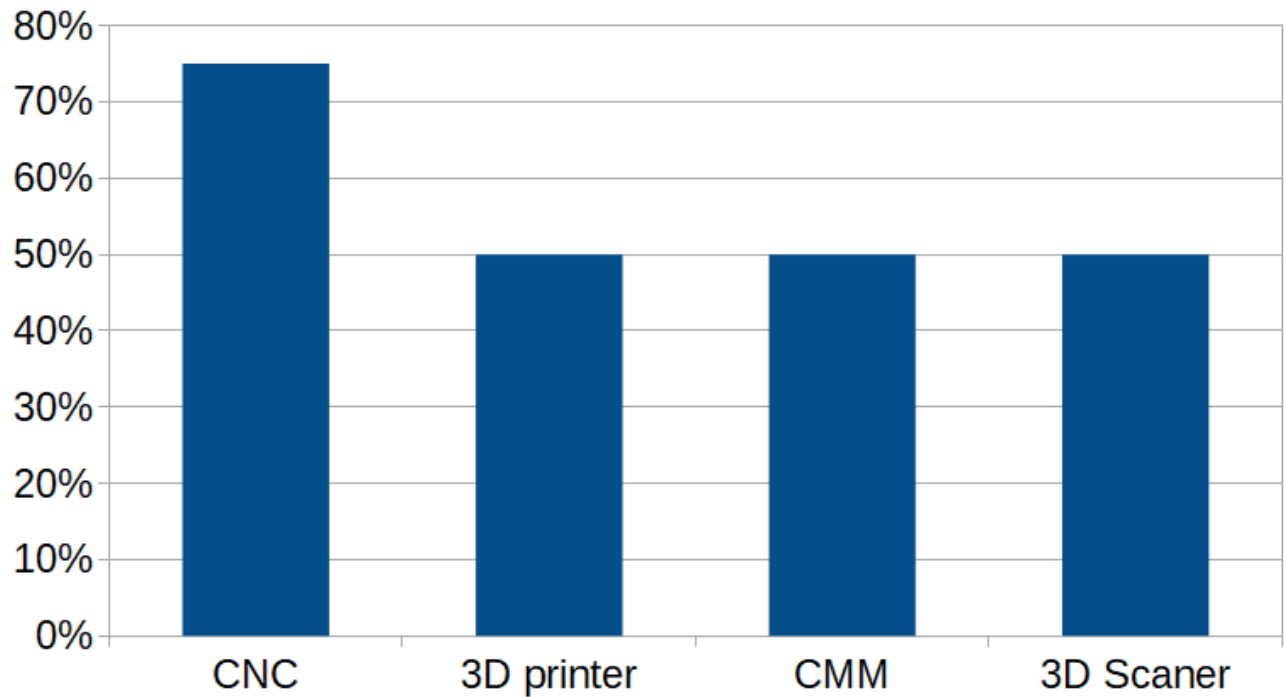


Fig. 3.24. Relevant examples of MACHINES AND TECHNOLOGICAL EQUIPMENT (MTE) currently used for teaching.

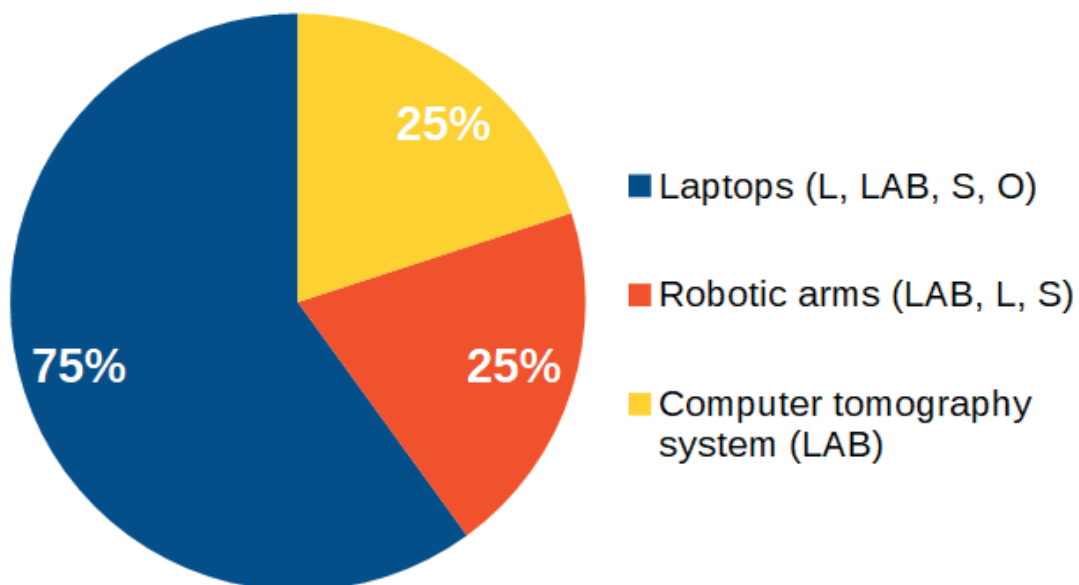


Fig. 3.25. Relevant examples of DEVICES (D) currently used for teaching.

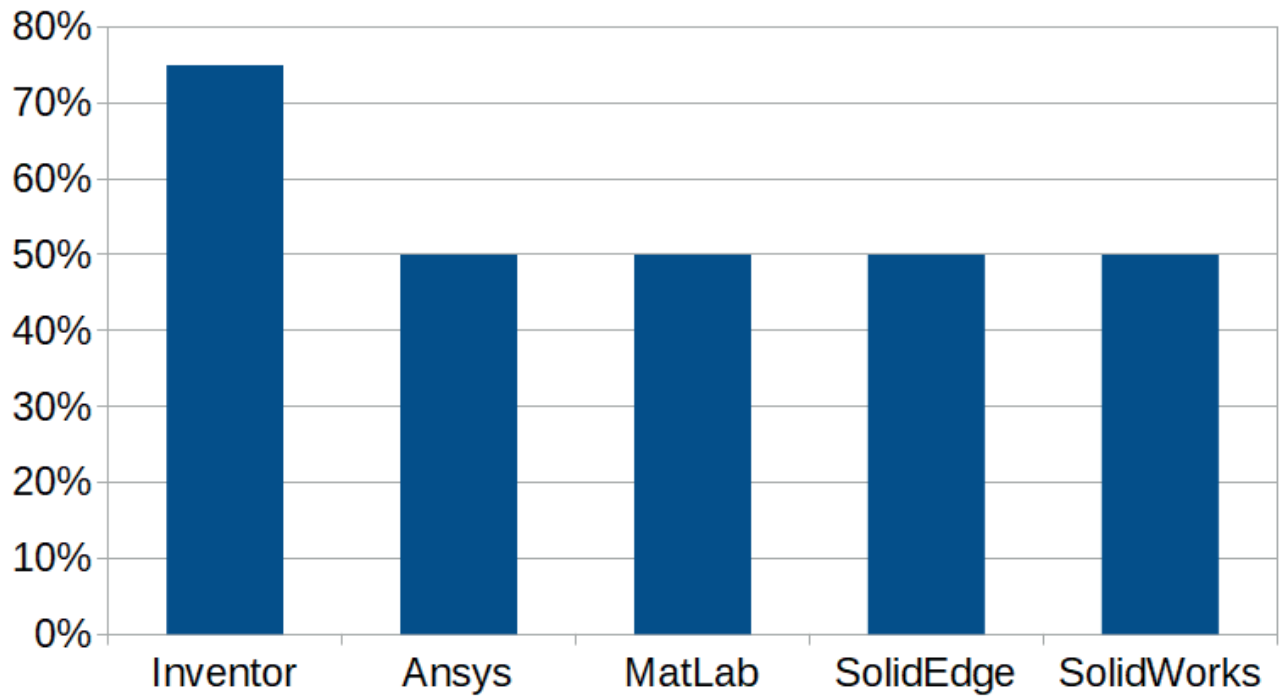


Fig. 3.26. Relevant digital tools, which are used in the product DEVELOPMENT.

