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CONTENTS

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Volume 127, Issue 1/2025, Pages 3-12
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Original Research

ROBOTIC ASSEMBLY AND TESTING LINE FOR DAMPERS AND GAS SPRINGS AS A UNIVERSAL SOLUTION FOR TIER 1 MANUFACTURERS

ZROBOTYZOWANA LINIA MONTAŻU I TESTOWANIA AMORTYZATORÓW ORAZ SPRĘŻYN GAZOWYCH JAKO UNIWERSALNE ROZWIĄZANIE DLA PRODUCENTÓW TIER1

Robert TOMASIEWICZ[1,*]

[1] CEO, ELPLC S.A., Rozwojowa 28, Tarnów, Poland

* Corresponding author: bartlomiej.juszczyk@elplc.com

Abstract

The production of automotive dampers and gas springs involves many identical processes and is often carried out by the same manufacturers. These manufacturers, in turn, seek lines and machinery that offer efficiency and versatility, while also raising their expectations regarding the quality and accuracy of inline testing processes. This paper presents, in diagram form, the key operations in the production processes of dampers and gas springs and also revisits one of the definitions of Technology Readiness Level (TRL). It describes the primary types of automated line and machine solutions in practice by Tier 1 manufacturers. The compilation concludes with a description of the outcomes of the R&D project POIR.01.02.00-00-0056/18-00 – 'Development of a Product Innovation in the Form of an Advanced Production Line for the Assembly and Testing of Dampers and Gas Springs for Use by International Tier 1 Component Manufacturers in the Automotive Sector.' The outcome is a production line consisting of compatible elements integrated via robotics: a damping force characteristic tester for dampers and gas springs, a gas filling and damper sealing device integrated with the damping force tester, and a gas filling and gas spring sealing device, also integrated with the damping force tester. The article includes the main project goals, an review of competing solutions, and an available patent review.

Keywords: gas springs, dampers, production lines, robotization

Streszczenie

Wytwarzanie amortyzatorów samochodowych i sprężyn gazowych zawiera wiele tożsamych procesów i często jest prowadzone przez tych samych producentów. Ci z kolei poszukują linii i maszyn cechujących się wydajnością i uniwersalnością, a także podwyższają swoje oczekiwania jeśli chodzi o jakość i dokładność procesów testowania inline. Niniejsze opracowanie opisuje w postaci diagramów najważniejsze operacje w procesach produkcji amortyzatorów i sprężyn gazowych a także przypomina jedną z definicji poziomu dojrzałości technologicznej (TRL). Opisano najważniejsze typy rozwiązań zautomatyzowanych linii i maszyn w praktyce producentów Tier1. Prezentowane zestawienie zamyka opis efektów prac nad projektem badawczo-rozwojowym POIR.01.02.00-00-0056/18-00 – „Opracowanie innowacji produktowej w postaci nowatorskiego ciągu technologicznego do montażu i testowania amortyzatorów oraz sprężyn gazowych, do zastosowania u międzynarodowych producentów komponentów na poziomie Tier1 w branży automotive”. Efektem tym jest ciąg technologiczny składający się z kompatybilnych elementów zintegrowanych za pomocą robotyzacji: testera charakterystyki siły tłumienia dla amortyzatorów oraz sprężyn gazowych, urządzenia do napełniania gazem i zamykania amortyzatorów zintegrowanego z testerem charakterystyki siły tłumienia oraz urządzenia do napełniania gazem i zamykania sprężyn gazowych zintegrowanego z testerem charakterystyki siły tłumienia. W artykule uwzględniono główne cele projektu, analizę rozwiązań konkurencyjnych i dostępną analizę patentową.

Słowa kluczowe: sprężyny gazowe, amortyzatory, linie produkcyjne, robotyzacja

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1. Introduction

The practice of the manufacturer of machines and devices shows that the needs of most customers are generally met by defining the production process as a sequence of operations (Fig. 1). The purpose of this sequence is to manufacture a product in proper way using various types of resources. The beginning of the production process can be defined as the moment of delivering materials (raw materials, semi-assembled products) to the first production station. Then a cycle of processing and machining operations takes place, following which the subassemblies are merged into the final product. The last phase of the production process is to perform quality control of the received product (Helmann 2013, Liwowski, Kozłowski 2011). Partial quality control also occurs on earlier steps in the form of supervisory vision system for assembly correctness checks.

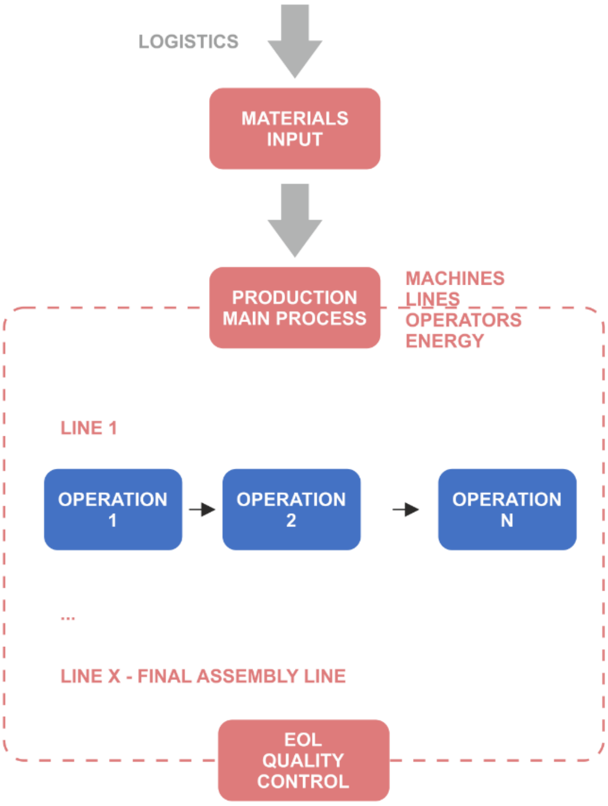

Fig. 1. Production process description example

Processing operations are a set of various production activities: screwing, crimping, welding, soldering, fitting, applying, etc. Many criteria for divisions and resources used can be entered here. Most often, they create a certain logical sequence resulting from previous research and development work on a specific product or group of products for which a given line is intended. At the stage of designing such a line or individual machines – at least a digital model of the target product already exists. This results in the parameters that the future line must handle. It is also necessary to take into account auxiliary processes that will run in parallel with the main production process, e.g. maintenance of traffic, i.e. meeting specific HMI and service standards (Nag, 2023). An important issue is ensuring a specific process stability described by the cycle time, number of pieces in time, etc. (Mazurczak, Gania 2008). Here, customers are increasingly reaching for smart factory-type IT tools that ensure traceability and predictive maintenance (Bortolini, Ferrari, Gamberi, Pilati, Faccio, 2017).

1.1. Production processes of a damper and gas spring

The production process of a damper or gas spring (Fig. 2) can also be described in this way, starting from cutting and forming the tubes, up to functional tests, assembling elements and packaging. In both cases, the process is similar, but there several differences, which are shown in Fig. 3 and Fig. 4.

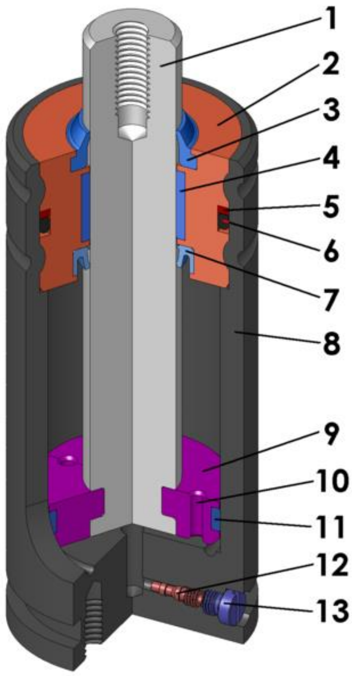

Fig. 2. 3D-view of a gas spring with sectional view (Silberwolf, 2007). 1) Piston rod; 2) Head cap; 3) Piston rod wiper; 4) Piston rod guide bushing; 5) Retaining ring; 6) O-ring; 7) Piston rod seal; 8) Cylinder; 9) Piston; 10) Flow-restriction orifice; 11) Piston guide bushing; 12) Valve; 13) Valve-sealing screw

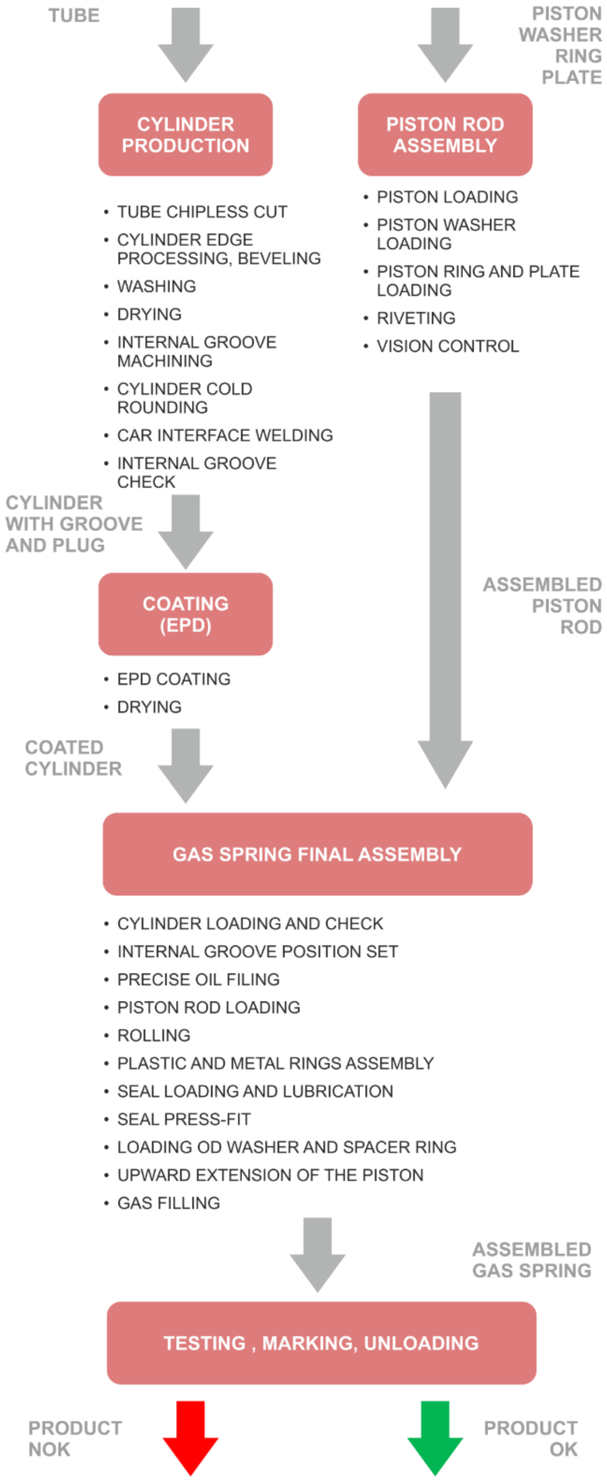

Fig. 3. Example of gas spring production process

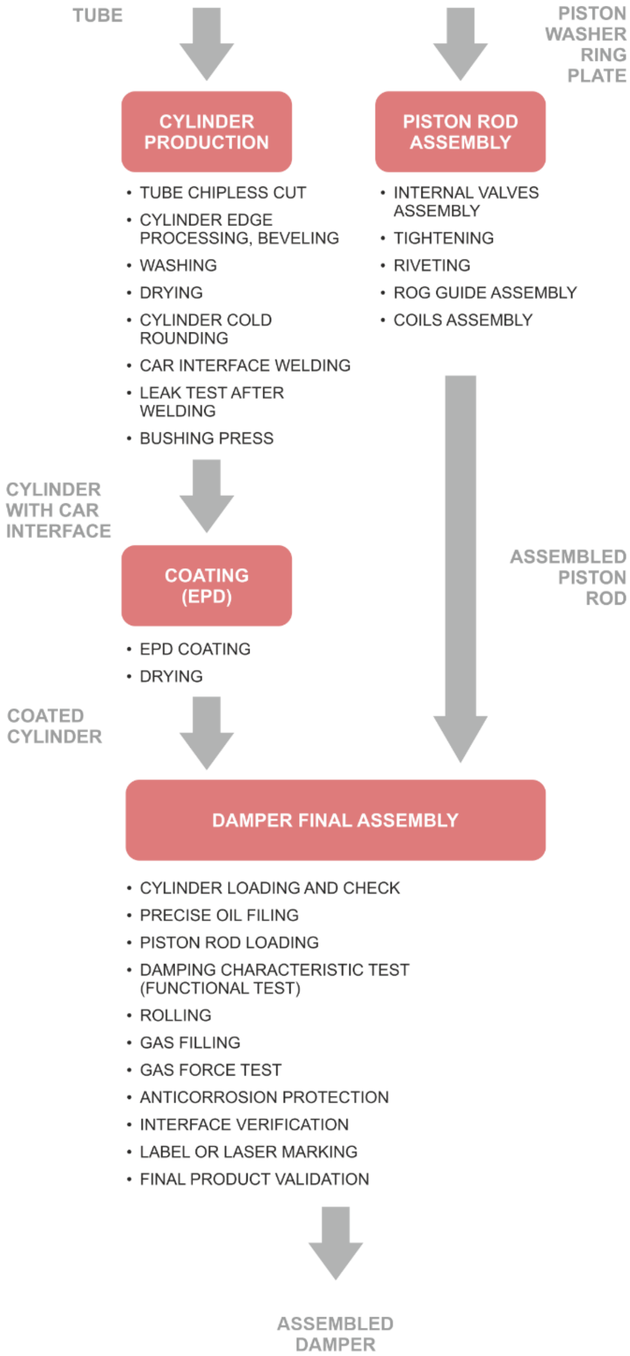

Fig. 4. Example of dampers production process

1.2. Technology readiness level

Technology readiness levels (TRLs) are a method for estimating the maturity of technologies during the acquisition phase of a program. TRLs enable consistent and uniform discussions of technical maturity across different types of technology. [1] TRL is determined during a technology readiness assessment (TRA) that examines program concepts, technology requirements, and demonstrated technology capabilities. TRLs are based on a scale from 1 to 9 with 9 being the most mature technology as seen in Table 1 (Wikipedia 2024; Mihaly, Heder 2017; Deutsch, Meneghini, Mermut, Lefort 2012) TRL was developed at NASA during the 1970s. In 2013, the TRL scale was further canonized by the International Organization for Standardization (ISO) with the publication of the ISO 16290:2013 standard (Wikipedia 2024; Mihaly, Heder 2017). This scale is also used to describe research and development projects co-financed by the European Union (Table 1).