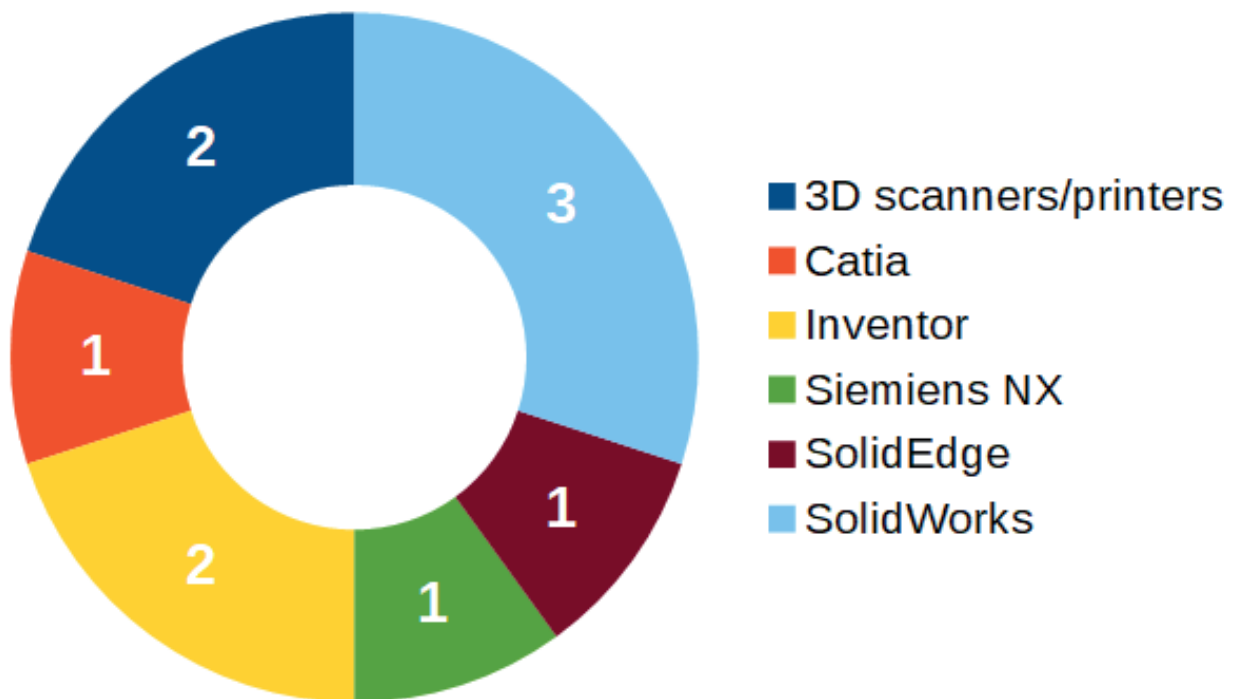


Fig. 3.27. Relevant digital tools, which are used in the product DESIGN.

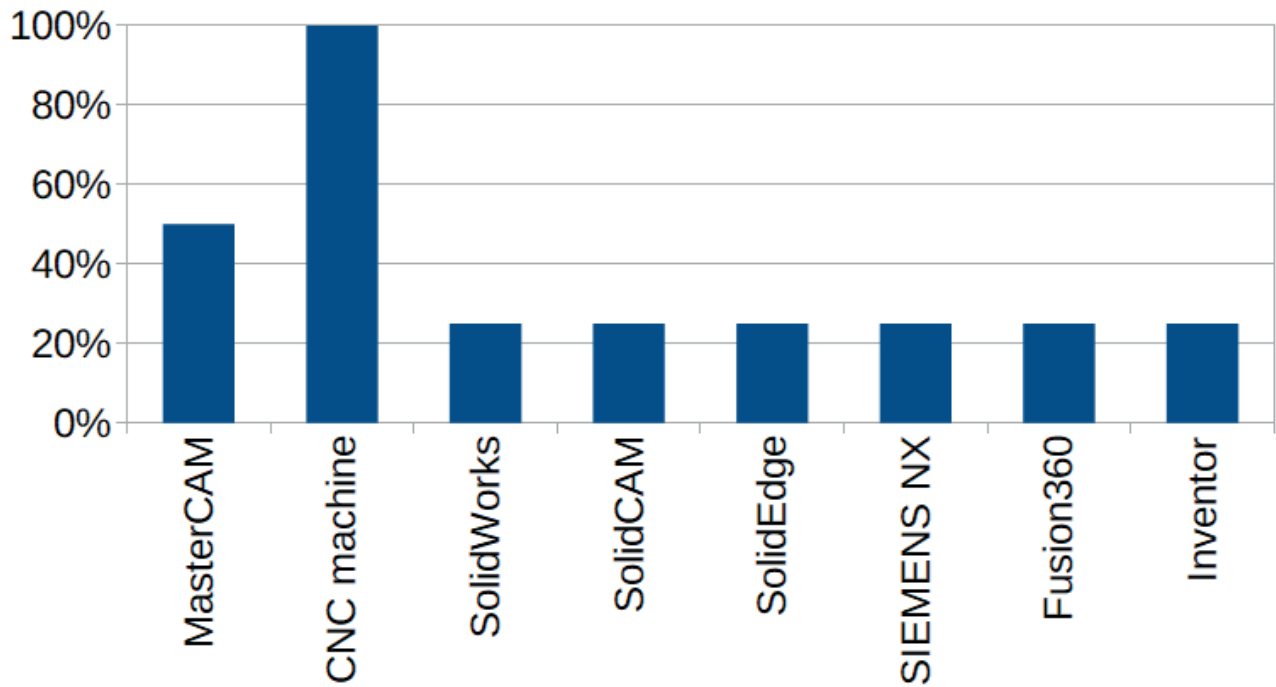


Fig. 3.28. Relevant digital tools, which are used in the product MANUFACTURING.

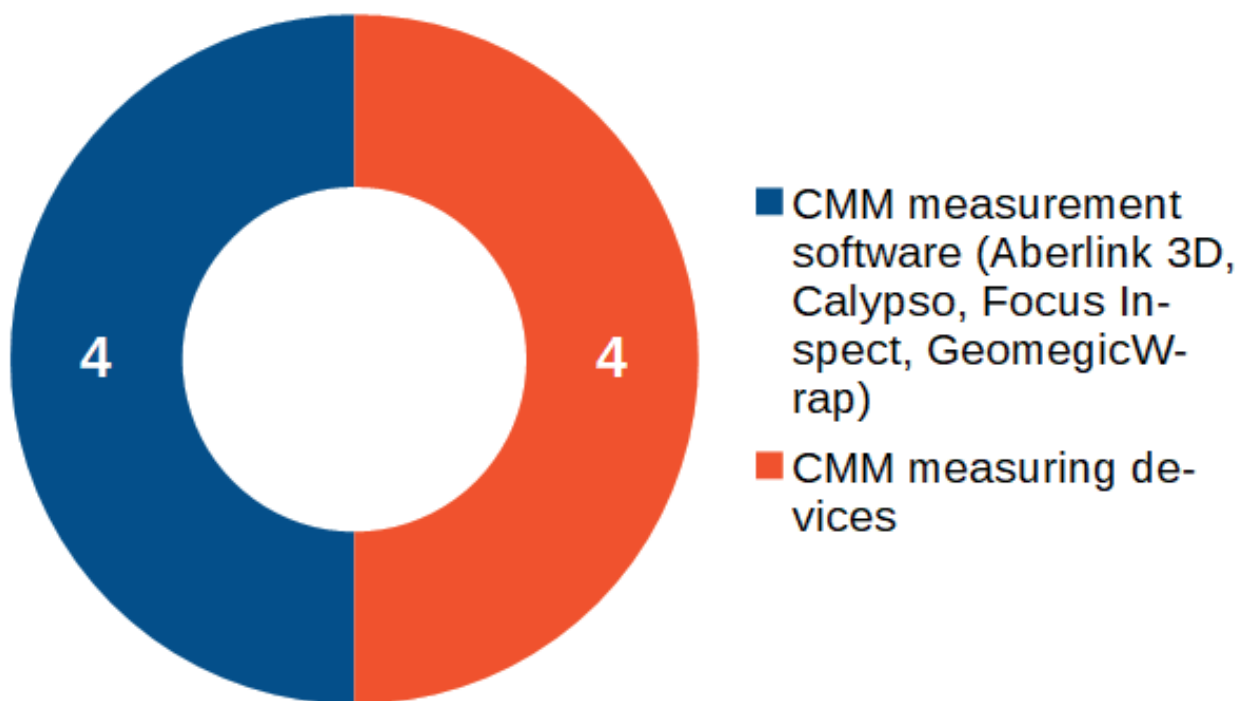


Fig. 3.29. Relevant digital tools, which are used in the product INSPECTION PHASE.