Table 1. TRL definitions (European Commision, 2019)

TRL Lvl	Description
1	Basic principles observed
2	Technology concept formulated
3	Experimental proof of concept
4	Technology validated in lab
5	Tech. valid. in relevant industrial environment
6	Tech. demo in relevant industrial environment
7	System prototype demo in operational environment
8	System complete and qualified
9	Actual system proven in operational environment

2. Overview of most common automated solutions for Tier 1 manufacturers

2.1. Gas spring cylinder production line

The input resources for this line (Fig. 5) are a steel pipe of the appropriate diameter and a selected assembly tip. The output of the line is a cylinder prepared for electrophoretic deposition (EPD) painting and later used in the assembly of a gas spring.

The cylinder line is divided into several functional modules (Fig. 5):

Module 1 – automatic tube feeder synchro-nized with the cutting machine (Fig. 6).

Module 2 – automatic, chipless cutting of the tube to a size depending on the manufactured reference, preparation of the cylinder edge (chamfering), edge cleaning, forming the inlet cone with blow-off.

Module 3 – automatic cleaning of the cylinder by spraying using a dedicated cleaning emulsion at an elevated temperature, internal and external drying of the cylinder, excess liquid tank.

Module 4 – multi-position rotary table:

- cylinder loading from module 3 – dedicated manipulator,
- profiling of internal grooves – CNC drive with a vision system,
- cylinder positioning – changing the grip height with a dedicated manipulator,
- cold rolling of the cylinder end – CNC drive with a vision system,
- resistance welding of the end with the cylinder (Fig. 7),
- checking the correctness of the groove profile using the flow method – measurement with a flow meter at controlled movement of the measuring piston inside the cylinder.

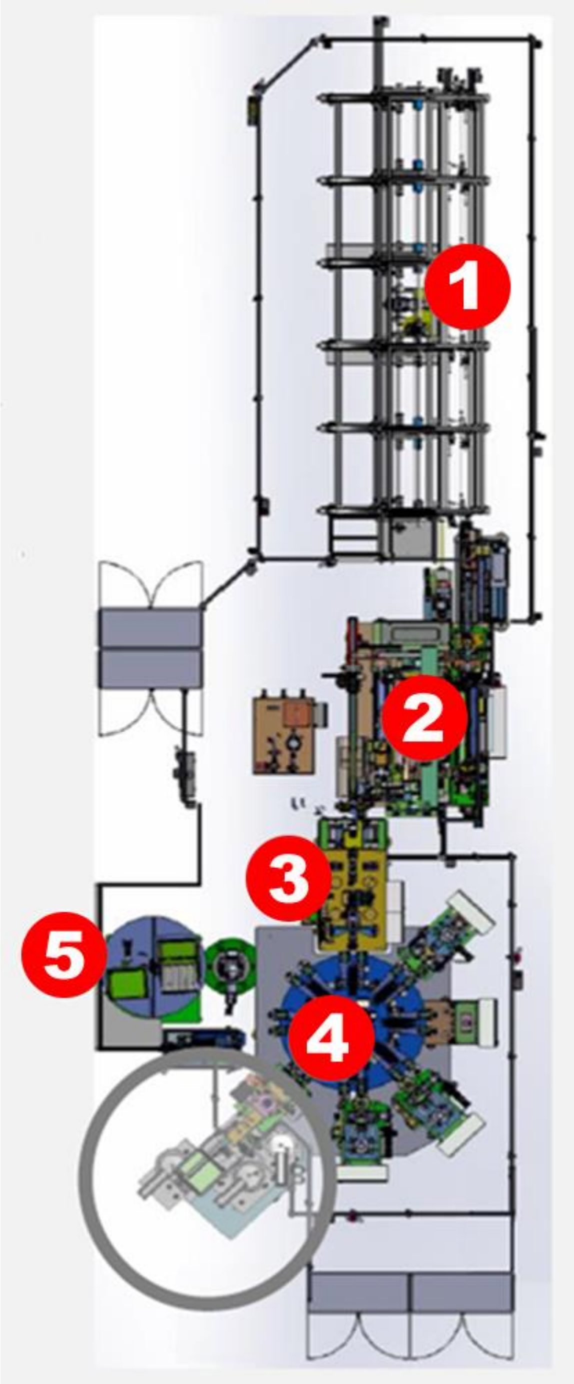

Fig. 5. Cylinder production line layout

Module 5 – unloading to the receiving basket – a universal 6-axis robot equipped with a vacuum gripper loading the semi-finished product into dedicated baskets of the washing machine (Fig. 8).

The range of cylinders manufactured includes external diameters of Ø15÷Ø28 mm, material thickness of 1÷2 mm and height of 100÷1100 mm.

Fig. 6. Tube feeder synchronized with cutting station

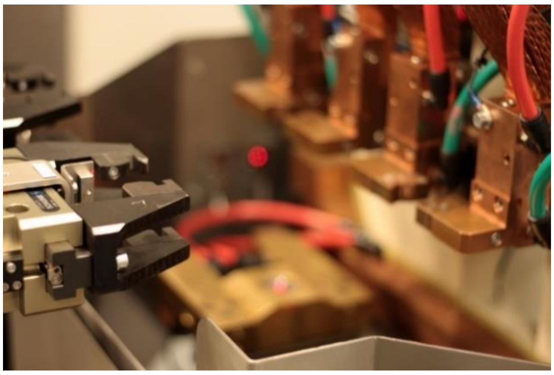

Fig. 7. Resistance welding station (module 4)

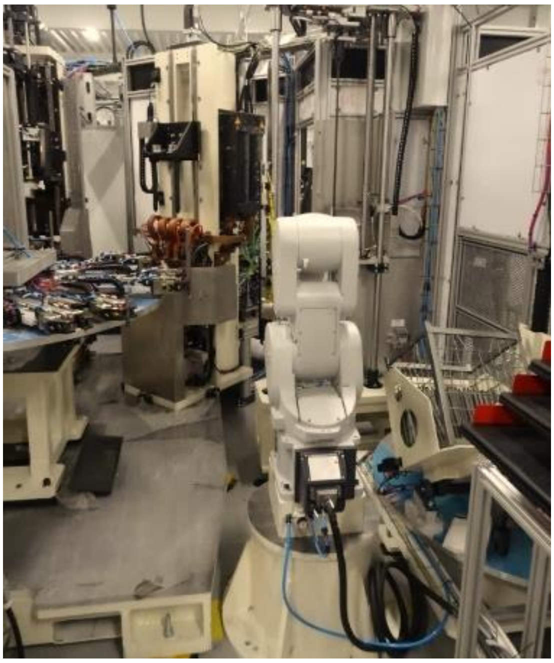

Fig. 8. Unloading robot

2.2. Gas springs final assembly line

A line for the final assembly of a gas springs (Fig. 9). The input includes: cylinders ready for further assembly after EPD painting and drying, additional elements in the form of rings and seals, and filling gas and oil dosed with an accuracy of 1 g. The piston rod elements are also fed, which are merged into a whole piston rod assembly. The piston rod assembly is then mounted to the cylinder together with additional elements, and the whole is filled with gas under pressure reaching several tens MPa and tested.

The line was designed to meet customer expectations related to reducing the space occupied by the lines, the number of operators necessary for service and ensuring the outflow of finished pieces every 7-8 s (depending on the dimensions of a given production reference). All these assumptions were achieved thanks to the use of a compact design with universal robots (Fig. 11) and rotary tables inside and redundant stations, e.g. the test station (Fig. 10).

The line control system supports 34 servo axes, 20 distributed compact I/O and safety modules, 2 coupled universal robots, 4 SCARA robots for fast Pick&place operations and the CC Link IE Field (1Gbps) industrial communication network.

Fig. 9. Gas springs assembly line 3D model; 1) piston rod loading; 2) piston rod assembly; 3) coated cylinders loading; 4) gas spring assembly; 5) gas filling and functional testing; 6) unloading station

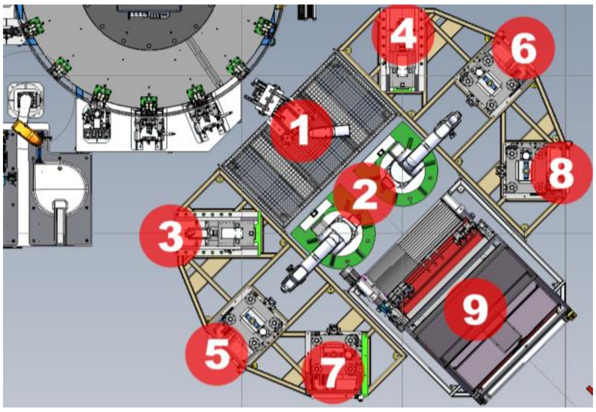

Fig. 10. Redundant stations at line output; 1) transfer from gas spring assembly module; 2) synchronized universal robots handling gas filling stations, functional testers and unloading; 3) gas filling station 1; 4) gas filling station 2; 5) functional tester 1; 6) functional tester 2; 7) functional tester 3; 8) functional tester 4; 9) unloading station

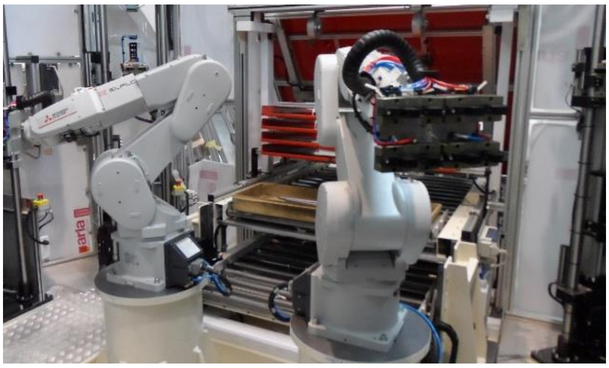

Fig. 11. Universal robots tandem, unloading station at background

2.3. Modular line for dampers assembly and testing

The line (Fig. 12, Fig. 13) assembles a ready-made twin-tube cylinder with a piston rod assembly, a floating piston. The input components are: a tube closed on one side, an internal tube with a valve, a ready-made piston rod assembly with a guide, an overlay, oil, nitrogen, labels. At the output of the line, an assembled damper is expected, ready for final assembly. Modularity was assumed for flexible adjustment of the pallet flow and exchange of stations, as well as the easiest possible changeover to different references.

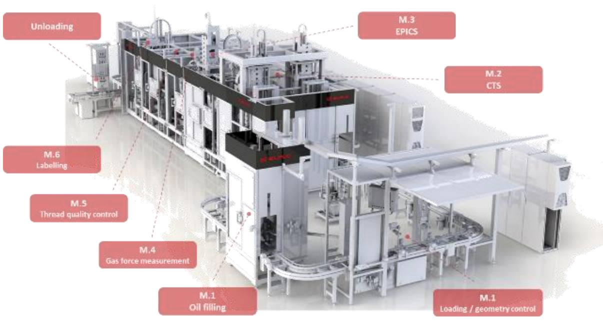

Fig. 12. Dampers modular line 3D model

Fig. 13. Assembly line panoramic photo

Description of individual line modules:

- **module 1** – initial module consisting of a loading station and filling the damper with oil;
- **module 2** – module for pressing the damper piston rod guide integrated with the module for controlling the damper damping characteristics (CTS for the inline process);
- **module 3** – module for filling with nitrogen and closing the damper by rolling (EPICS for the inline process);
- **module 4** – module for measuring the force generated by nitrogen in the damper and for length control;
- **module 5** – module for pressing the sliding pad and thread quality control;
- **module 6** – module for printing and sticking the label;
- **module 7** – station for checking selected damper dimensions.

The ranges of the CTS inline tester (Fig. 14) main parameters are described in Table 2.

Table 2. Main parameters ranges

Parameter	Value, range
Tube diameter range	30 ÷ 60 mm
Tube height range	120 ÷ 600 mm
Product height range	120 ÷ 1000 mm
Maximum product weight	8 kg
Oil dosing volume	60 ÷ 600 ml
CTS[1] – test force	-6500 ÷ 6500 N
CTS – stroke range	0 ÷ 400 mm
CTS – test speed	0,5 ÷ 1000 mm/s
CTS – maximum acceleration	10 g
CTS – acceleration curves	sin, triangle, trapezoid
CTS – test frequency	16 Hz
Damper Closing Force (EPICS)	45 ÷ 150 kN
Gas pressure (EPICS)	2,5 MPa max.
Gas force control	20 ÷ 500 N
Cap diameter	40 ÷ 80 mm
Spring bed ring – diameter	30 ÷ 300 mm
Spring bed ring – position	25 ÷ 100 mm
Transport pallet size	320 x 320 mm

[1] CTS – functional characteristics tester.

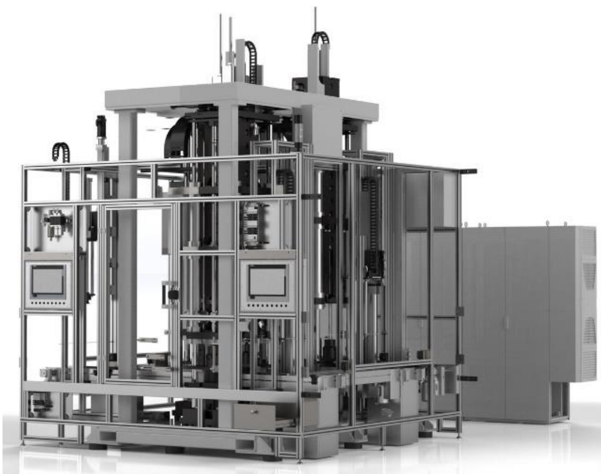

Fig. 14. CTS testing module/station 3D model

2.4. Piston rod valve assembly line

A line consisting of several stations for assembly and visual inspection of the piston rod valve for monotube and twintube dampers (Fig. 15). The first section is a set of automatic and manual stations, where the manual assembly of components, valve crimping and riveting take place. In the second section, a special cartridge and sealing is assembled. Finally robotic unloading takes place.

Fig. 15. Piston rod valve assembly line

2.4. Leak testers

Autonomous station (Fig. 16) for damper leak testing using the pressure drop measurement method equipped with integrated ATEQ devices. Easy-to-use test station for dampers, supporting products with a cylinder diameter of 30÷80 mm, cylinder length up to 600 mm. Test pressure: 400÷700 kPa.

Fig. 16. Leak tester measurement devices

3. Research and development of robotic assembly and testing line for dampers and gas springs

3.1. Project main objective

The objective of the project was to develop an innovative, robotized, technological process for the assembly and testing of dampers and gas springs, enabling Tier 1 end-users to enhance the efficiency and flexibility of production. The planned research, development, and implementation work was expected to yield a more versatile product for interested customers. Due to the scope of work and the results anticipated, the project aligns with the Polish National Smart Specialization 14: Automation and Robotics of Technological Processes, specifically Section I: Process Design and Optimization, subsection 6: Design, Optimization, Automation, and Robotics of Production Processes. It also aligns with the thematic scope of the competition in Research Area I: Innovative Technologies for Production, Regeneration, Recovery, and Recycling, within Research Group A: New Technologies for Production, Regeneration, Recovery, Recycling, and Disposal, and Development of Existing Technologies, particularly under Research Issue I.A.1: Improved or New Technological Lines and Production Technologies for Vehicles and Automotive Parts.