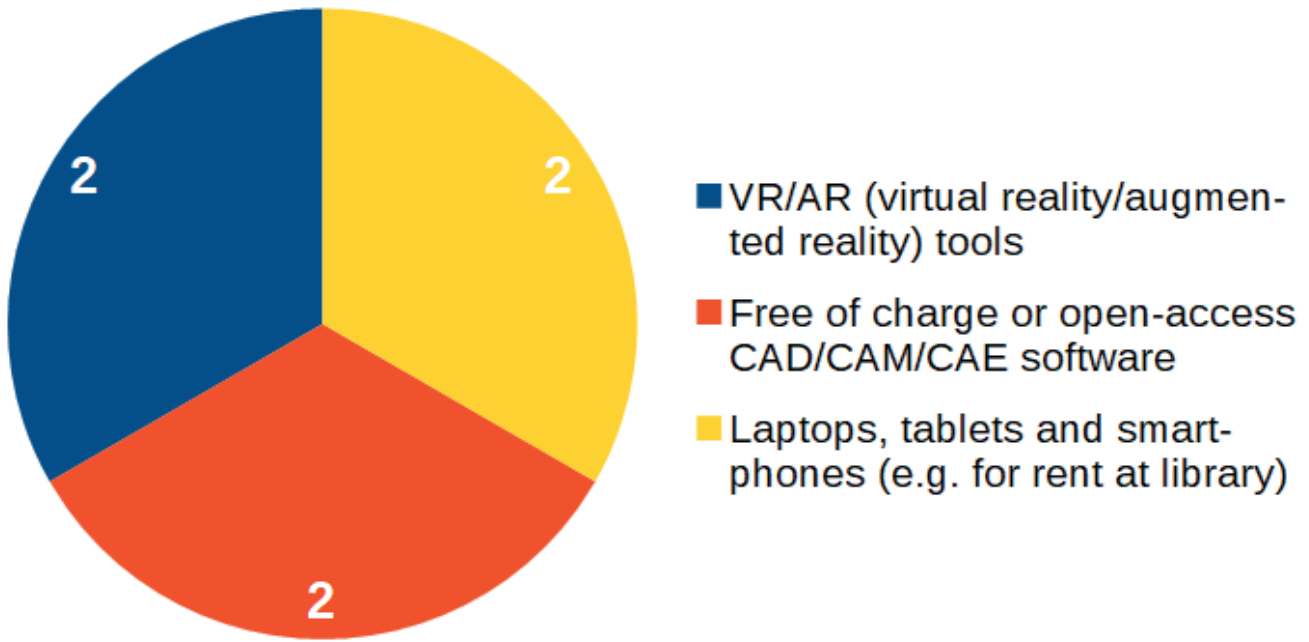


Fig. 3.30. Digital tools which organizations would mostly like to use in the future.

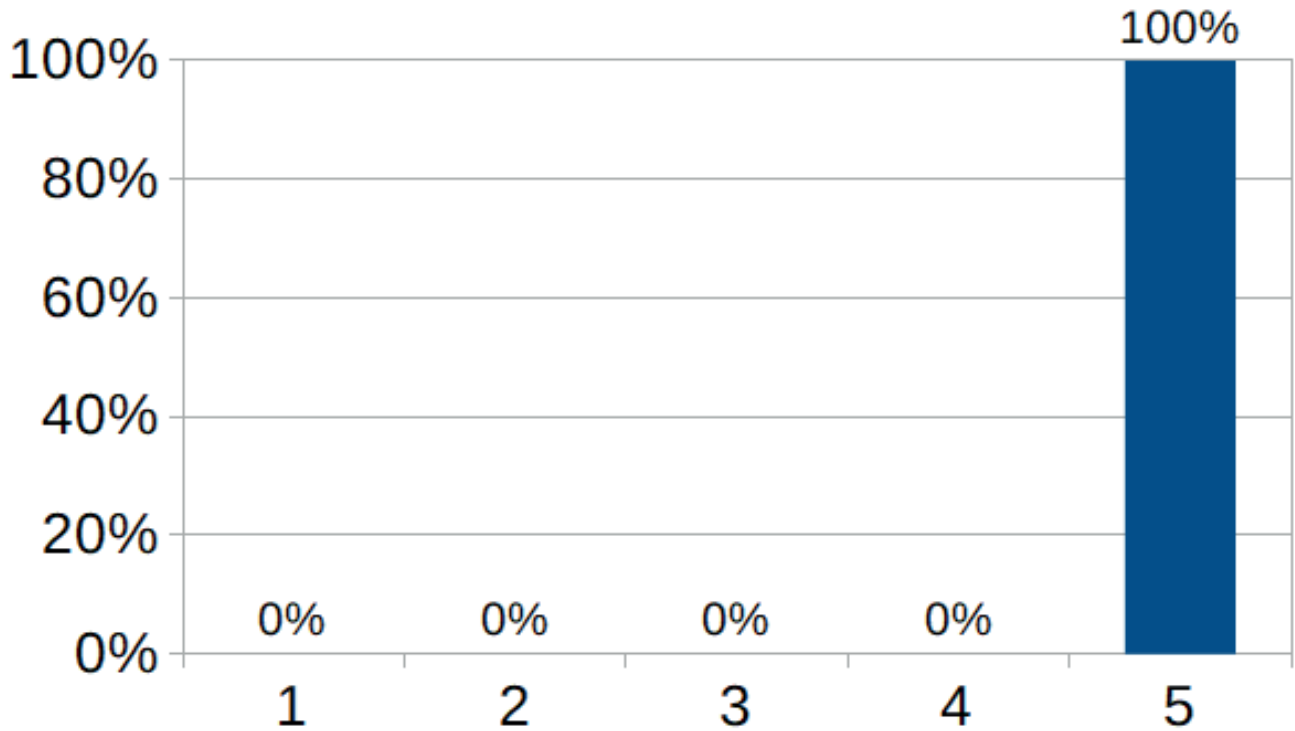


Fig. 3.31. Importance of digitalization within the next 5 years in the teaching organizations: 1 (it is not important), 5 (it is very important).

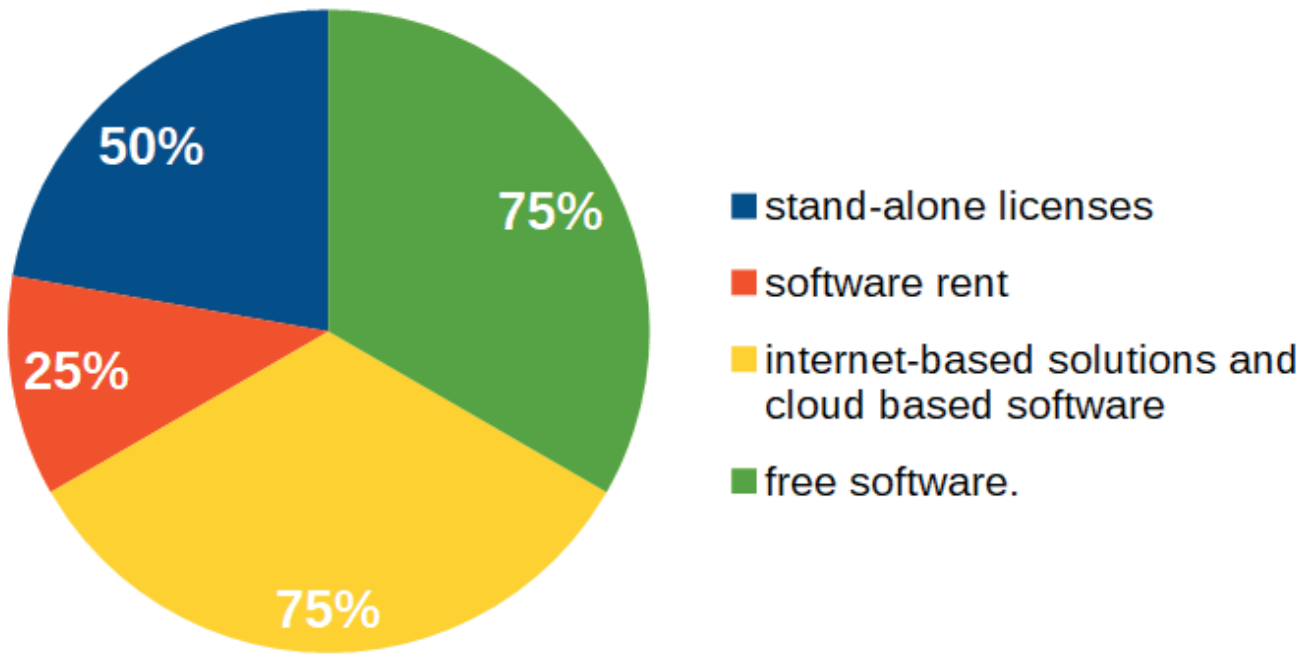


Fig. 3.32. Expected types of teaching software in the next 5 years.