3.2. Target market

The target recipients of the project results have been defined as Tier 1 manufacturers. These companies are engaged in the production of all components essential for vehicle manufacturing. In this case, they are manufacturers of dampers and gas springs. During the project’s implementation, the global damper market responded to increasing demand for cars` by continuously expanding its production capacities, which contributed to an upward trend in the industry’s revenues. Similar growth prospects exist for the gas spring market, which is projected to reach a global value of USD 10.5 billion by 2026, with a compound annual growth rate (CAGR) of 5.8% over the period 2018–2026 (Persistence Market Research, 2023).

3.3. Analysis of competitive entities and solutions

In the target market, there are competing entities; however, they do not present direct competition, as they do not offer a single universal solution but instead separate solutions for dampers and springs. Brief list of main competitors in this area:

- Inova GmbH,
- Tekno Alfa S.R.L,
- Samac S.R.L,
- MTS Systems Corp.,
- Mondragon Assembly S Coop.,
- SIASUN Robot & Automation Co., Ltd.

List of other main issues encountered by users of machines and equipment:

- use of hydraulic motors, which significantly increase the likelihood of high-scale errors. Testing using hydraulic motors, due to its mechanical limitations is less precise than testing with a linear electromagnetic drive,

- electromagnetic linear drive and high accuracy measurement used – but testing devices intended exclusively for laboratory use and cannot be applied in industrial inline testing,
- processes – not demonstrate adequate thermal resistance under industrial conditions,
- mediocre or poor measurement during testing with significant errors (up to 10%), resulting in the rejection of components that could potentially pass the full test,
- closed systems not designed for integration with other modules or for process automation, which makes them not universal and not flexible.

3.4. Patent analysis

Before project start was independently conducted an analysis of available and protected solutions, technologies, and research and development outcomes, the existence of which could potentially pose a barrier to the ongoing pro-innovative activities. This analysis covered documents contained in the following patent databases:

- Polish Patent Office;
- World Intellectual Property Organization;
- European Patent Office;
- Baz-Tech (databases of Polish technological journals);
- online patent database lens.org

The subject-based search was carried out based on the names of companies identified as main competitors, including: MTS Systems, Mondragon Assembly S. Coop., SIASUN Robot & Automation Co. Ltd., Techno Alpha Co. Ltd., Industrial Gas Springs Inc., Kayaba Industry Co. Ltd., Ahaus Tool & Engineering Inc. The object-based search was carried out using the following keywords: assembly and testing line for hydraulic dampers, method of testing automotive gas springs, method of measuring damping force in gas springs, nitrogen dosing control inside the damper. The subject of the research was classified according to the International Patent Classification as F01 – machines or engines in general, power plants in general, steam engines, and F16F – springs; shock absorbers: means for vibration damping.

As a result of the research, 5 solutions related to damping testing devices were selected, but they do not possess the characteristics that distinguish and define the Project outcome. However, the three closest solutions were identified, including:

- CN101441130A – Durable test stand and test method of gas spring for automobile – a test stand used to assess the physical stretchability level of gas springs;
- US 8844345 B1 – Imparting motion to a test object such as a motor vehicle in a controlled fashion – a device for testing that imparts controlled motion to the test object, based on a linear electromagnetic motor with a non-iron core;
- US6360580B1 – Device and method for testing vehicle shock absorbers – a device for testing vehicle shock absorbers that achieves more accurate measurements by normalizing the resonance amplitude and adopting a fixed wheel suspension elasticity value before starting the tests.

The state of the art as of August 8, 2018, indicated that the available solutions do not possessed the key functionalities planned for development in the Project, which eliminated any barriers for the implementation of the Project results arising from intellectual property rights.

3.5. Project result

An in-depth analysis of market needs, available solutions, and our own expertise resulted in the successful completion of the project. All stages were conducted, from design through part manufacturing, assembly, programming, and concluding with commissioning and a full set of documentation. During the work, 3D models of the line were created, one of which is shown in Fig. 17. A photograph of the constructed line during commissioning stage is visible in Fig. 18.

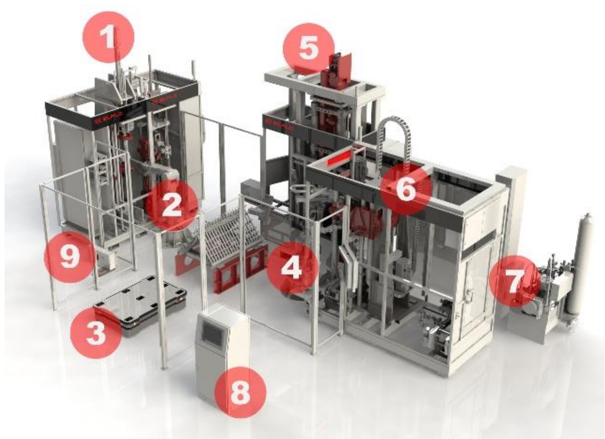

Fig. 17. Robotized assembly line 3D model

Assembly line main features:

1. Stationary machine for testing the CTS characteristics of gas springs.
2. Robot for handling gas springs.
3. Autonomous trolley – AMR robot.
4. Robot for handling dampers.
5. Stationary machine for testing the CTS characteristics of dampers.

6. Stationary machine for rolling and gassing EPICS – dampers.
7. Hydraulic unit.
8. Data collection system – TRACEABILITY.
9. AMR robot charging station.

Fig. 18. Line commissioning at Company R&D facility

Developed line meets several conditions:

Universality of the technological line devices – the "all-in-one" solution takes up 32% less usable space and consumes 90% less oil (reduction from 500 to 50l of oil per year) compared to solutions with a characteristic tester module with a servo-hydraulic drive,

Scalability and compactness of the technological solution through modularity and compatibility – both parts (dampers and gas springs) or each one can be supplied / operated independently,

Increased measurement accuracy – reduction of measurement errors from 4% to 1.5%,

Shortening the loading time in the production cycle due to robotization (~20%),

High work autonomy thanks to the use of robotic logistics service (AMR vehicle).

4. Summary

Development work related to the implementation of a modular production line for the assembly and testing of automotive dampers has been completed. The work was carried out as planned, from November 1st, 2019, to April 30th, 2022.

The line, featuring an improved method for the assembly and testing of dampers and gas springs for the automotive industry, has reached Technology Readiness Level (TRL) 9 upon completion of the Project. Achieving this TRL level was possible through the development of a technological line consisting of separate yet compatible elements/modules:

- a tester for assessing damping force characteristics for dampers and gas springs,
- a technological line for assembling and gas-filling dampers,
- a technological line for assembling and gas-filling gas springs.

Although the R&D work commenced at TRL 4, no industrial research was planned within the Project. The technology advanced through the appropriate combination and transformation of existing scientific and technical knowledge in the relevant area. Achieving the final result involved a series of tasks:

- developing the operational schema and design of the devices and the entire technological line,
- designing a dedicated control system for each device and the entire technological line, enabling automation in the transportation of damper and gas spring components,
- integrating and fully automating the technological line, as well as tasks aimed at its final validation and demonstration.

Acknowledgments

Work on the POIR.01.02.00-00-0056/18-00 project "Development of a product innovation in the form of an innovative technological line for the assembly and testing of dampers and gas springs, for use in international manufacturers of components at the Tier1 level in the automotive industry" received funding under the Smart Growth Operational Program 2014-2020.

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Original Research

DEVICE FOR AUTOMATIC ACCURACY INSPECTION OF DIAL INDICATOR READINGS

URZĄDZENIE DO AUTOMATYCZNEJ KONTROLI DOKŁADNOŚCI WSKAZAŃ CZUJNIKÓW ZEGAROWYCH

Tomasz SAMBORSKI[1,*], Andrzej ZBROWSKI[2], Stanisław KOZIOŁ[1]

[1] Łukasiewicz Research Network – Institute for Sustainable Technologies, Kazimierza Pułaskiego 6/10, 26-600 Radom, Poland
[2] Rzeszów University of Technology, Powstańców Warszawy 12, 35-959 Rzeszów, Poland

* Corresponding author: tomasz.samborski@itee.lukasiewicz.gov.pl

Abstract

The authors present a research method and a prototype of a system for automatic accuracy inspection of manual measuring instrument readings. Most commonly used measuring instruments, such as dial indicators and bore gauges, require periodic accuracy inspection. The developed system is intended for inspection automation, minimising potential human errors connected with manual inspection and visual assessment of readings. The precise mechatronic actuators, measurement systems, and inspection software used in the system enable automatic execution of standard inspection procedures in accordance with the formal recommendations of the Central Office of Measures. The scientific and research results obtained will benefit the development of methods for processing and analysing measurement data.

Keywords: measuring instruments, errors, inspection procedures

Streszczenie

W artykule autorzy zaprezentowali opracowaną metodę badań oraz budowę prototypowego systemu do automatycznej kontroli dokładności wskazań ręcznych narzędzi pomiarowych. Narzędzia pomiarowe powszechnie stosowane do pomiarów warsztatowych takie jak czujniki zegarowe i średnicówki wymagają okresowej kontroli dokładności wskazań. Zbudowany system służy do automatyzacji kontroli i uniezależnienia jej wyników od potencjalnych błędów popełnianych przez personel w trakcie jej realizacji, związanych z ręczną metodą kontroli i wzrokową oceną poprawności wskazań. Zastosowane w systemie precyzyjne mechatroniczne układy wykonawcze, układy pomiarowe i oprogramowanie sterujące, umożliwiają automatyczną realizację standardowych procedur kontrolnych, zgodnych z formalnymi zaleceniami Głównego Urzędu Miar. W zakresie efektów naukowo-badawczych główny obszar wykorzystania uzyskanych rezultatów stanowi rozwój metod przetwarzania oraz analizy danych pomiarowych.

Słowa kluczowe: narzędzia pomiarowe, błędy, procedury kontrolne

1. Introduction

Dial indicators are used for precise linear measurements (length and diameter) of the runout of rotating elements with an accuracy ranging from 0.01 to 0.001 mm. Despite significant advancements and availability of sophisticated measurement techniques, such as coordinate measuring machines and optical techniques, dial indicators are still widely used, particularly in the machine industry and research laboratories. This is due to their small size, autonomous operation, satisfactory precision, and availability of accessories that facilitate measurement system configurations. Dial indicators are commonly used for the configuration of precision machining systems, inspection of machine tool accuracy (Zong et al., 2018), industrial robot calibration (Chen et al.,

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2022), and quality control of batch or one-off production. As for the R&D activity, linear measurements with dial indicators are widely used in diverse scientific and technical fields, such as medical equipment construction (Eslami et al., 2016), lithium–ion cell deformation studies (Grimsmann et al., 2017), innovative human–machine interface development (Gleeson et al., 2010), and concrete deformation measurements during degradation (Macioski et al., 2024).

The operating principle of dial indicators, which involves precise measurement of the movement of the measuring tip using a mechanical or electronic mechanism, makes them highly sensitive to various forms of mechanism wear, contamination, and other factors that can impede proper operation. In the machine industry, their occurrence is even more likely due to the presence of dust, lubricants, and aerosol. The critical importance of measurements employing dial indicators necessitates stringent supervision of their accuracy and functionality. Consequently, many research centres strive to improve the verification process of dial indicators' metrological properties and the apparatus used for this purpose (Arief et al., 2021; Hemming et al., 2001; Iordache et al., 2010; Wang, 2011). Ensuring precision of dial indicator inspection equipment at a level of 0.1 μm constitutes another important issue (Lui et al., 2015). Additionally, research aims to improve the durability of dial indicator mechanisms by applying anti-wear coatings (Stancekova et al., 2015).

In Poland, legal regulations mandate periodic accuracy verification of dial indicators to ensure their reliability. As per orders of the President of the Central Office of Measures published in the Official Journal of Measures and Assay (Order no. 50 and Order no. 53), verification involves a series of tests using precise length standards and auxiliary metrological instruments. These tests require exceptional care and significant expertise from the personnel conducting them. Mechanical dial indicators are subjected to the following tests:

- Verification of the scatter and hysteresis of the measuring pressure.
- Determination of the change in indication caused by lateral pressure.
- Determination of the scatter range of indications at three measurement points.
- Verification of the damping of the indicating system.
- Verification of the influence of indicator tilt on reading.
- Determination of the indication and hysteresis errors.

Conducting the full set of tests using a single automated precision inspection device facilitates and shortens the process of dial indicator verification, significantly reducing dependency on personnel skills and efficiency. In facilities with high technical standards, where precision measuring instruments are commonly used, accuracy inspection is a crucial, yet quite costly, area of operations.

2. Inspection system prototype

The goal was to build a device for technical condition and accuracy inspection of dial indicators used in workshop (laboratory) and inspection measurements, mainly in the machine industry. The authors adopted the concept of an inspection system enabling the automated execution of a complete set of tests provided for in metrological regulations on a single testing device (Figure 1).

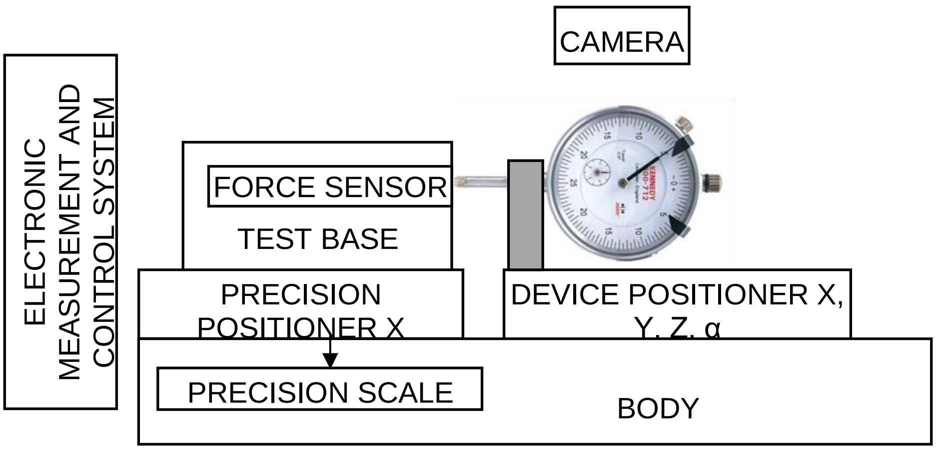

Fig. 1. Diagram of the modular functional system of the inspection system

According to the diagram (Figure 1), the tested instrument – a mechanical or electronic dial indicator, or a bore gauge with interchangeable tips and extensions with a measuring range of up to 500 mm – is mounted in a holder adapted to its construction, ensuring proper and secure fixing and deflection of the measuring tip corresponding to the measuring range (up to 50 mm). The four-axis positioner allows setting the instrument relative to the measurement base and the force sensor, depending on its dimensions and construction, so that the measuring tip rests on the measurement base or the force sensor and slides over its surface, and the entire instrument can assume any angular position. The force sensor is used to measure the pressure force of the indicator's measuring tip, and the measurement base, moved by precision positioner X, to precisely deflect it by distances controlled by the precision scale. The camera is used to record the readings of the measuring instrument (hand or display) in real time. All functional modules of the inspection system are mounted on a stable body resistant to thermal and dynamic interference. The electronic system, in accordance with the programmed procedures, controls the positioners' operation, records camera images and measurement results, and generates a test report. Figure 2 presents the concept in the form of a structural system diagram.

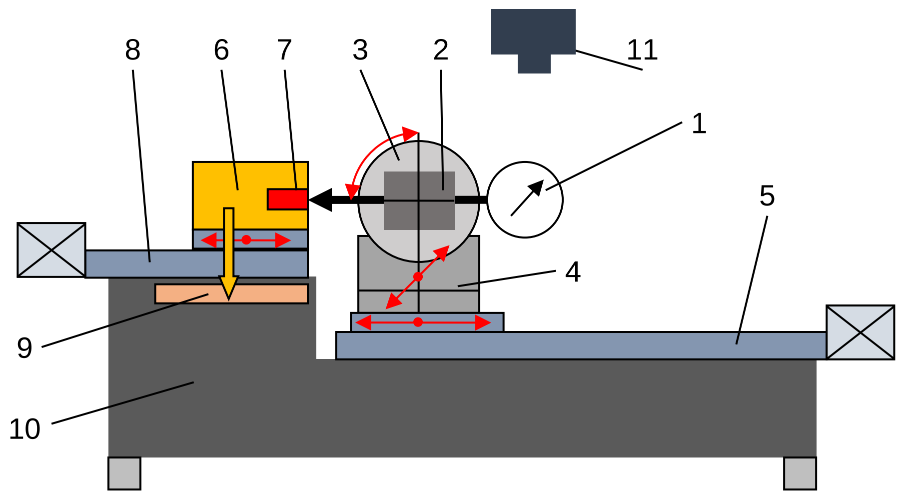

Fig. 2. Structural diagram of the measuring instrument inspection system: 1 – tested measuring instrument, 2 – instrument holder, 3 – precision rotary module, 4 – precision linear manipulator (transverse/vertical), 5 – adjustment linear module (longitudinal), 6 – head with measurement base, 7 – force sensor, 8 – precision linear module, 9 – optical measurement scale, 10 – granite body of the inspection device, 11 – camera

2.1. 3D model of the inspection device

Figure 3 presents a 3D model of the mechanical structure of the device developed based on the assumed concept. The dial indicator to be tested (1) is mounted in a clamping holder (2) by inserting it into an 8 mm diameter hole and tightening it with a screw. The clamping holder is equipped with slide guides (6) to which a support plate is attached. By adjusting the position of the sliding cover within the plate, pressure can be applied to the measuring tip of the indicator, causing it to move. The slide guides (6) and the support plate are moved relative to the clamping holder (2) using a screw with a manual knob (7). Thus, it is possible to mount the dial indicator (1) in the clamping holder (2) and move its measuring tip to a desired position of the hand. The clamping holder (2), along with the slide guides (6), support plate, and screw (7), forms a compact assembly mounted on a movable part of a rotary positioner (3) and can be rotated around the horizontal axis by any angle. This allows the implementation of a standard inspection procedure consisting in the verification whether the readings are not dependent on the dial indicator's position.

The described assembly is installed on the movable component of a cross-positioner consisting of two linear drives (4), which can move the sensor perpendicularly to its main measurement axis, and on the movable component of the linear module (5), which moves the entire assembly along the device in the direction of the main measurement axis of the sensor positioned as shown in Figure 1. The linear module (5), which is a precision screw linear drive with a servo motor, serves to position the tested dial indicator or bore gauge so that its measuring tip rests against the frontal surface of the measuring head (8).

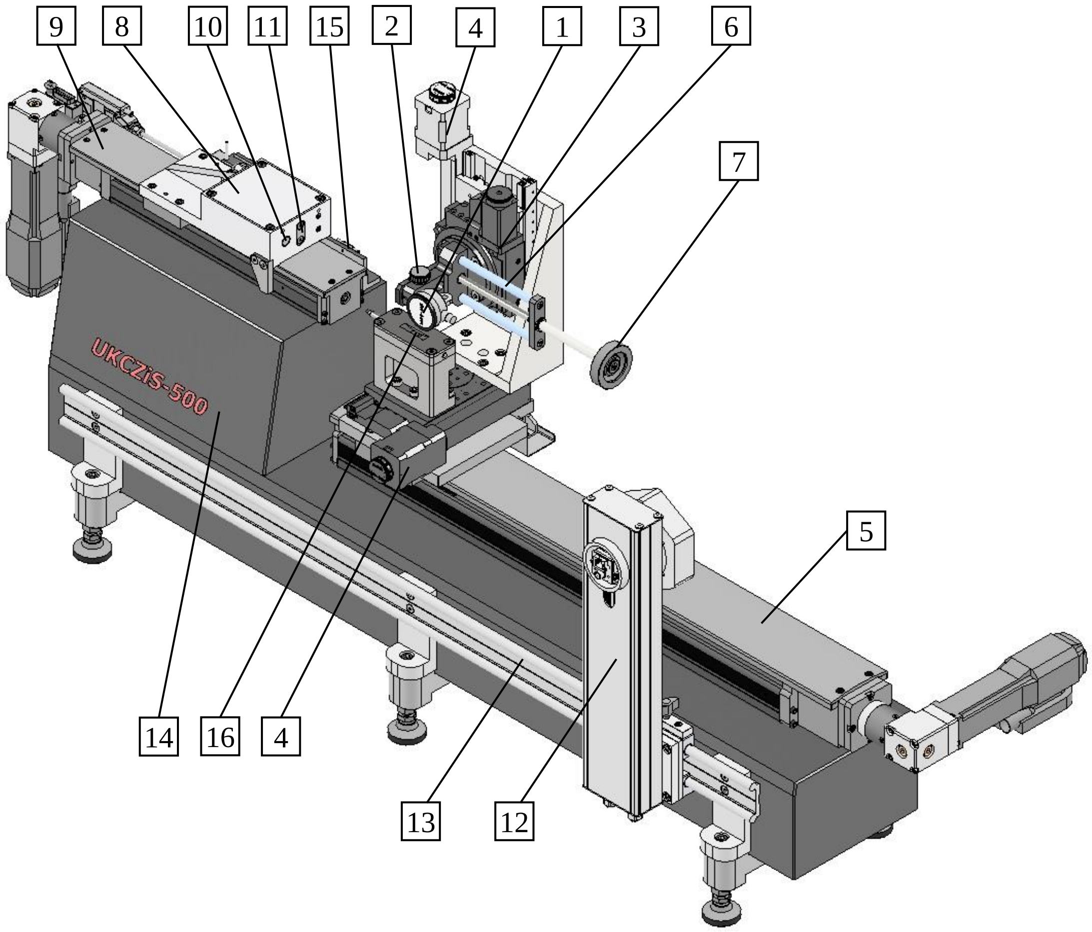

Fig. 3. Concept of the device for automatic accuracy inspection of dial indicator readings (3D model): 1 – tested dial indicator; 2 – indicator holder; 3 – rotary positioner; 4 – linear positioner; 5 – linear module with servo motor; 6 – support plate guide rails; 7 – adjustment screw; 8 – measuring head; 9 – linear module with servo motor; 10 – force transducer; 11 – contact surface; 12 – camera with illuminator; 13 – camera guide rail; 14 – granite body; 15 – precision measuring scale; 16 – sliding reference plate

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The measuring head (8) is equipped with the following elements enabling the execution of standard inspection procedures:

- Strain gauge force sensor (10): Its surface, intended for applying the measured force, coincides with the frontal surface of the head and is used to measure the pressure force of the measuring tip of the tested instrument across the entire measurement range.
- Hardened steel insert with a smooth contact surface (11): This serves to support the measuring tip of the tested instrument (1) during inspection and its movement resulting from the change in the distance between the holder (2) and the measuring head (8).

The contact of these elements with the measuring tip of the tested measuring instrument is achieved by appropriately adjusting the positioner (4), which guides the tip to the selected element. The measuring head (8) is mounted on the movable component of the precision axis (9) and can move, deflecting the measuring tip of the tested instrument. The position of the head (8) is determined with an accuracy of 0.5 µm using the optical measuring scale (15) connected to the device body (14), cooperating with a reader connected to the head. To verify the correctness of the indication, the relative readings of the tested instrument (analogue or electronic) (1) and the readings of the scale (15) are compared. Inspection of the full-range measurement is possible thanks to appropriate ranges of movement of the precision axis (9) and scale (15). The sliding reference plate (16), moved by the head (8), is used to verify the effect of lateral force acting on the measuring tip resting on it on the change in the indicator's readings.

A digital camera (12) with an illuminator is used to read and graphically record the readings of the tested instrument (1). The camera, mounted on a bracket and slide guide (13), can be moved along the device and positioned so that the tested instrument is within its field of view. Electronic inspection of the device operation allows synchronization of the readings of the measuring scale (15) with the image recorded by the camera. This enables precise selection of measurement points of the tested instrument when performing the standard hysteresis testing procedure.

The functional modules of the device determining its accuracy and stability, i.e., the precision axes (5 and 9) along with the assemblies mounted on them, and the optical scale (15), are fixed to a monolithic granite body (14), ensuring the constancy of their mutual positioning and resistance to mechanical vibrations. The body, equipped with adjustable feet, can be mounted and levelled on the flat surface of a laboratory table.

Additionally, optional equipment enabling the accuracy inspection of two-point bore gauges with dial indicators was developed for the device. Figure 4 shows the method for setting the bore gauge in the device for automatic accuracy inspection of dial indicator readings.

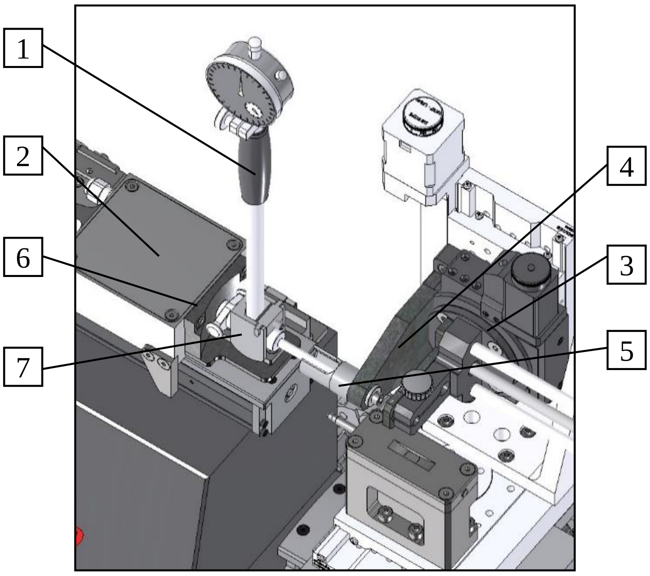

Fig. 4. Method for setting a two–point bore gauge with a dial indicator in the device for automatic accuracy inspection of dial indicator readings: 1 – tested bore gauge; 2 – head of the inspection device; 3 – setting module of the inspection device; 4 – bracket; 5 – fixed support element; 6 – movable support element; 7 – bore gauge holder

The tested bore gauge (1) is placed between the head of the inspection device (2) and the setting module of the inspection device (3). The setting module (3) is rigidly attached to the bracket (4) with the fixed support element (5) with a smooth, flat and hardened support surface perpendicular to the direction of movement of the module (3), against which the anvil of the bore gauge rests. On the frontal surface of the head (2), the movable support element (6) is mounted, whose smooth and hardened support surface has the shape of a cylinder with a vertical geometric axis. Against the cylindrical surface of the support element (6), the contact anvil of the bore gauge (1) and its guide rest. The bore gauge is held in the holder (7) ensuring its stable position, in which its measurement axis is parallel to the direction of movement of the measuring head (2). Precise movement of the head (2) and its individual positions indicated in the inspection computer or read on the monitor can be compared with the readings of the dial indicator of the bore gauge.

2.2. Control system for the operation of the inspection system and software

The authors developed a structure of the inspection system for the device used to verify dial indicators (Figure 5), which consists of the following five functional modules:

The travel module composed of two EMMS-AS-40 servo motors controlled by drivers and a CPX PLC. The PLC communicates with the motor drivers via a CanOpen network and with a PC via Ethernet using the Modbus/TCP protocol. The current position of the travel module is read from an absolute encoder located in the servo motor, and the position of the measurement module is read from an optical encoder.

The indicator stem position measurement module composed of a linear scale, an LIP 481R optical linear encoder mechanically connected to the measurement module, and an EIB 741 processing module. Data from the EIB 741 module is transmitted to the measurement module controller via Ethernet.

The pressure force measurement module consisting of a force sensor with a measurement range of 20 N, a signal amplifier, and an RS485/RS232 converter. The current force value is read by the PC via the RS232 port using the Modbus protocol.

The lateral load module for the indicator stem including linear and rotary positioners, a 3-axis controller, and a power supply. The positioners are controlled and managed by the PC through a USB port using manufacturer's STANDA protocol.

The CCD camera, which takes photos of the dial face when the measurement scale confirms the programmed position has been reached by the linear actuator in the measurement module.

The software developed on the Delphi7 Enterprise platform, allowing control and management of the inspection system modules and the execution of tests.

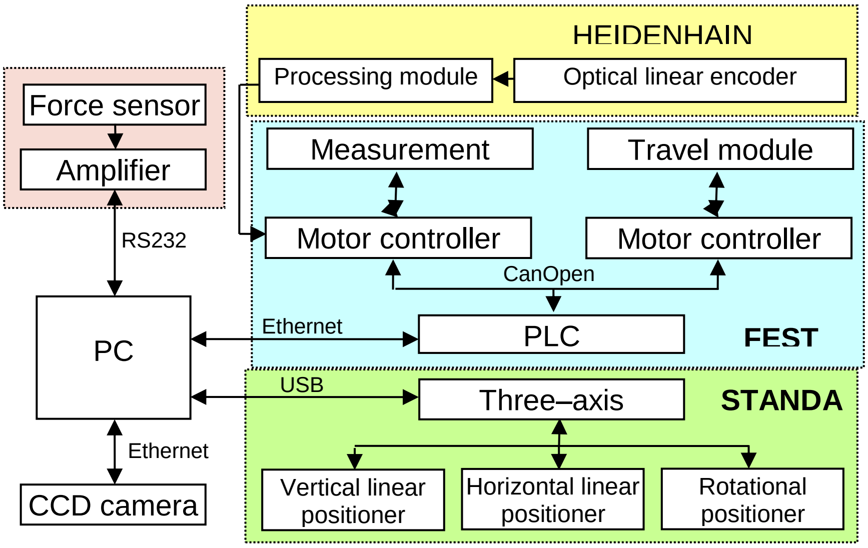

Fig. 5. Diagram of the inspection system structure

The developed software of the inspection system automatically executes inspection procedures, generates test reports, and archives measurement results. The developed operator interface (Figure 6) allows for the following:

- System performance verification.
- Selection of the tested object and its data, description of the conducted test.
- Automatic execution of standard or custom test procedures.
- Measurement result archiving and verification and inspection over their output format.