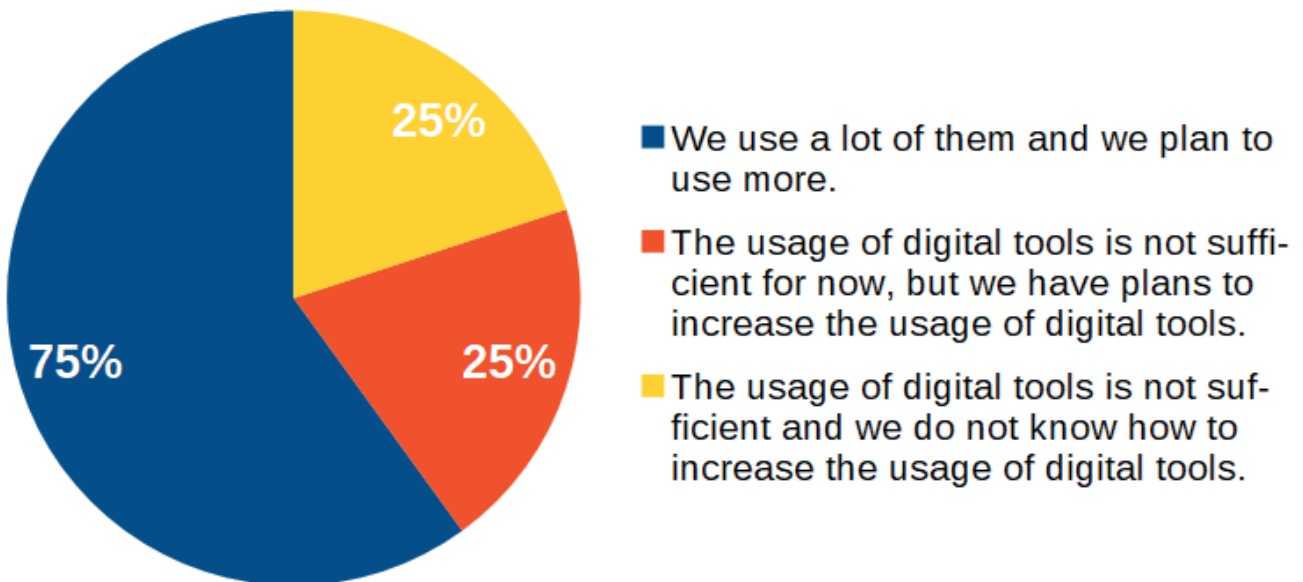


Fig. 3.33. General opinion regarding the use of digital tools in the teaching process.

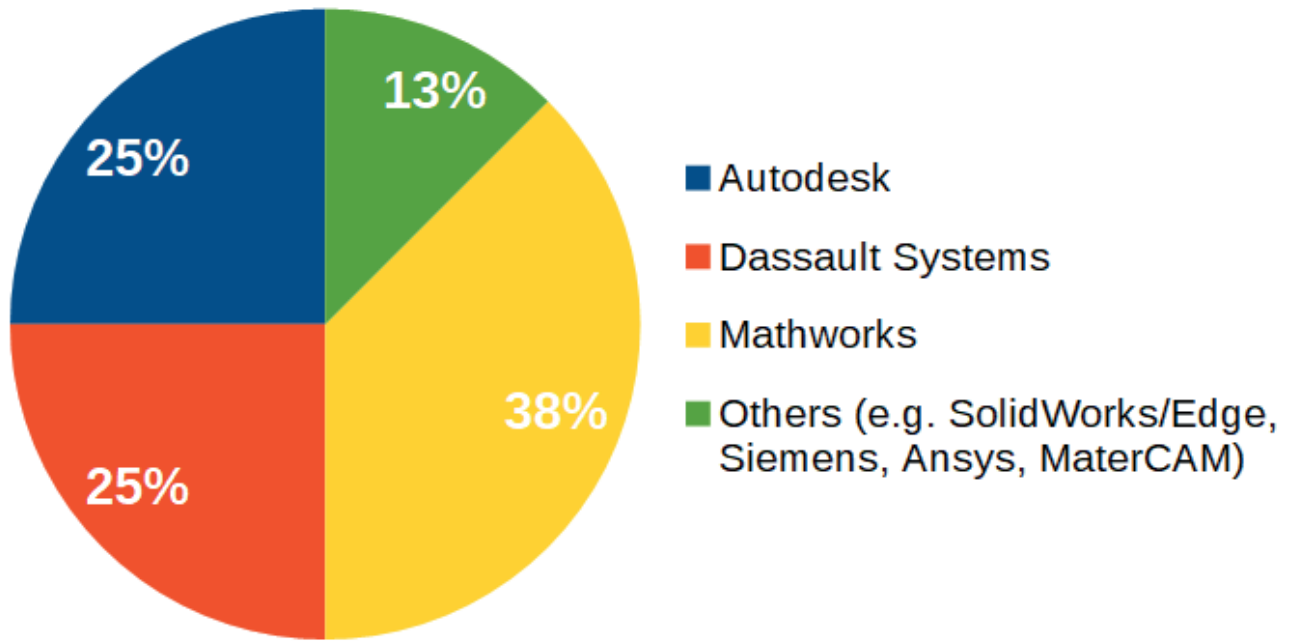


Fig. 3.34. Digital tools suppliers for ProDem (Product Development and Manufacturing) education taking into account Software (S).

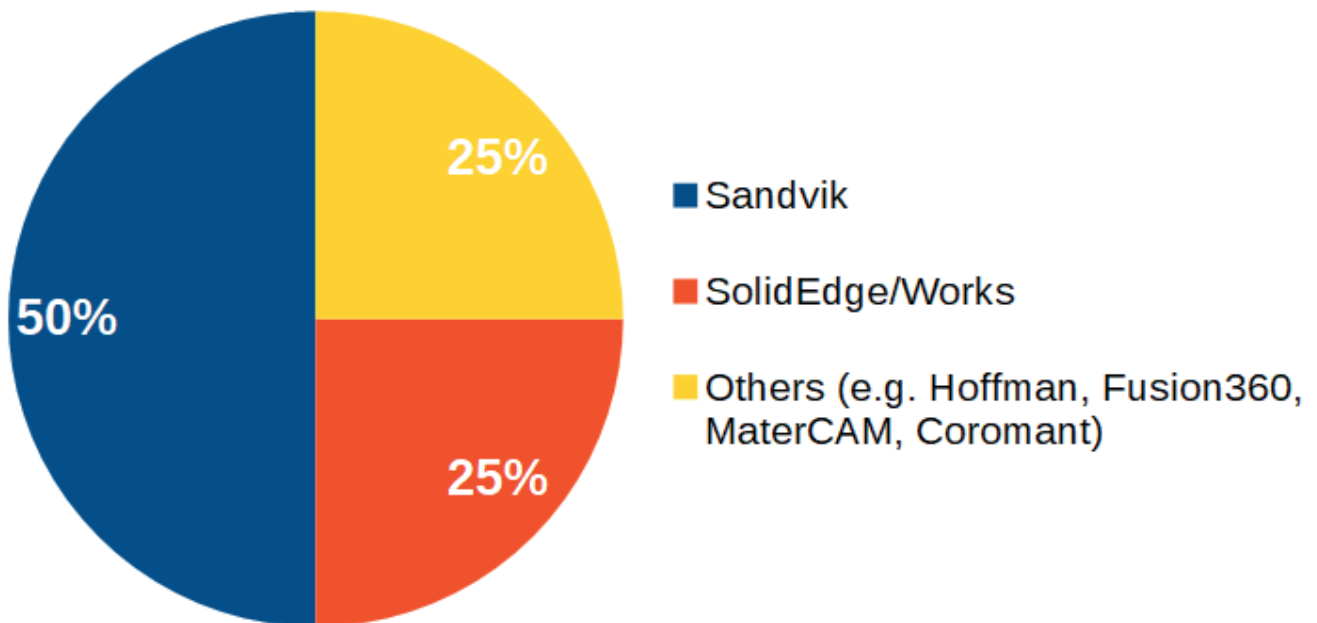


Fig. 3.35. Digital tools suppliers for ProDem education taking into account Internet-tools (IT).