Fig. 6. Sample screens of the control software of the device for monitoring dial indicators (main menu screen and the pressure force check procedure screen)

The software allows the following: testing a measuring instrument recorded in the system; recording a new instrument in the system; removing an instrument from the system; editing the description of an instrument recorded in the system; editing the information about the tests performed; and editing the measurement results obtained.

After entering the data concerning the tested instrument and identifying the test, the operator initiates the selected inspection procedures. Depending on the procedure type, it may be necessary to enter detailed execution conditions, confirm subsequent stages, and approve the results. The software screens also inform the operator about the statuses of individual actuators to monitor and assess the correctness of the instrument test execution.

3. Results of verification tests of the inspection device prototype

The authors constructed a prototype of a device for the automatic accuracy inspection of manual measuring instruments, based on the developed virtual 3D model and verified technical documentation (Figure 7).

A computer inspection system responsible for powering and controlling the modules with electrically controlled drives, as well as software for the automatic execution of inspection procedures, were activated. Tests were conducted on the working and setting movements performed by linear rolling modules and movements of the tested instrument's positioner. Systems measuring the deflection of the moving measuring element of the tested instrument, and the force of the measuring tip, as well as a vision system with a camera recording indicator's readings with a mechanical hand were also activated (Figure 8).

a) b)

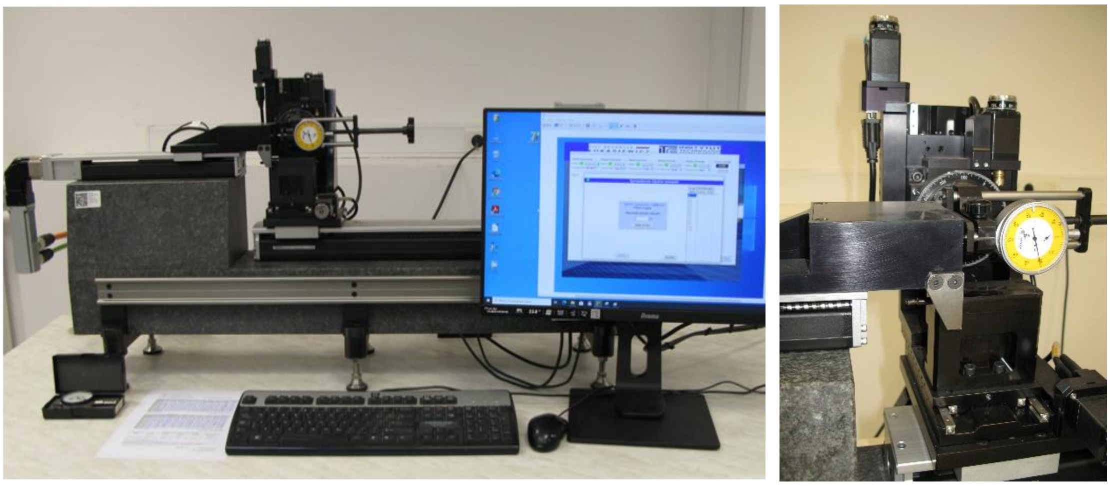

Fig. 7. Prototype of the inspection device with a laptop: a) general view of the measuring station, b) measuring head and positioner of the tested instrument with the controlled dial indicator

Fig. 8. Prototype of the inspection device – use of the camera to ensure precision of dial indicator's readings

Verification tests involved a series of inspection tests on 8 dial indicators selected out of 35 such measuring instruments used at the Łukasiewicz–ITEE Prototyping Centre. Proof tests of each of them were performed five times to verify the repeatability of the results of the measurements obtained. A month prior to verification tests, the selected indicators had passed manual inspection at the Quality Control Laboratory. Due to limited equipment resources, manual inspection was restricted to determining indication errors and measurement hysteresis.

Table 1 presents sample inspection results for the ETALON indicator with a measuring range of 0–10 mm and a resolution of 0.01 mm. The indicator with identification number NP/001-00, was approved in 2000 and since then it has been sporadically used at the Quality Control Laboratory. Cells marked in blue show the inspection measurement results obtained using the described device, while those marked in green the results of measurements performed manually. From the table it follows that manual and automatic measurements are sufficiently consistent, and the results of the automated inspection cover the full metrological characteristics required by the Central Office of Measures (Regulation no. 50; Regulation no. 53).

Table 1. Inspection measurement results for the ETALON indicator with a measuring range of 0–10 mm and a resolution of 0.01 mm obtained using the described device (*blue*) and through manual measurements (*green*)

Measuring force				
required	measured automatically (average value)		standard deviation	
0.4 ÷ 1.5 N	1.05 N		0.0122	
Measuring force dispersion				
permitted	measured automatically (average value)		standard deviation	
0.7 N	0.56 N		0.0292	
Measuring force hysteresis				
permitted	measured automatically (average value)		standard deviation	
0.6 N	0.23 N		0.0122	
Change in indication due to lateral force				
permitted	measured automatically (average value)		standard deviation	
0.005 mm	0.003 mm		0.0007	
Indication errors				
	permitted	measured manually	measured automatically (average value)	standard deviation
for 1/10 rotation	±0.005 mm	0.005 mm	0.005 mm	0.0007
for 1/2 rotation	±0.008 mm	0.008 mm	0.007 mm	0.0010
for 1 rotation	±0.010 mm	0.008 mm	0.008 mm	0.0010
for 2 rotations	±0.015 mm	0.013 mm	0.012 mm	0.0013
for the entire measuring range	±0.020 mm	0.015 mm	0.013 mm	0.0019
Measuring hysteresis				
permitted	measured manually		measured automatically (average value)	standard deviation
0.003 mm	0.003 mm		0.003 mm	0.0004

Tests of the prototype of the device and the developed software, conducted using measuring instruments employed at the Łukasiewicz–ITEE Prototyping Centre, confirmed the possibility of executing complete, standard verification procedures as part of periodic measuring instrument inspection

4. Summary

The authors constructed and developed a prototype of a mechatronic device for the automatic accuracy inspection of manual measuring instrument readings. This device enables dial indicators and two-point bore gauges with dial indicators to be fully tested automatically, during periodic inspection, in accordance with the regulations of the Central Office of Measures (Regulation no. 50 and Regulation no. 53). The solution significantly accelerates the inspection process and eliminates potential human errors. It carries out an automatic test programme analogous to the advanced sensor calibrators offered by Steinmeier (https://www.feinmess-suhl.com) and allows for a much broader control of measuring tools compared to the instrument offered by Mitutoyo (https://shop.mitutoyo.eu). The precision and scope of the tests performed correspond to the standard needs of the engineering industry and to the metrology regulations in force (Order No. 50; Order No. 53).

The device has been verified and implemented to test measuring instruments used at the Łukasiewicz–ITEE Prototyping Centre, in both laboratory measurements and experimental production. It is intended mainly for the machine industry, where dial indicators and bore gauges are employed in production processes and quality control, and difficult working conditions necessitate more frequent inspections.

The original structural solutions developed at Łukasiewicz–ITEE, are patented (patents no. PL239823 and PL243868).

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Original Research

ANALYSIS AND MODELING OF DESIGN PROBLEMS IN THE CONTEXT OF RANDOM TECHNOLOGICAL CHANGES

ANALIZA I MODELOWANIE PROBLEMÓW PROJEKTOWYCH W KONTEKŚCIE LOSOWYCH ZMIAN TECHNOLOGICZNYCH

Paweł KNAST [1,*]

[1] Department of Mechanics and Mechanical Engineering, Faculty of Polytechnic, Calisia University, Poland

* Corresponding author: p.knast@uniwersytetkaliski.edu.pl; pawel@knast.pl; phone +48 603 97 37 83

Abstract

This article presents a novel approach to analyzing and modeling design challenges, addressing the impact of dynamically changing technologies. Based on extensive research and industrial experience, the author developed hypotheses defining key modeling parameters: time, displacement, mass, and temperature. Through advanced mathematical formulas and numerical calculations, the author demonstrates how each parameter can be effectively integrated to model randomly changing technological processes. Calculations and the structuring of measurement space into virtual cubes enable precise forecasting and adaptability to variable conditions, significantly enhancing the accuracy and responsiveness of industrial processes.
By analyzing historical data and iterative scenario modeling, this methodology facilitates rapid switching between design variants, allowing designers to identify optimization paths and adjust processes in response to unpredictable changes. The author suggests that these foundations may serve as a robust basis for developing intelligent machines with artificial intelligence technology, capable of automatic response and adaptation in dynamically evolving operational environments.

Keywords: stochastic design, artificial intelligence, process modeling, time analysis, system optimization, data integration, adaptive processes

Streszczenie

W niniejszym artykule autor przedstawia nowatorskie podejście do analizy i modelowania problemów projektowych, uwzględniając wpływ dynamicznie zmieniających się technologii. W oparciu o wieloletnie badania i doświadczenie przemysłowe, opracowano hipotezy definiujące kluczowe parametry modelowania: czas, przemieszczenie, masę i temperaturę. Autor, korzystając z zaawansowanych wzorów matematycznych oraz obliczeń numerycznych, ukazuje, jak każdy z tych parametrów można efektywnie integrować w celu modelowania losowo zmiennych procesów technologicznych. Podjęte obliczenia i strukturyzacja przestrzeni pomiarowej na wirtualne sześciany umożliwiają dokładne prognozowanie oraz dostosowywanie się do zmiennych warunków, co znacząco zwiększa precyzję i adaptacyjność procesów przemysłowych. Dzięki analizie danych historycznych i iteracyjnym scenariuszom, metodologia pozwala na szybkie przełączanie wariantów projektowych, umożliwiając projektantom identyfikowanie ścieżek optymalizacyjnych i dostosowywanie procesów do nieprzewidywalnych zmian. Autor sugeruje, że te założenia mogą stanowić solidną podstawę dla rozwoju inteligentnych maszyn z technologią sztucznej inteligencji, zdolnych do automatycznego reagowania i adaptacji w kontekście dynamicznie zmieniających się środowisk operacyjnych.

Słowa kluczowe: projektowanie stochastyczne, sztuczna inteligencja, modelowanie procesów, analiza czasu, optymalizacja systemów, integracja danych, procesy adaptacyjne

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1. Introduction – Innovative Technologies as a Driver of Social Development

The purpose of this study is to develop a universal procedure for modeling complex design problems for randomly changing technological processes. This work presents an analysis and proposes solutions that enable more precise design and management of processes subject to dynamic and often unpredictable changes.

The foundation of this research lies in the efforts of scientists and engineers to create solutions that improve the quality of life for people worldwide. The more complex the production process, the greater the demands placed on the designed machines. Increased customer awareness and the variability of geopolitical conditions contribute to the rise in randomly changing production processes, which must meet new requirements.

The level of innovation in an economy is reflected in the number of patents granted. According to data published in the World Intellectual Property Indicators 2021 report, the highest number of patent applications came from China (1,497,159), followed by the United States (597,172) and Japan (288,472) (WIPO, 2021). The percentage share of patent applications by region is as follows:

1) 66.6% Asia
2) 19.3% North America
3) 10.9% Europe
4) 1.6% Latin America and the Caribbean
5) 1.1% Oceania
6) 0.5% Africa

Most projects are currently carried out in Asia, with China playing a leading role. However, translating investments in innovation into products remains a challenge. Global statistics divide economies into four technological groups: low, medium, medium-high, and advanced technology (Galindo--Rueda & Verger, 2021). The more advanced the industry, the higher the demands placed on designers in terms of skills and speed of response to changing conditions.

Every institution operates in the real world and must be prepared for changing economic conditions. The more complex the process, the more resilient it must be to changing conditions. Therefore, 21st-century designers need to analyze far more variables than in the past. Creating innovative designs requires vision, experience, and the courage to face challenges. In the past, less complex technical solutions were developed, and designers did not have access to advanced tools supporting analysis and decision-making, which are available today.

In the following sections of this work, the author presents a set of original methods to support the analysis, evaluation, and optimization of various design processes.

2. Review of Forecasting, Optimization, and Project Management Methods

2.1. Introduction

Modern technological processes are defined by high variability and dynamism, driven by rapid technological advancements, evolving customer demands, and fluctuating market and geopolitical conditions. Managing projects within such unpredictable environments necessitates the use of advanced analytical and modeling methods that can effectively support decision-making and the optimization of technological processes. Developing a methodology that integrates a variety of tools and techniques has become essential, as it enables a more profound understanding of project complexity and facilitates adaptation to dynamic changes.

Since 1993, the author of this study has conducted extensive observational research and actively participated in the design of machines and industrial technologies. These experiences have revealed the necessity of organizing and systematizing tools that are useful for modeling design problems, especially in the context of unpredictable technological changes and the need to manufacture various products on a single production line. Historically, limited access to databases and insufficient data processing capabilities posed significant barriers to comprehensive project analysis. However, the development of Big Data technologies in recent decades has enabled efficient collection, processing, and analysis of vast data sets, creating new opportunities for modeling, project management, and customized production (tailored to the specific requirements of each client within the same production setup).

Today, with advanced tools, it is possible to apply multiple complementary methods within a single project, allowing for comprehensive verification across different contexts–technological, economic, social, legal, and environmental–while meeting the principles of a circular economy.

2.2. Comprehensive Overview of Analysis and Modeling Methods

This section aims to provide an extensive review of analytical and modeling tools that can aid engineers and designers in making informed decisions and optimizing technological processes. As highlighted by Trott et al. (2016), the methodology for managing technological entrepreneurship requires innovative approaches to integrate production processes. Table 1 classifies these methods into three main categories: universal methods, customer-oriented methods, and specialized methods. Each category has unique applications, essential at different stages of technology design and implementation. This classification aligns with the reliability concepts discussed by Saleh and Marais (2006), emphasizing the importance of robustness from the earliest design stages.

2.2.1. Universal Methods

Universal methods, as presented in Table 1, encompass a range of techniques widely employed across various industries and scientific disciplines. This includes 25 tools, such as the *Affinity Diagram*, *PDCA*, *Six Sigma*, and *Gantt Chart*. For instance, the Affinity Diagram facilitates the organization and analysis of complex data, which is particularly beneficial in the context of random technological changes, where there is a need to group unpredictable operations into logical clusters. Six Sigma, on the other hand, is effective in reducing process variability, which is critical when implementing new technologies under unstable conditions.

As depicted in Table 1, the use of universal methods allows for flexible project management and swift adaptation to changing conditions. The Gantt Chart exemplifies this, enabling dynamic project planning, which ensures efficient responses to unpredictable changes in both technological and organizational environments.

2.2.2. Customer-Centric Methods

Adapting technological projects to evolving customer needs requires methodologies that allow for continuous monitoring and response to market expectations. Table 2 outlines seven customer-centric methods, including Customer Satisfaction Score (CSAT), Net Promoter Score (NPS), and Quality Function Deployment (QFD). These methods provide organizations with tools to effectively assess how new technologies impact customer satisfaction and loyalty, which is crucial for maintaining market competitiveness.

As illustrated in Table 2, using methods like QFD facilitates a quicker translation of customer requirements into technical specifications, thereby enhancing the efficiency of product adaptation to evolving market demands. This enables organizations to introduce innovations more effectively, meeting the expectations of consumers and service users.