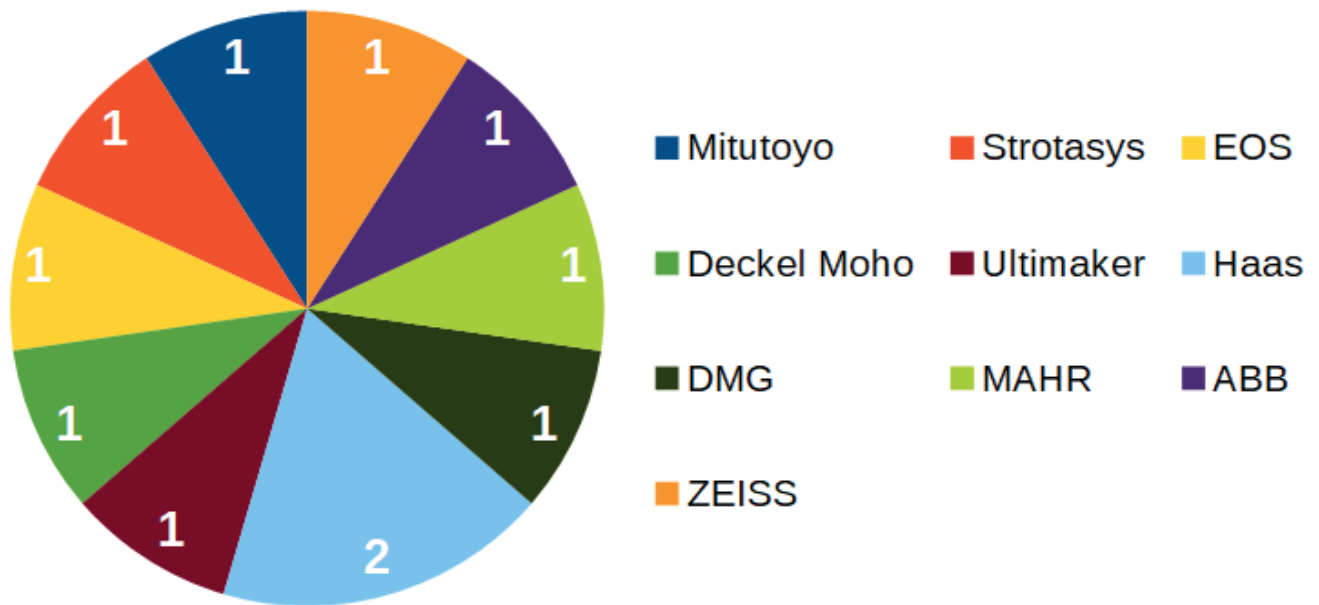


Fig. 3.36. Digital tools suppliers for ProDem education taking into account Machines and technological equipment (MTE).

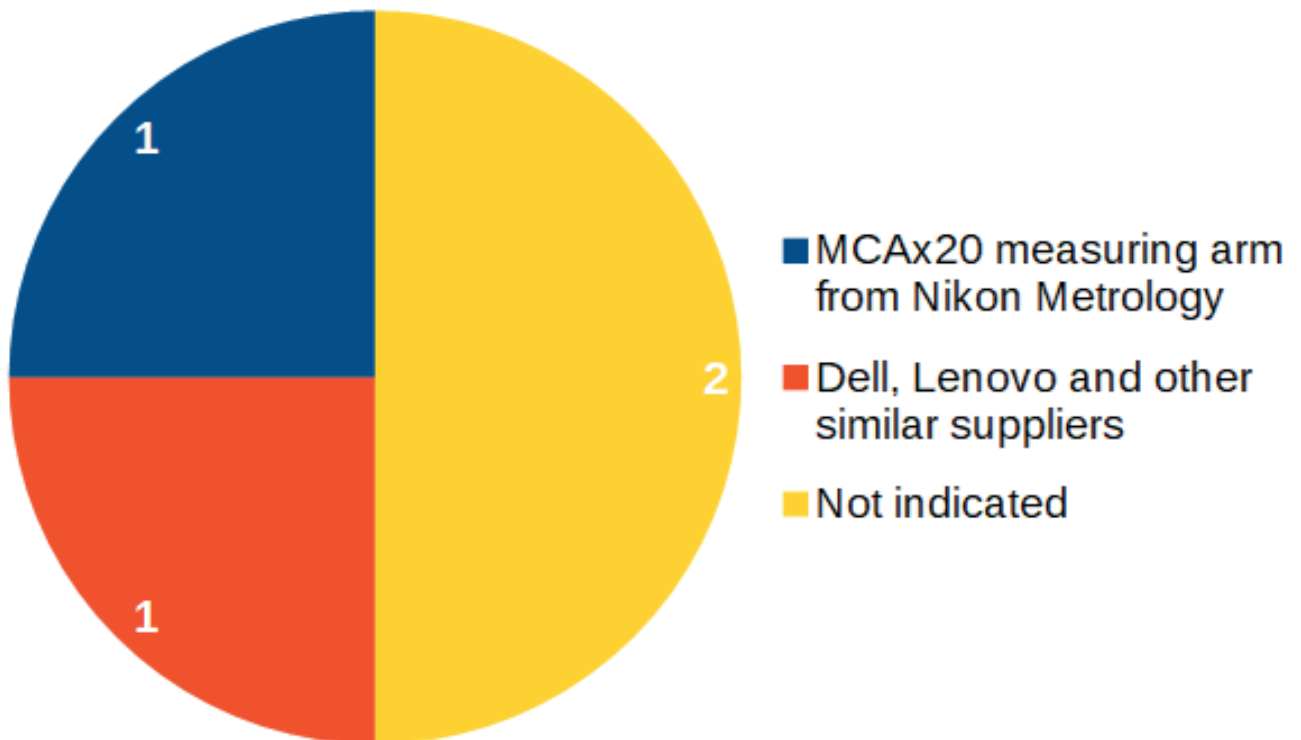


Fig. 3.37. Digital tools suppliers for ProDem education taking into account Devices (D).