2.2.3. Advanced Specialized Methods

The design of complex technological systems, influenced by numerous random variables, requires the application of sophisticated, specialized methods. One of the most effective approaches to managing such projects is the combination of sequential optimization and reliability assessment, which facilitates precise planning and control of technological processes (Du & Chen, 2004).

Sequential Minimal Optimization has proven to be a fast and efficient algorithm for training Support Vector Machines (SVMs), significantly enhancing the analysis of large datasets (Platt, 1998). Additionally, the SVM model, developed by Cortes and Vapnik (1995), has become a widely recognized tool in data analysis due to its versatility and precision.

As the modern information society grows increasingly complex-encompassing embedded systems and diverse applications – the requirements for system reliability have also intensified. Addressing these growing concerns has driven the advancement of sophisticated methods for modeling and optimizing technological systems (Pham, 2006).

A summary of specialized techniques is provided in Table 3, featuring 24 selected tools such as the Monte Carlo Method, Markov Model, and Harmonic Analysis. These tools allow for precise simulations and risk assessments, offering insights into how random factors affect projects, thereby enabling early detection of potential issues.

The Monte Carlo Method, as demonstrated, is particularly effective in simulating risk scenarios, providing insights into how different variables influence project stability and technological processes. Similarly, the Markov Model is employed in analyzing stochastic systems, offering predictive capabilities and facilitating the understanding of dynamic technological changes, thus enhancing the efficiency of managing complex design processes.

The breakthroughs in analyzing design problems have been made possible by the evolution of Big Data technologies, which support the efficient collection, searching, and analysis of extensive data sets. In the past, limited access to advanced databases and data processing tools hindered comprehensive project analysis, reducing the ability to integrate various methods effectively. Today, Big Data technologies enable the use of complementary tools, allowing for comprehensive analysis across diverse contexts––technological, organizational, market, economic, and environmental.

Table 4 presents a summary of 40 essential software tools that assist in project management. Integration with cloud-based solutions and real-time collaboration tools enhances flexibility and efficiency, making it easier to adapt projects to rapidly changing conditions.

2.3. Multi-Context Approach for Project Verification

A multi-context approach enables comprehensive project assessment across technological, economic, environmental, social, and legal dimensions, addressing the complexities inherent in modern technological processes. By integrating methods from Tables 1, 2, 3, and 4, this approach enhances adaptability and resilience, supporting the core goal of effective modeling and optimization of design problems in the face of random technological changes.

Universal methods such as Gantt Charts and PDCA (Table 1) aid in dynamic planning and continuous improvement, ensuring that technological solutions are integrated smoothly within projects. Tools like Digital Twins facilitate virtual simulations, allowing organizations to mitigate risks associated with system compatibility and performance before physical implementation. Customer-centric approaches, including Customer Satisfaction Score (CSAT) and Net Promoter Score (NPS) (Table 2), assist in aligning projects with evolving market demands, while economic analysis tools ensure cost-efficiency and optimized resource allocation. Scenario planning and sensitivity analyses help organizations navigate financial viability even under fluctuating conditions.

Specialized methods like Life Cycle Assessment (LCA) and Environmental Impact Analysis (EIA) (Table 3) are essential for evaluating sustainability, enabling projects to minimize ecological impacts and comply with environmental regulations. This is particularly important for projects aiming to meet the principles of a circular economy. Furthermore, projects often face scrutiny regarding their social and ethical implications. Utilizing Social Impact Assessments (SIA) alongside methods like Quality Function Deployment (QFD) (Table 2) ensures that projects respect community welfare, data privacy, and ethical standards, fostering trust and adherence to regulatory frameworks.

Legal compliance is a critical aspect of project verification, especially for projects with global reach. Integrating compliance tools from Table 4 helps maintain adherence to diverse legal requirements, reducing potential liabilities and ensuring that technological solutions meet all necessary standards. Additionally, predictive modeling and real-time analytics, supported by software tools listed in Table 4 such as LIBSVM and Monte Carlo simulations (Table 3), allow organizations to anticipate challenges and adjust strategies dynamically, making project management more resilient to unexpected changes.

The multi-context approach directly supports the effective modeling and optimization of design problems, which is the central theme of this study. By integrating universal, customer-centric, and specialized methods, projects can be holistically evaluated and managed, ensuring flexibility and robustness against random technological changes. This comprehensive verification process leads to more informed decision-making, proactive risk management, and long-term project success, essential for thriving in an environment where technological advancements and market demands evolve rapidly.

Table 1. Universal Methods

Lp.	Method Name	Usefulness in Decision-Making, Optimization, and Process Improvement	Usefulness in Analyzing and Modeling Design Problems in the Context of Random Technological Changes
1	Affinity Diagram (K-J Method)	Facilitates the organization and synthesis of brainstorming data, enabling identification of critical elements and informed decision-making.	Essential for grouping unpredictable technological variables into logical clusters, aiding in the structured analysis of random changes.
2	APQC (American Productivity & Quality Center)	Provides a framework for process structures and performance metrics, enabling strategic decision-making and process optimization.	Assists in evaluating efficiency and adaptability to changes in the technological landscape, fostering resilience in process adjustments.
3	Brainstorming	Encourages rapid idea generation and creative solutions, enhancing the adaptability and flexibility of decision-making processes.	Vital for fostering organizational adaptability, particularly in environments experiencing sudden technological changes and innovation.
4	BS 5750 Quality Standard	Supports the maintenance of process quality by aligning decision-making with established quality benchmarks.	Quality standardization simplifies management under changing technological conditions, promoting stability and consistency in dynamic environments.

Table 1 (cont.). Universal Methods

Lp.	Method Name	Usefulness in Decision-Making, Optimization, and Process Improvement	Usefulness in Analyzing and Modeling Design Problems in the Context of Random Technological Changes
5	Five Whys (method for identifying root causes by asking "why" five times)	Facilitates the identification of fundamental issues, enabling more effective, targeted decision-making.	Highly effective for swift problem resolution in response to unexpected technological challenges, driving root-cause analysis of unforeseen changes.
6	Gantt Chart	Enables structured project management through timeline visualization and tracking, supporting clear scheduling and progress oversight.	Allows for dynamic adjustments in project timelines to accommodate random and unforeseen technological shifts, enhancing project flexibility.
7	Ishikawa Diagram	Provides a structured approach to identifying causes of issues, supporting more precise and efficient process improvements.	Aids in understanding the influence of various factors on project quality, especially in dynamic technological environments where causes are varied.
8	Just-In-Time (JIT)	Optimizes production by aligning outputs with real-time demand, reducing waste and enhancing resource allocation efficiency.	Facilitates agile resource management in response to rapid changes in technology, reducing the impact of unexpected shifts in demand and supply.
9	Kaizen	Focuses on continuous, incremental improvements in processes, fostering sustained growth and development in performance.	Supports adaptive, incremental changes necessary for continuous alignment with unpredictable technological advancements.
10	KPI (Key Performance Indicators)	Provides metrics for monitoring progress toward business goals, allowing ongoing optimization of organizational processes.	Enables the evaluation of goal attainment and strategic alignment in the face of fluctuating technological variables.
11	Lean Project Management	Minimizes waste by focusing on value-driven outcomes, enhancing resource efficiency and operational simplicity.	Allows rapid adaptation to evolving technological requirements, supporting lean, resource-efficient project strategies in volatile conditions.
12	Lean Software Development	Streamlines software development processes, fostering efficiency in IT project management and product delivery.	Ideal for managing random technological changes in IT, as its adaptability to varying project conditions supports sustained alignment with changes.
13	Matrix Diagram	Clarifies relationships among project components, facilitating a more integrated understanding of project elements.	Essential for adapting to technological variability by mapping dependencies and interactions, enhancing overall project resilience.
14	PDCA (Plan-Do-Check-Act)	Provides a continuous improvement cycle for process optimization, promoting iterative decision-making and refinements.	Enables responsive adjustments to technological shifts by supporting structured iteration and continuous learning.
15	PMA (Performance Measure Approach)	Enhances operational resource management by linking performance metrics to operational goals.	Reduces risk and fosters rapid response in technological projects by monitoring key performance metrics under changing conditions.
16	PRINCE2 (Projects in Controlled Environments, a structured project management method)	Provides a robust, structured approach to project management, enhancing control and accountability.	Effective in managing unpredictable technological shifts by ensuring consistent project controls and structured methodologies.
17	RBD (Reliability Block Diagram)	Visualizes system reliability, supporting resource allocation and preventive maintenance.	Facilitates reliability assessments, particularly critical in fluctuating technological environments where system dependability must be ensured.

Table 1 (cont.). Universal Methods

Lp.	Method Name	Usefulness in Decision-Making, Optimization, and Process Improvement	Usefulness in Analyzing and Modeling Design Problems in the Context of Random Technological Changes
18	Six Sigma (6σ)	Reduces process variability and defect rates, leading to enhanced quality and optimized performance outcomes.	Mitigates error rates resulting from sudden technological changes, maintaining consistency and quality standards in unpredictable environments.
19	SMO (Sequential Minimal Optimization)	Optimizes support vector machine models, enabling efficient, rapid decision-making through machine learning.	Useful in optimizing AI algorithms for adaptive responses to technological changes, particularly in data-intensive environments.
20	SORA (Sequential Optimization and Reliability Assessment)	Supports process optimization by incorporating uncertainty into planning, fostering robust project outcomes.	Especially relevant for assessing and modeling risks in technology-intensive projects, enhancing predictive reliability in dynamic contexts.
21	SPC (Statistical Process Control)	Monitors and controls processes statistically, ensuring stability in operational processes.	Allows rapid adaptation of production processes to technological changes by identifying deviations early.
22	SWOT (Strengths, Weaknesses, Opportunities, Threats) Analysis	Aids strategic planning by analyzing strengths, weaknesses, opportunities, and threats.	Essential for assessing risks and opportunities in response to unexpected technological changes, enhancing strategic flexibility.
23	TQM (Total Quality Management)	Engages employees in continuous improvement, boosting overall process quality and efficiency.	Minimizes risk associated with technological change by embedding quality practices at all organizational levels, supporting resilient adaptation.
24	Tree Diagram	Assists in modeling decision pathways, providing a structured approach to complex decision-making.	Useful for probabilistic scenario analysis, particularly in technology-driven contexts where decision complexity is elevated.
25	LIBSVM (Library for Support Vector Machines)	Facilitates machine learning and data processing, enabling advanced analysis and optimization.	Supports optimization problem-solving, multi-class classification, probability estimation, and parameter selection in technology-centric projects.

Table 2. Customer-centric methods

Lp.	Method Name	Usefulness in Decision-Making, Optimization, and Process Improvement	Usefulness in Analyzing and Modeling Design Problems in the Context of Random Technological Changes
1	CES (Customer Effort Score)	Measures the ease with which customers achieve their goals, supporting customer service process optimization.	Helps companies identify improvements in adaptive processes in response to technological changes, enhancing customer experience and efficiency.
2	CSAT (Customer Satisfaction Score)	Assesses customer satisfaction levels, guiding decisions to optimize product and service offerings.	Enables the evaluation of the impact of technological changes on customer satisfaction, providing insights into areas for further improvement.
3	NPS (Net Promoter Score)	Measures customer loyalty, supporting customer service and retention strategy optimization.	Allows companies to quickly adapt strategies to respond to technological changes, maintaining customer loyalty and engagement in evolving markets.
4	DRS (Dual Response Surface)	Optimizes processes and products through experimental design, improving response precision and adaptability.	Facilitates scenario modeling and prediction of technological changes' impacts on products, enhancing resilience to market shifts.
5	DACE (Design and Analysis of Computer Experiments)	Supports engineering and analytical process optimization by allowing detailed experimental design and analysis.	Enables modeling of complex technological projects with multiple variables, improving adaptability to random process changes.

Table 2 (cont.). Customer-centric methods

Lp.	Method Name	Usefulness in Decision-Making, Optimization, and Process Improvement	Usefulness in Analyzing and Modeling Design Problems in the Context of Random Technological Changes
6	QFD (Quality Function Deployment)	Translates customer needs into technical specifications, aiding product development and ensuring customer-centric designs.	Helps companies adapt products to evolving technological demands, ensuring relevance and alignment with customer expectations in dynamic markets.
7	MUSA (Multi-Criteria Satisfaction Analysis)	Assesses customer satisfaction across multiple service and product aspects, providing a holistic view of customer experience.	Analyzes the impact of new technologies on customer satisfaction, modeling future customer behaviors and preferences to inform strategic planning.

Table 3. Specialized methods

Lp.	Method Name	Usefulness in Decision-Making, Optimization, and Process Improvement	Usefulness in Analyzing and Modeling Design Problems in the Context of Random Technological Changes
1	Boolean Algebra	Optimizes processes through logical evaluation of design scenarios, ensuring systematic and efficient analysis.	Facilitates modeling of random technological scenarios, improving precision in scenario-based decision-making.
2	Harmonic Analysis (Fourier Analysis)	Useful for analyzing signals and processes that vary over time, aiding in frequency-based data decomposition.	Enables modeling of dynamic technological changes, capturing time-based fluctuations essential in adaptive processes.
3	Pareto-Lorenz Analysis	Identifies key factors affecting processes based on the 80/20 principle, improving focus on critical issues.	Effectively models technological changes by allocating resources based on priority, optimizing resource management.
4	Rosenbrock Function	Optimizes nonlinear problems, supporting complex engineering processes by minimizing error margins.	Aids in optimization analysis for new technologies, ensuring robust solutions to nonlinear design challenges.
5	RNG (Random Number Generator)	Essential for simulations and optimizing processes requiring random data, adding stochastic elements for realistic modeling.	Enables modeling and simulation of processes involving unpredictable variables, enhancing system flexibility in real-time adjustments.
6	CMMI (Capability Maturity Model Integration)	Improves process quality and supports organizational function integration, facilitating higher standards.	Prepares organizations for dynamic technological shifts by aligning process maturity with adaptability.
7	Kriging	A spatial data prediction tool that aids in precise optimization of resources in design.	Allows analysis of spatial variables in technological projects, particularly beneficial in predictive modeling of environmental conditions.
8	LS (Least Squares Method)	Minimizes discrepancies between predicted and actual values, enhancing predictive accuracy in variable processes.	Useful in modeling design problems with random variables, providing stable and reliable projections.
9	MCMC (Markov Chain Monte Carlo)	Enables scenario simulation and outcome prediction, enhancing decision-making under uncertainty.	Assists in analyzing complex design problems with uncertain variables, refining risk assessment in unpredictable technological environments.
10	Dimensionality Reduction	Reduces the number of variables in complex systems, streamlining process optimization by focusing on critical data.	Enables efficient analysis of projects with numerous technological variables, managing complexity in large-scale simulations.
11	Mission and Vision Statement Methods	Crucial for strategic, long-term decision-making, guiding organizations toward consistent objectives.	Adapts organizational actions to evolving conditions, allowing better process planning to meet future challenges.
12	Gaussian Quadrature Methods	Used for precise integration calculations, supporting process optimization through accurate numerical results.	Enables precise modeling of design problems under variable conditions, reducing calculation errors in complex scenarios.

Table 3 (cont.). Specialized methods

Lp.	Method Name	Usefulness in Decision-Making, Optimization, and Process Improvement	Usefulness in Analyzing and Modeling Design Problems in the Context of Random Technological Changes
13	Markov Model	Analyzes stochastic systems, aiding in the optimization of processes with inherent randomness.	Models systems where changes occur stochastically, useful in anticipating technological fluctuations.
14	Reliability Modeling, Analysis, and Optimization	Minimizes failure risks by analyzing system variables, improving operational dependability.	Models system behavior under dynamic changes, enhancing robustness in unpredictable conditions.
15	MDO (Multidisciplinary Design Optimization)	Enables optimization of various project aspects, promoting efficiency across engineering disciplines.	Assists in modeling projects requiring flexibility in response to technological variability, ensuring comprehensive adaptability.
16	RBMDO (Reliability-Based Multidisciplinary Design Optimization)	Optimizes engineering projects with a focus on reliability under challenging conditions.	Enables risk prediction and adapts projects to variable operational conditions, enhancing reliability in fluctuating environments.
17	BLUP and BLUE (Best Linear Unbiased Predictions and Estimators)	Aid in precise decisions based on predictive models, ensuring reliability in statistical projections.	Enable accurate estimation of effects in technological systems, particularly useful in quality control and variance prediction.
18	Moore's Law	Helps forecast technology development trends, guiding long-term planning in high-tech industries.	Allows modeling of long-term technological projects, offering insights into development pace and innovation potential.
19	Hotelling’s T-squared Distribution	A statistical tool for multivariate analysis, aiding in the detection of significant deviations across variables.	Assists in analyzing technological variables and their impact on future outcomes, supporting robust design through statistical validation.
20	Taguchi Method	Optimizes design parameters, minimizing the impact of random variables on process quality.	Enables better modeling and optimization of projects under variable conditions, enhancing resilience against random fluctuations.
21	Monte Carlo Simulation	Widely used to predict outcomes based on random sampling, supporting probabilistic decision-making.	Facilitates modeling and prediction of outcomes in scenarios with multiple random variables, ensuring adaptable planning in uncertain fields.
22	VR (Virtual Reality)	Simulates complex scenarios, valuable for testing design concepts and training personnel in a controlled environment.	Enables modeling and testing of new technological solutions, reducing real-world trial risks and accelerating the innovation cycle.

Table 4. Summary of software supporting design work

Creator/Key Person	Program/Software	Year
Patrick J. Hanratty	PRONTO	1957
Ivan Sutherland	Sketchpad	1960
MAGI	Modele krawędziowe 3D (Synthavision)	1969
Siemens	Siemens NX	1973
Bentley Systems	MicroStation	1980
Graphisoft	ArchiCAD	1982
Autodesk	AutoCAD	1982
Dassault Systèmes	CATIA	1982
Vectorworks, Inc.	Vectorworks	1985
IMSI/Design, LLC	TurboCAD	1986
T-FLEX	T-FLEX CAD	1989
Parametric Technology Corporation (PTC)	Pro/ENGINEER	1989
CAS Berlin	Interactive NURBS modeling program	1993
Siemens Digital Industries	Solid Edge	1995
Dassault Systèmes	SolidWorks	1995

Table 4 (cont.). Summary of software supporting design work

Creator/Key Person	Program/Software	Year
Autodesk	Revit	1997
Visionary Design Systems (VDS)	IRONCAD	1998
Alibre, Inc.	Alibre Design	1999
Autodesk	Autodesk Inventor	1999
IntelliCAD Technology Consortium (ITC)	IntelliCAD	1999
Trimble Inc.	SketchUp	2000
Bricsys nv	BricsCAD	2002
CAD Schroer	MEDUSA	2002
Kubotek3D	KeyCreator	2004
Remograf AB	Remo 3D	2005
SpaceClaim Corporation	SpaceClaim	2007
Encore Software, LLC	PunchCAD	2008
Alludo	CorelCAD	2011
PTC	PTC Creo	2011
Autodesk	Fusion 360	2013
Promine Inc.	Promine	2015
Robert McNeil and Associates	Rhinoceros 3D	2020
AgiliCity d.o.o	Modelur	2021
Bricsys nv	BricsCAD Shape	2022

2.4. The Importance of Historical Data in Analyzing Technological Trends

Historical data play a crucial role in the process of analysis and modeling, particularly in understanding and predicting trends within technological systems. In the 2021 publication, *Theory of Efficient Preparedness and Operation of the Military and Emergency Manufacturing Industry*, I introduced a unique hypothesis known as *4 Steps + What Next?* (4SH+WN) (Knast, 2021), which emphasizes continuous inquiry by asking, "what next?" at every decision point.

Every decision made within a workplace or institution impacts production, safety, and future opportunities, either creating new possibilities or imposing constraints. The *4SH+WN* methodology facilitates the modeling of complex design problems, especially for processes subject to random technological changes, by enabling better scenario planning and future forecasting. The foundation of this approach is the idea that all history is essentially everything that has passed. By this definition, even a fraction of a second ago is already history. Time dictates history, and though it cannot be reversed, it serves as a foundation upon which future predictions can be built. Hence, data gathered from past events can be stored, analyzed, and archived for future use.

In this framework, knowledge, scientific principles, formulas, and computational procedures are regarded as recorded history, expressed through numbers, dates, events, and statistical data. This historical record allows for a comprehensive understanding of machine operation times, human and machine behavior in various random scenarios, and other critical patterns. The collection of historical data, therefore, is boundless, limited only by the creativity of the designer who leverages it to forecast future scenarios based on identified trends and recorded similarities.

Decisions have a direct influence on the future, impacting not only the *time* that is yet to come but also the safety, efficiency, and success of processes. For instance, automated measurement systems in technologically unpredictable environments must be capable of reacting to events and waiting for triggers. Each decision affects safety in its broadest sense, encompassing the prevention of accidents, injuries, equipment damage, environmental risks, logistical and organizational disruptions, financial losses, legal consequences, and adherence to schedules and contractual obligations. Additionally, decisions can either create new opportunities or restrict them––affecting technological development, creativity, financial gains or losses, and overall safety and sustainability.

Moreover, decisions are not always explicit; sometimes, the act of *not making a decision* is itself an unconscious decision with consequences. Thus, understanding the impact of decisions, including those that may seem negligible, is vital. The *4SH+WN* methodology encourages constant reflection on the future implications of every action taken.

The methods and software tools described throughout this work aim to contribute to making the world a better and safer place. In the global macroeconomic context, production companies must be agile and responsive to changes. Figure 1 illustrates how events that occur anywhere in the world can quickly influence other regions through the interconnectedness facilitated by the Internet. For instance, a military conflict in one area can have a significant effect on global commodity prices. Technologies developed in one country are often rapidly disseminated across borders, reaching new enterprises and societies.

Global corporations, when designing a new product and distributing it through their worldwide networks, must adapt it to meet the expectations of customers across diverse regions, not just in a single country or continent. There are industries, of course, where specific products or services have limited applicability due to unique characteristics and purposes. The recent period of pandemics and climate change has highlighted how diminishing borders and increasing global interconnectedness force a reevaluation of production approaches. With modern production systems relying on vast amounts of information, many of which are random variables, the role of historical data becomes ever more essential.

For individual designers, the sheer volume of data to analyze can be overwhelming, underlining the need for robust methodologies to tackle design problems associated with randomly changing technological processes. By systematically organizing and utilizing historical data, designers can develop more adaptable, efficient, and resilient solutions that anticipate future challenges and capitalize on emerging opportunities.

3. Four Key Parameters in Modeling Technological Processes Amidst Random Changes

The evolution of design methodologies over the past 30 years has been remarkable, driven by the need for *stochastic design* and adaptive approaches in modern engineering. In the 1980s, drafting boards remained the standard tool in design offices worldwide, despite the early availability of CAD programs. It was not until the 1990s that the widespread adoption of 2D CAD software began, driven by demands for more efficient and precise design documentation. By the late 1990s and into the 2000s, the industry saw rapid advancements with the development of 3D CAD and engineering software capable of performing complex simulations–such as motion, deformation, and stress analysis–which are essential for assessing the strength and functionality of structural components.

Through my research spanning over three decades, I have developed an *original methodology* that identifies *four key parameters* essential for modeling and understanding random phenomena in technological processes: *time, path of displacement, mass,* and *temperature.* These parameters serve as the foundation for robust methodologies that can adapt to *random technological changes,* integrating principles of *artificial intelligence, process modeling,* and *system optimization.* This approach not only aids in accurate design but also ensures adaptability, essential in the rapidly changing technological landscape of the 21st century. The following sections will provide detailed justification for these parameters, showing how they support adaptive processes and contribute to broader goals in *data integration* and *technological innovation.*

3.1. Methodology for Continuous Analysis: The "What Next?" Approach

The complexity of real-world technological processes arises not only from the physical and chemical phenomena involved but also from various factors such as mathematical simplifications, numerical rounding, data sampling rates, measurement inaccuracies, model precision, and the ability to interpret results. A model that accurately reflects reality allows for more reliable conclusions and better decision-making.

Based on this understanding, I have developed a unique *four-step methodology* enhanced by a continuous inquiry, encapsulated in the principle of *"What Next?"* This method allows for a precise and iterative analysis of each process, ensuring that no aspect is overlooked and that each stage flows seamlessly into the next. This is illustrated in **Fig. 1**, which demonstrates how the structured approach ensures adaptability and forward-thinking, essential for effective management of *random technological changes.*

3.2. The "What Next?" methodology proceeds as follows

To introduce the "What Next?" methodology, it is essential to recognize that effective decision-making in uncertain environments relies on a systematic approach that not only anticipates future developments but also grounds actions in present realities. This methodology proceeds through the following four steps.

a) **Reality — and what next**?

Every process begins by observing and understanding the current state. Establishing this baseline is critical for building accurate models. However, recognizing the present is just the starting point. What next? The method requires anticipating shifts and preparing for adaptation, guiding the direction of further actions.

b) **Data Collection — and what next**?

Collecting data is essential, but it must be treated as a dynamic and ongoing process. What next? Effective data analysis ensures that collected information is transformed into actionable insights. Identifying patterns, anomalies, and trends allows for a deeper understanding of underlying processes, which is crucial for building reliable models.

c) **Building a Model of Reality — and what next**? Models are created to represent reality as accurately as possible. But their true value lies in their ability to predict and adapt. What next? After constructing a model, it is essential to validate and refine it through iterative testing. This step ensures that the model can handle real-world variability and adapt to unexpected changes, making it a robust tool for decision-making.

d) **Interpreting Simulation Results – and what next? Decision-making**.

Interpreting the results of simulations is crucial, but it should always lead to the question: What next? The insights gained must inform strategic decisions, guiding improvements, adjustments, and future planning. This final step ensures that actions are not just reactive but are proactively shaping the course of future developments.

This "**What Next?**" approach has been extensively tested across multiple projects over the years, consistently yielding positive results. Its flexibility and iterative nature make it an ideal framework for integrating artificial intelligence and adaptive technologies into design processes. The methodology's ability to trace back to historical data and combine this with forward-looking forecasting creates a robust system for managing unpredictable technological changes.

3.3. Bridging Historical Data with Future Forecasting

One of the key strengths of this original methodology is its ability to integrate historical data with predictive scenarios. This approach enhances the understanding of technological processes by creating a continuous feedback loop between past data and future projections. Fig. 1 illustrates how each stage, from data collection to decision-making, feeds into a continuous and adaptable loop, allowing for a seamless transition between understanding the past and anticipating the future.

By leveraging historical data, systems can identify patterns and trends that inform current operations. Combining this with multi-scenario forecasting improves the reliability of predictions, offering a higher probability of accuracy. This unique integration allows for strategic planning that is both informed by past events and adaptable to future changes. Current research continues to refine this integration, with the aim of further enhancing the precision and applicability of predictive models, which will be discussed in forthcoming publications.

3.4. Connection to the Core Theme – Managing Random Technological Changes

The seamless integration of the "What Next?" approach with the core theme of this study – Analysis and Modeling of Design Problems in the Context of Random Technological Changes – demonstrates its practical value. Fig. 1 visually captures how this methodology ensures a structured, adaptive response to the complexities of modern engineering environments. As technological changes become more frequent and unpredictable, the ability to adapt quickly and effectively is crucial. This method encourages a forward-thinking mindset, ensuring that systems are not just reactive but are strategically positioned to handle uncertainty.

3.5. Conclusion. Advancing Adaptive Design Through the "What Next?" Methodology

The *"What Next?"* methodology, meticulously developed by the author over decades of research and industrial application, presents a comprehensive framework for addressing complex design problems, particularly in the context of *random technological changes.* This approach has been extensively verified through numerous projects, demonstrating its effectiveness in real-world engineering environments. Unlike conventional methodologies, which often follow linear or static models, the *"What Next?"* approach introduces a dynamic, iterative system that enables continuous analysis, adaptation, and decision-making.

The strength of this methodology lies in its ability to not only address current challenges but also to create a robust connection between *historical data* and future scenarios. This dual capability allows for tracing past events to understand root causes while simultaneously building predictive models that prepare for potential future outcomes. The author posits a *hypothesis* that this ability to explore multiple variant scenarios––continuously asking "what next?" at every step––makes this method particularly suited to the demands of the 21st century. By generating and analyzing a range of possible scenarios, the approach enhances preparedness, adaptability, and strategic foresight.

Fig. 1 illustrates the broader implications of this methodology, showing how decisions made at one point can have ripple effects throughout a system, particularly in a highly interconnected, globalized world. As global integration and digitization increase, every decision influences a network of processes and organizations. The *"What Next?"* methodology ensures that each decision not only addresses the immediate issue but also considers its impact on safety, future possibilities, and constraints. By creating a structured loop of inquiry, this approach fosters a deeper understanding of complex systems and allows organizations to navigate changes more effectively.

Fig. 1. The higher the level of globalization and digitization in the world, the stronger the impact of each decision on other organizations. Every decision creates new opportunities or limits them to varying degrees. The speed of response to change, alongside technological development, is essential for efficient functioning in the 21st century

3.6. Integration of the "What Next?" Hypothesis and Decision-Making Cycle

The *"What Next?"* methodology can be visualized through a structured decision-making cycle, as depicted in Fig. 2. This figure represents the *hypothesis* of a four-step cycle, enriched with the continuous question of *"what next?"* The core concept revolves around analyzing the consequences of decisions and their impact on the environment. Each decision is not an endpoint but a point of reflection, prompting further actions and adjustments based on a comprehensive assessment of the situation.