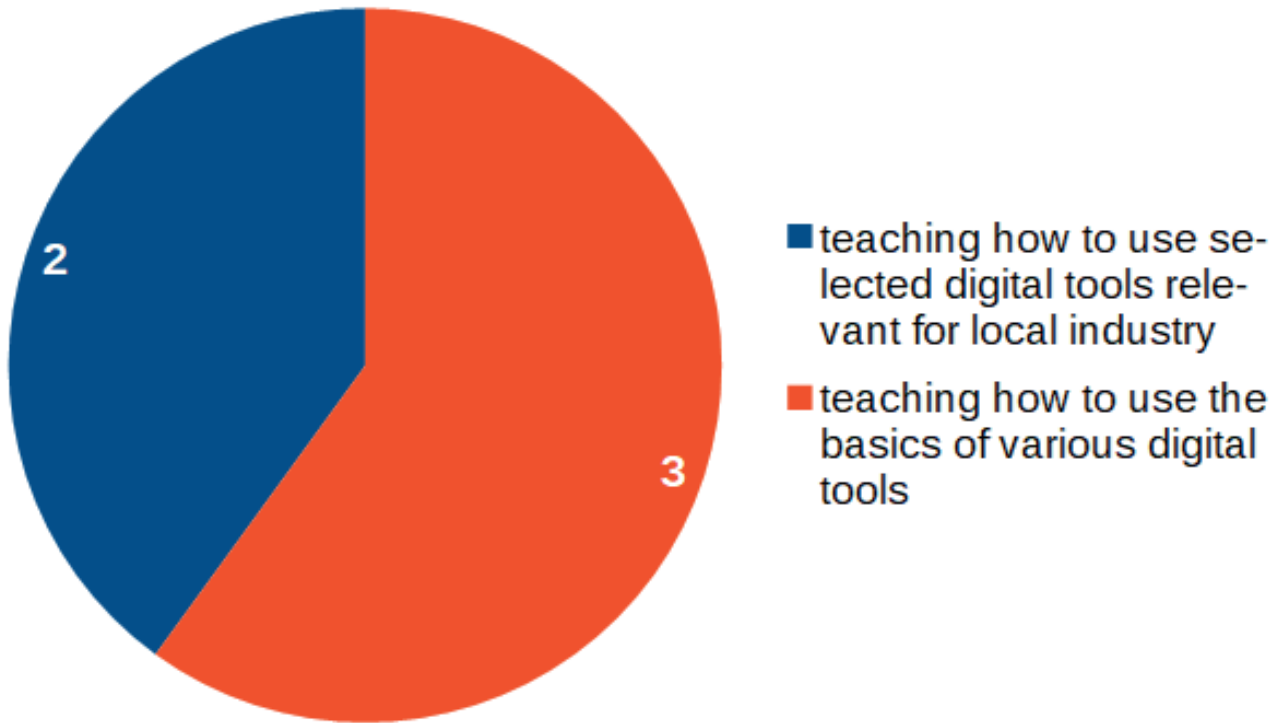


Fig. 3.38. Goals on which academic teachers of bachelor students are mostly focused on.

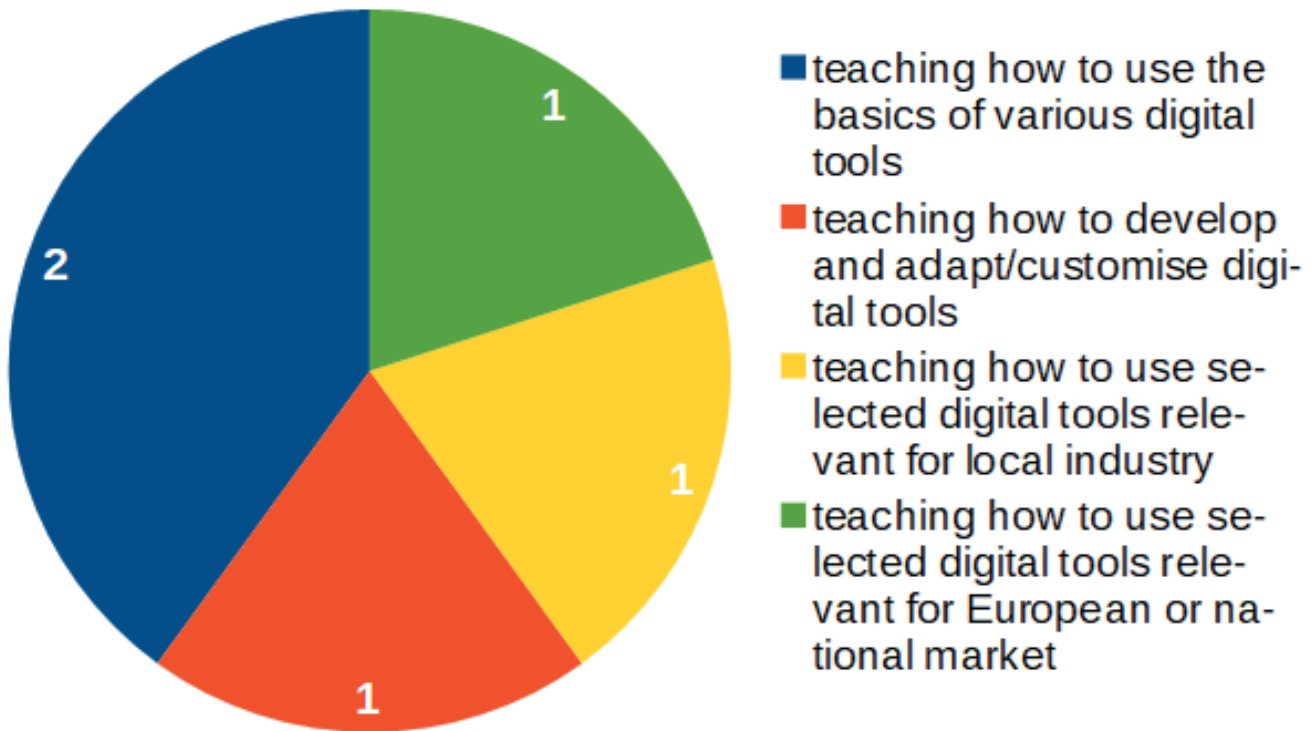


Fig. 3.39. Goals on which academic teachers of master students are mostly focused on.

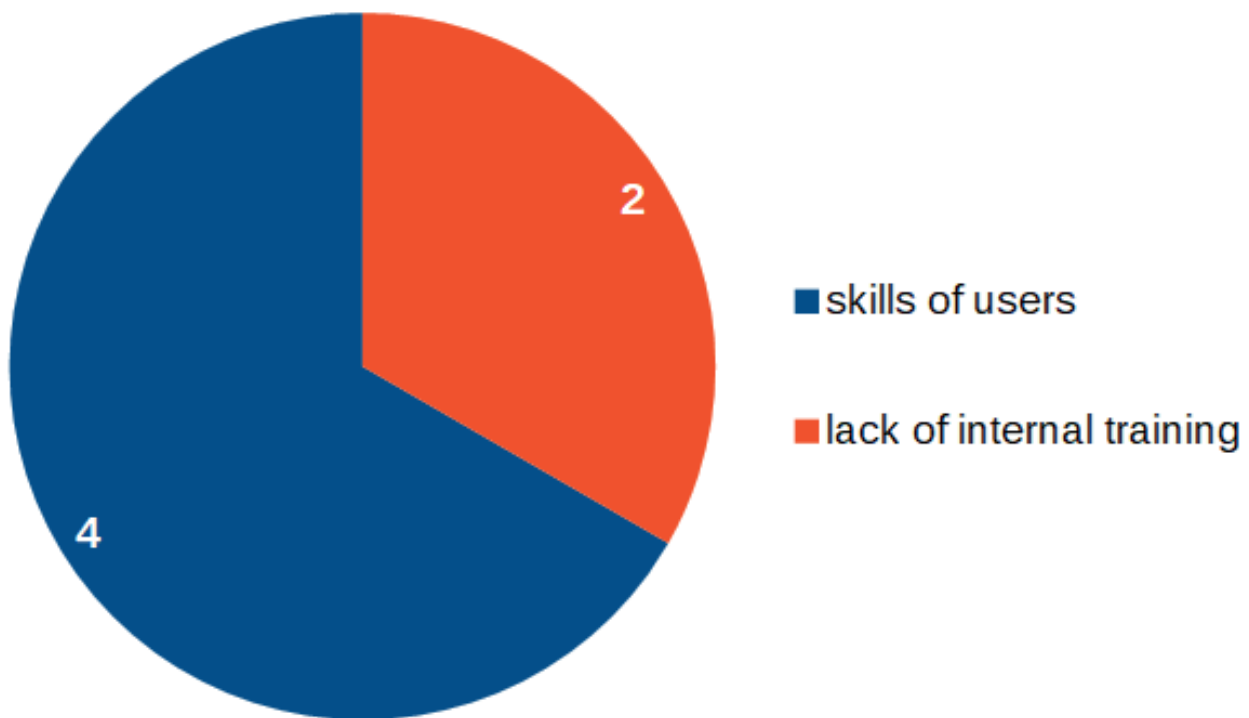


Fig. 3.40. The main limitation to increase the efficiency of the digital tools usage in teaching organizations.

The answers to the university survey were provided by the partners participating in the DIGMAN project from Estonia, Lithuania, Poland and Norway (Fig. 3.20). The most frequently used digital tools in teaching students are software, internet tools and technological equipment (Fig. 3.21). The most frequently used software (S) by universities are SolidWorks and Inventor (Fig. 3.22). They also use internet tools (IT) in the form of manufacturers websites (lectures and laboratories) and distance learning platforms (in all forms of classes, see Fig. 3.23). The most frequently used machines and technological equipment (MTE) are CNC, CMM, 3D scanners and 3D printers (Fig. 3.24). On the other hand, in the area of devices (D), laptops, robotic arms and computer tomography systems are used (Fig. 3.25). For the respondents, the most relevant digital tools used in the subsequent product life cycles are:

- in the **Product development**: Inventor, Ansys, Matlab, SolidWorks and SolidEdge (Fig. 3.26),
- in the **Design**: SolidWorks, 3d scanners/printers and Inventor (Fig. 3.27),
- in the **Manufacturing**: CNC machines and MasterCAM (Fig. 3.28),
- in the **Inspection**: CMM measuring software and devices (Fig. 3.29).

It can be seen, that there is a group of digital tools that are used both in the teaching process at universities and by manufacturing companies.

Academic teachers would mostly like to use in the future VR/AR (virtual reality/augmented reality) tools, free of charge or open-access CAD/CAM/CAE software and laptops, tablets and smartphones (Fig. 3.30). They also assume that the use of digital tools will remain very important in the next 5 years' perspective (Fig. 3.31). There is also an expectation that the teaching software will be provided by the suppliers in the form of internet-based solutions, cloud based software and free of charge (Fig. 3.32).

In general, the universities use a lot of digital tools in the area of ProDem (Product Development and Manufacturing) and they plan to use more (Fig. 3.33). It is related to software (S) producers such as Mathorks, Dassault Systems and Autodesk (Fig. 3.34). In the area of Internet tools (IT), solutions related to software producers and tools such as Sandvick, SolidWorks/Edge, Hoffman, Coromant (Fig. 3.35). However, the use of digital tools in the field of Machines and technological equipment (MTE) is very diverse (Fig. 3.36). Two Universities did not state any devices (D) used in the ProDem, while the other two have mentioned that laptops (various producers) and measuring arms (Fig. 3.37).

Academic teachers of **bachelor** students are mostly focused on teaching how to use the basics of various digital tools (Fig. 3.38). This is in line with the expectations of manufacturing companies.

Academic teachers of **master** students at their university are also mostly focused on teaching how to use the basics of various digital tools (Fig. 3.39). This, in turn, differs from the expectations of production companies, which pay more attention to teaching how to use selected digital tools relevant for the local industry. The main limitation to increase the efficiency of the digital tools usage are mainly skill of users and lack of internal training (Fig. 3.40).

4. DISTANCE LEARNING PERSPECTIVE IN PRODUCT DESIGN AND MANUFACTURING EDUCATION

New teaching methods, which are based on the use of digital tools (e.g. appropriate software tools), have been developed for decades. However, the COVID-19 pandemic highlighted their high importance and usefulness. Distance learning techniques have been successfully implemented also in mechanical engineering and manufacturing engineering classes. Lectures, exercises, laboratories have been performed by the use of this approach and thanks to the choice of various modern digital software tools.

Distance learning mainly concerns taking part in classes on-line (not in a place where university is located) and this is a general term used in modern teaching, while in e-learning students usually use a variety of materials (lectures, films, quizzes, surveys) and tools (chats, forums) shared within e-learning platform. There is also a term “remote learning” which may be assigned to a situation in which a student has no access/limited access to a computer and perform their learning tasks under periodical supervision of a teacher.

There is no clear answer whether distance learning, hybrid classes or physical presence in a classroom is better both for students and teachers. This issue generates a lot of academic discussion and arguments towards each of approaches may be easily found. Nevertheless, the future of education may also be a combination of many techniques and tools which have not been implemented so far (eg. the usage of virtual environments).

Universities around the world have implemented various digital software tools (Fig. 4.1) that help teachers and students to perform their duties/tasks. The use of the tools requires both training and experience. Moreover, access to PC and internet is crucial. In order to avoid accessibility problems governments and local organizations may also offer financial help. An important element of the use of the software is also training which should be offered for teachers (mainly those who are junior teachers) and students in their first semesters.

These sites will help by allowing to work with existing lesson plans, create new online learning resources, and host virtual interactive multimedia classrooms.

3P Learning	Loop
Bloomz	ManagedMethods
Buncee	Microsoft Teams
ClassDojo	Osmo
Deck Toys	Parlay
EdModo	Pronto
EdPuzzle	Seesaw
Edulastic	Skype
Eduplanet	Slack
Explain Everything Whiteboard	
FlipGrid	start.me
Genially	StudyBee
Google Classroom	
Habyts	Sutori
Hapara	Webex
Kahoot!	Wooclap
Kapwing	Zoom

Fig. 4.1. Virtual Learning Platforms

4.1. Experience of the Digman project partner

The data for the guidebook have been collected from all the project partners (individuals involved in the project). On the basis of an analysis of data completed by partner's institutions by using Tab. 4.1 structure some conclusions can be drawn.

	MS Teams	GSuite	Moodle	Other platform	Other platform	Remarks
Lecture						
Exercises						
Project						
Laboratory						
Seminar						
Diploma project						
Other activity						

Table 4.1. Pattern for data collection

The main conclusions resulting from answers of the DIGMAN project partners.

Partner institutions use various platforms for communication and didactic activity.

4.1.1. Rzeszów University of Technology, Poland

Rzeszow University of Technology uses various platforms in different faculties acc. to special needs of technical course e.g at the Faculty of Mechanical Engineering and Aeronautics for Lecture, laboratory, Seminar, Diploma project MS TEAMS and Moodle platforms have been mainly used.

It may be stated that the Microsoft Teams and Moodle platforms are used mostly in teaching at RUT. The following strategy of teaching was implemented:

1. At the beginning of lockdown, caused by COVID-19, different approaches were tested by the use of the indicated platforms. For instance, some lectures have been recorded before classes and shared with students, some were performed in a live streaming, some were performed with the use of text chat.

2. In the middle of summer semester 2020, when feedback from students was received in discussions, the preferred option was to perform lectures in live streaming sessions on Microsoft Teams and the recorded lectures were shared on the Moodle e-learning platform or (if the same content was presented to several groups) recorded lectures were shared before a lecture time and a teacher was available in the time of lecture (MS teams discussions with students took place).

3. Exams and tests were finally performed by the use of Teams and Moodle too. For examples, students received the questions on MS Teams, and they had the defined time for answers. They were answering using a sheet of paper and a pen, took photos of their answers, changed photos to pdf files and they uploaded the files to Moodle. Teacher could evaluate the answers by downloading pdf files from Moodle platform.

4. In the academic year 2020/2021 the main tools used within the university were Microsoft Teams and Moodle. All teachers adapted to the new situation and were able to use the tools effectively.

Most of classes were performed in the same time as they were planned before summer semester for stationary classes.

Some additional remarks resulting from experience of the Rzeszów University of Technology are as follow:

E-learning is a very effective in the case of projects which require (from students) preparation of different documents, because students can present them efficiently to all participants by screen sharing option. In the case of stationary classes document sharing is possible by the use of projectors, however this is more time consuming.

- Verification of results of exams and tests is a challenge for teacher who cannot be 100% sure whether a student wrote answers without someone's help.
- E-learning platforms are convenient tools in the case of student or teacher absence in university lecture rooms.
- Preparation of lectures and e-learning classes is time consuming and evaluation of electronic documents is not very comfortable for a teacher.
- Teaching which is focused on the use of software (e.g. CAD/CAM systems) is efficient if students have an access to licensed software.

4.1.2. Kaunas University of Technology, Lithuania

The platforms that have been used in the case of specific classes are as follow:

- Lecture, Laboratory, Seminar, Exercises , Diploma project and Team working- MS TEAMS platform,
- Lecture, laboratory, Seminar, Exercises , Diploma project, Team working, Tests, Quezes and questionnaires – ZOOM platform,
- Lecture, laboratory, Seminar, Exercises , Diploma project, Tests, Quezes and questionnaires - Moodle platform,
- Lecture, Seminar, Exercises , Diploma project, Team working - BigBlueButton platform.

Every single study course shall appear in Moodle, indicating a scope, aim and topics, literature to study, learning outcomes and types of assessment. It is mandatory for all courses at KTU. Moodle is used as a platform to submit all reports foreseen in the study course. Plagiarism check is conducted in Moodle through eLaba for every assessment, which impact to final grade is more than 30 %. Synchronic and asynchronous teaching and learning is possible.

Under the circumstances of COVID-19 pandemic, educational institutions face dramatic and complex challenges in teaching and learning. Around 1.54 billion school and university students throughout 185 countries in Europe, Asia, North and South America were affected by COVID-19 pandemic at the end of March 2020 (Schleicher, 2020). The latest studies show that during the pandemic, educational institutions had to rethink their educational mission, needs and expectations, priorities as well as the question how they will organize and manage teaching and learning process to achieve expected learning outcomes (Reimers et al., 2020).

During the pandemic, teachers have played crucial role overcoming practical, personal, and institutional constraints to assure effective virtual education (Pyhältö et al., 2020). They had to transform their teaching contents and tools, rethink students' engagement practices, manage their expectations, address social exclusion and emotional downturn of their students. At the same time students also had the unique experience related to changed learning environment and tools. This paper aims to reveal shift of students' attitudes and expectations on their learning due to the pandemic.

To explore students different experience the focus groups method was selected for this study. Focus groups are useful when it comes to investigating what participants think, but they excel at uncovering why participants think as they do (Morgan, 1988). Four focus groups per five participants were conducted online in one of the universities of Lithuania in June of 2021. Undergraduate (two groups) and postgraduate (two groups) students from social sciences (two groups) and Chemistry and Electronics engineering (two groups) were explored. First year students were excluded from the focus groups, as they had no previous experience in face-to-face learning in university context.

The main findings of the study: students' new study habits were developed. Students stressed the importance of "why" in all the activities they were asked to participate in during online learning – especially passively listening to teachers. Distractions were more

of an issue than in face-to-face learning. Students highlighted they started multitasking and mostly stopped making notes as all the material became available online.

Though most students enjoyed the freedom and flexibility online studies provided, they would prefer at least some of the activities face to face. Mixed learning method is wanted the most for the future. Students would prefer theoretical lectures online and tutorials as face-to-face activities.

Students emphasize the importance of good relations with teachers which influence the good learning atmosphere. Those relationships which were not formed before the pandemic, were mostly formal and based mostly on the completion of the compulsory tasks only. Mentoring and supervising relationships became even more important during the pandemic.

Similar tendencies were evident regarding the peer-to-peer relationships – peers were important for motivation and as a support in completing the more complex tasks, but in cases where these relationships were not formed before, they were not developed during the online learning period.

4.1.3. University of Stavanger, Norway

In general, online teaching is significantly efficient if you have the right equipment (e.g. I-pad for main host and laptop for co-host). Teaching efforts are very minimal and dissemination effectiveness increases exponentially. However, need steep learning curve to deal with all the initial breakdowns. Practicing couple of time together with another staff member can resolve the fore mentioned.

Teachers currently train practitioners those who lost jobs around whole Norway under the further education system. They use online ZOOM live streaming. We received very good feedback.

<https://www.uis.no/nb/studier/e-msk585-welding-and-in-service-inspection-technologies>

Using only: ZOOM platform it is possible to submit current situation:

- Lectures: More efficient than in the classroom, but very much depending on the lecturer as the transition from traditionally teaching and distance teaching require some skills using digital tools and proper equipment.
- Exercise: breackout rooms enables efficient group work and coordination.
- Projects: some activities, not yet start full scale. For some courses it was practical to use Zoom. Students were divided into smaller groups by the lecturer, and they had the responsibility to have digital meetings themselves to complete the project. Presentation of the project in front of class works fine using Zoom.
- Seminars: acceptable.
- Laboratory: Some of the labs using CAD/CAM/COMPUTER software was run successfully during the academic year. In Norway students has the choice if they want to use

their webcam and most students didn't share their webcam. In many sessions students didn't participate in the dialog leaving the lecturer in the blank if they understood the exercise and the level of knowledge that was in the class. This made it more difficult to focus on specific parts of the curriculum. We did split the class up into smaller groups and this took more resources as we needed to have more skilled people running each group. There was an option to use breakout rooms for one-to-one guidance and this worked well as both the student and the lecturer could share their screens. We needed to extend the deadline for completing the lab exercises and we had many sessions one-to-one as many students wasn't motivated or found it harder to complete tasks from home. Many of the lab classes were recorded and videoclips were uploaded to our LMS Canvas. However, Students didn't get the hand on experience and the possibility to ask questions during lab these exercises.

- Diploma projects: not yet started.

Some of the backside of using distance learning as the only source of teaching is the decrease in mental health among students. Many students are moving to bigger cities living alone for their first time in small student apartments. They don't have any social network and many students experienced to be isolated and felt loneliness during the academic year. For the use of home exams there are possibilities to cheat the system by letting other people help them complete tasks.

4.1.4. CENTOFORM s.r.l., Italy

For Lecture, Laboratory, Exercises , Exams , Centoform is using Cisco Webex platform. During COVID-19 emergency CENTOFORM s.r.l. in its IFTS course (Higher Technical Education and Training - EQF level 4) in Mechanical Design „Technician for mechanical and industrial design” used Cisco Webex as e-learning platform integrated with DropBox (file-sharing software) in order to share documents and materials with students. Teachers gave online live lessons and they recorded them through Cisco Webex, so students who were not able to attend, could watch them asynchronously. However, synchronous lessons are preferred because the majority of them are practical lessons, so students can exercise while the teacher gives an explanation and ask them back to put it into practice synchronously. Besides lessons and exercises, Centoform uses Cisco Webex also for each signature periodical exams. COVID-19 emergency period was the first time IFTS course used e-learning methodology, because Emilia-Romagna Region, the regional authority who finances the course, prefers to have the course in presence. For the academic year 2020-2021, the IFTS course has started in November 2020, held both online (271 hours) and in presence (221 hours). In addition, the course included 20 hours of project work and 288 hours of stage in company, for a total amount of 800 hours. The IFTS course finished in July 2021, when the students did the final test in presence. All the 19 students enrolled obtained the certification. For the online lessons, Centoform has adopted Cisco Webex e-learning platform integrated with DropBox file-sharing platform. In the near future the idea is to try to enhance e-learning methodology by using MS Teams as repository for documents and materials and for video conferencing (when its functionalities will be improved).

5. CONCLUSIONS

Teaching in the area of manufacturing engineering challenges fast changes in technological developments. New digital tools belonging to groups which have been presented within the guidebook (i.e. software, machines and technological equipment, devices, internet (intranet) tools) are brought into market every day by companies around Europe. Most universities have adapted their infrastructures to basic requirements of industry. Unfortunately, many universities have limited financial resources and, in this situation, they should continuously verify expectations of local manufacturing companies and look for a balance between newest innovations and real needs of industry, also taking into account their resources and the expectations of students. Partners of the DIGMAN project have reported, that nowadays, most of the teaching processes should involve internationalization of study programmes. In the area of product development and manufacturing education it does not mean exclusively the exchange of students or academics between institutions but also fast and wide sharing the best literature (i.e. files, books, research papers), best practices in examination of students, experience regarding user (student) friendly technological machines, devices and CAx systems. It may also be expected to share internal infrastructures between European universities widely for the aims of teaching. The teaching process cost reduction should be visible as the result of such actions.

In the case of master programmes there is still the need for extended research activities performed by master students, implementation of e-learning practices, and improving a general quality of teaching outcomes.

The guidebook has presented the requirements of four production phases such as product development, design, manufacturing and inspection which are useful for educators. The abovementioned requirements have been presented on the basis of individual experience of all the DIGMAN project partners and on the basis of feedback collected from local companies. Partners indicated important areas which should be considered by educators withing their didactic classes.

Performers of the DIGMAN project hope that the general ideas developed within this guidebook can help in understanding of the current state of teaching and allow to build, in the future, better courses based on various digital tools.