The diagram in Fig. 2 outlines how the methodology guides decision-making across four key dimensions:

1) **Historical Data** – *and what is next?* By understanding past events, the methodology enables the identification of patterns and trends, which are critical for building accurate models of future scenarios. This backward analysis serves as a foundational step in ensuring that each decision is grounded in historical insight.
2) **Safety** – *and what is next?* Maintaining safety is a core requirement in any technological system. By continuously evaluating the imply-cations of each decision on safety, the methodology ensures that risks are mitigated effectively.
3) **Future Possibilities** – *and what is next?* The ability to anticipate and model future scenarios allows for strategic planning that can adapt to various outcomes, making the methodology inherently more robust than static approaches.
4) **Creating New Opportunities or Limitations** – *and what is next?* Each decision opens new pathways or imposes constraints, which must be carefully assessed. The *"What Next?"* approach helps organizations maximize potential while minimizing risks, ensuring that future options remain viable.

The structured nature of this method creates a continuous chain of inquiry, leading to an infinite loop of questions and answers. Each step feeds into the next, maintaining a dynamic flow of information and analysis. This iterative process enhances the ability to forecast future scenarios with greater precision, making the system more resilient to change. While traditional approaches may falter under the weight of complexity, the *"What Next?"* methodology thrives, using this complexity as a basis for deeper understanding and more accurate predictions.

To further enrich this section, it is essential to highlight that the proposed "What Next?" methodology facilitates rapid switching between scenarios, enabling the navigation of paths influenced by each key aspect triggered by a single decision. Every decision carries consequences, and thus decision-making presents challenges at every stage of design. Until a machine or process is activated, it remains impossible to be 100% certain of its functionality. Post-completion, with historical data in hand, it may become evident that an error was made. Such errors, however, can typically be attributed to unintentional oversights despite best intentions.

The system proposed herein, grounded in historical data to reveal the effects of each decision, is viewed by the author as a valuable approach. Moreover, past decisions should not be evaluated through a single lens or criterion. Single-criterion evaluations obscure the complexity of the model and leave numerous aspects unexplored.

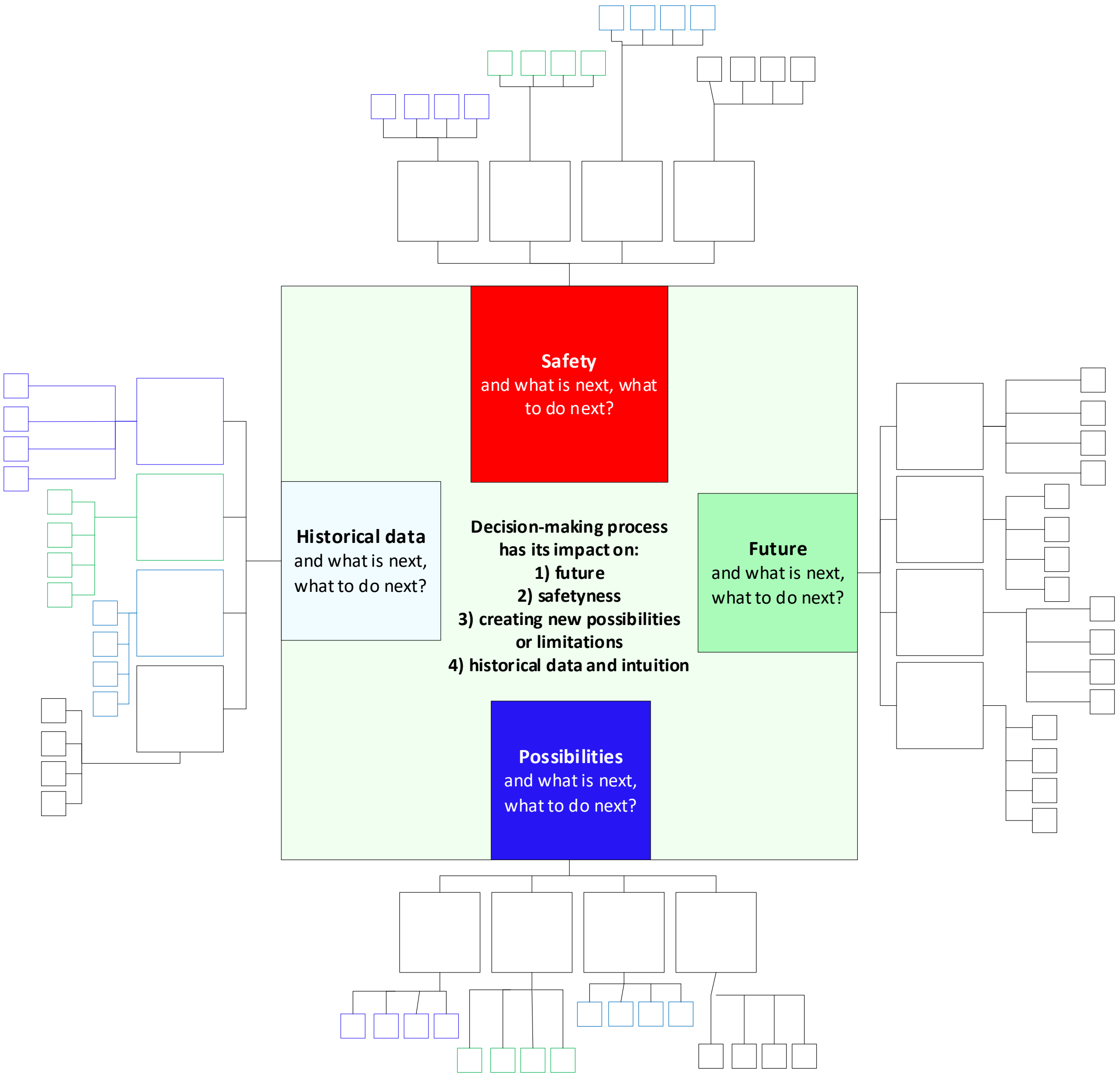


Fig. 2. The *"What Next?"* methodology, an original framework developed by the author, forms a multi-threaded network across four core areas – **Safety**, **Future**, **Possibilities**, and **Historical Data** – which are adaptable to any process or scientific discipline, fostering universal applicability and flexibility

In this methodology, the *"What Next?"* question, enhanced by the supplementary *"and what to do next?"*, serves as a structured approach to understanding complex environments and decision-making processes. As shown in Figure 2, it constructs a multi-threaded network across four primary domains: **Safety**, **Future**, **Possibilities**, and **Historical Data**. These domains provide a comprehensive view, universally applicable to both technological processes and fundamental aspects of human existence. Importantly, these threads are not rigidly defined; they can be modified or expanded to suit specific analytical or strategic needs. This flexibility makes the methodology inherently adaptable and suitable for various scientific disciplines and practical problem-solving scenarios, as it does not constrain the user to a fixed structure. Instead, it encourages a dynamic and responsive approach, ideal for situations requiring adaptive and strategic foresight.

3.7. Universal Application and Future Research Directions

The author asserts that this methodology is not confined to engineering alone. Its principles can be applied across a wide range of fields, including business management, logistics, healthcare, and other areas where the need for adaptive, real-time decision-making is crucial. By creating a flexible system that allows for both *retrospective analysis* (looking back at past events) and *future-oriented planning*, the methodology presents a universal tool for addressing the complexities of modern systems.

A key aspect of this approach is its ability to *integrate historical insights* (combine knowledge from past experiences) with *future forecasting* (predicting future events), effectively bridging the gap between past events and future possibilities. This unique capability allows for a more *holistic understanding* (comprehensive view of the whole system) of processes, facilitating more accurate predictions and better-informed decisions. The author introduces a *hypothesis* that this approach, by fostering the *exploration of multiple variant scenarios* (analyzing different possible outcomes) and continuously asking, *"what next?"* at each stage, is more relevant and adaptable than many conventional methods. This makes it particularly valuable for modern systems, as it aligns with the need for more flexible and adaptive strategies in the 21st century.

Figure 3 highlights the complexity of modeling reality, showing how it consists of interconnected factors that are inherently multifaceted. Reality, in this context, is seen as *multi-threaded* (involving multiple, simultaneous processes), *behavioral* (reflecting actions and reactions), *stochastic* (possessing many scenarios that can occur randomly with different probabilities, much like rolling a die where outcomes range from one to six), and *predictive* (capable of forecasting future events). The figure illustrates how *reality is always complete (100%)*, but the *data collected* about the process often falls short, leading to a model that may not capture every detail. The more data we can gather and the better we can interpret it, the closer the model approximates reality. However, even with substantial data, there will always be scenarios or situations that change unpredictably, requiring rapid analysis and adjustment.

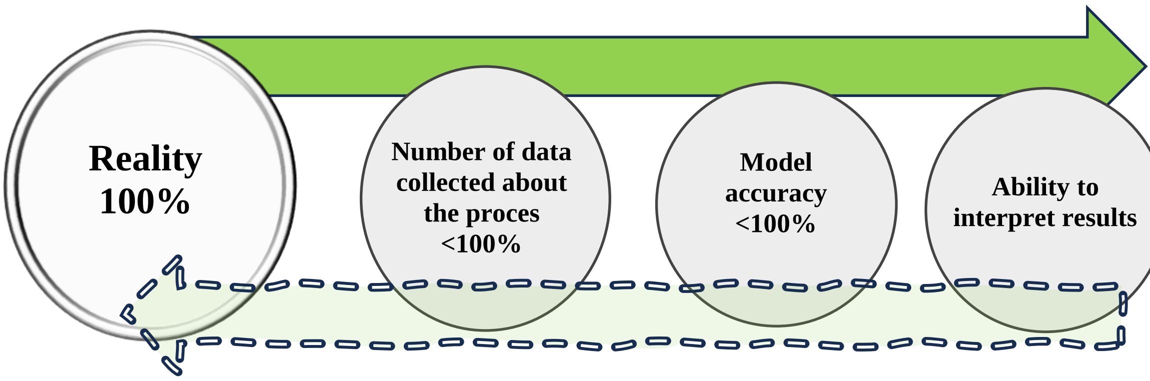


Fig. 3. The *"What Next?"* hypothesis with a supplementary question of *"and what to do next?"* This is an *original methodology* developed by the author, designed to analyze the consequences of decisions and their impact on the environment. The approach is based on the continuous inquiry of *"what next?"* at each stage, fostering a deeper understanding, proactive decision-making, and strategic adaptability

This dynamic aspect makes planning for future production, technological, and everyday events extraordinarily complex, necessitating instant processing of new information. The continuous feedback cycle, as depicted in Figure 3, underscores that the *accuracy of the model depends* on how well we can interpret results and adjust strategies in real-time. Thus, even with robust models, unexpected changes or new scenarios can still emerge, requiring adaptability.

The author's *hypothesis* concerning *model accuracy* (the ability of the model to precisely reflect reality) is especially significant here. While models aim to replicate reality, their effectiveness is inherently tied to the level of knowledge, skills, and experience of those developing them. A well-informed and experienced designer will build models that closely mirror real-world processes, reducing errors and inaccuracies. Conversely, models created with less knowledge or experience are prone to more significant deviations from reality, potentially leading to ineffective or even useless solutions. This awareness of the *imperfections* and simplifications in processes is crucial at the design stage, as it allows for the integration of *adaptive systems* (systems that can change and adjust based on new information) capable of adjusting to new information or unexpected scenarios.

This capability, once technically unattainable, has become feasible due to recent advancements in data processing and algorithmic development. The author is actively engaged in further research to develop sophisticated algorithms that enhance this methodology, aiming to improve its *predictive accuracy* (the ability to foresee and model future outcomes accurately) and applicability. Future publications will explore these developments in greater detail, providing insights into how this system can continue to evolve and adapt to new challenges, thereby offering a robust framework not just for engineering but for a broad spectrum of applications.

By acknowledging that reality is subject to constant change and by preparing for multiple outcomes, this methodology allows organizations to navigate complex, multifaceted realities with greater precision. The continuous loop of inquiry–asking *"what next?"* at every step–ensures that systems are not just *reactive* (responding after something happens) but can *proactively adapt* (adjust in advance) to new challenges. This approach aligns well with the needs of modern, interconnected environments, where quick adaptation is essential for success.

4. Four Key Parameters in Modeling Technological Processes Amidst Random Changes

Reality contains an infinite number of parameters that can not only be represented through mathematical, physical, and chemical dependencies but are also influenced by behavioral factors of living beings, nature, and economics.

An excess of information complicates swift decision-making and requires enormous computational power from computers. Too much collected data can cause a model to deviate further from reality, which, in extreme cases, renders it useless, as it prevents proper interpretation of simulation results. Reality is a set that has more data than we are capable of collecting, and the collected data is useful only as long as the model is sufficiently accurate, and the analyst can interpret the measurement results correctly. These can be recorded in the form of interrelated data sets, according to the following relational expressions (1) and (2):

$$R > D \cap M \cap I \quad (1)$$

$$100\% > (D \cap M \cap I) \cdot 100\% \quad (2)$$

where:
R – the set of phenomena occurring in reality, which can be expressed as a percentage,
D – the set of data recorded based on measurements in reality,
M – the set of elements processed in the model,
I – he set of results from simulations conducted in the model and their interpretation.

4.1. Time as the Key Parameter Describing Random Phenomena in Reality

Every movement can be repeated, and every design can be modified, but one technical parameter remains shrouded in the mystery of today's technological state. It is *time*, which we can measure but cannot reverse (see Figure 4).

Fig. 4. Time is a parameter that determines all processes occurring in the world because, in our current state of knowledge, we cannot turn it back

Time flows in one direction. Every action can be repeated, but it will not take place in the same time frame. This is akin to a process observed in a river. When stepping into the current, each fraction of a second brings a different drop of water into contact with us.

Repeating any action will always involve a different time. Customers demand that suppliers specify the delivery time of a product. To meet these requirements, employers strive to influence employees to complete tasks in accordance with schedules. Goods are expected to arrive at the production facility at a specified time. Any system failure leads to time disruptions and delays, creating a cascade of events with random variables.

Time begins in infinity, and on its axis, a zero point is set, symbolizing the start of the time measurement. From this point, we count and measure its passage. According to the author, it is possible to categorize time into four distinct types:

Absolute time (Figure 5) flows continuously, unidirectional, and beyond our control. It cannot be reversed, halted, or moved into the future; it can only be measured.

$$T_b(t) = \int_{-\infty}^{0} f(t)dt + \int_{0}^{t_1} f(t)dt \quad (3)$$

where:
T_b – absolute time,
$f(t)$ – function of time,
dt – integration variable,
t_1 – considered time interval.

The illustration (Figure 5) represents the concept of absolute time, flowing continuously from negative infinity, through a defined zero point (the start of measurement), and extending into positive infinity. This visual emphasizes the unidirectional nature of time, which progresses steadily and cannot be altered, paused, or manipulated. The years marked, such as "Year 0" and "Year 2024," signify specific points in time, demonstrating how events are anchored on this perpetual timeline.

According to the author of this study, determining the absolute beginning of time is almost impossible with the current state of scientific knowledge. It represents a kind of "**black hole of ignorance**," a boundary to our present understanding of the universe. This lack of complete knowledge about the absolute origins of time presents a fascinating challenge for scientists, inspiring new research and exploration. Reflections on the beginning of time and its absolute nature impact numerous scientific and philosophical disciplines, offering a perspective for discoveries that could fundamentally broaden our comprehension of reality.

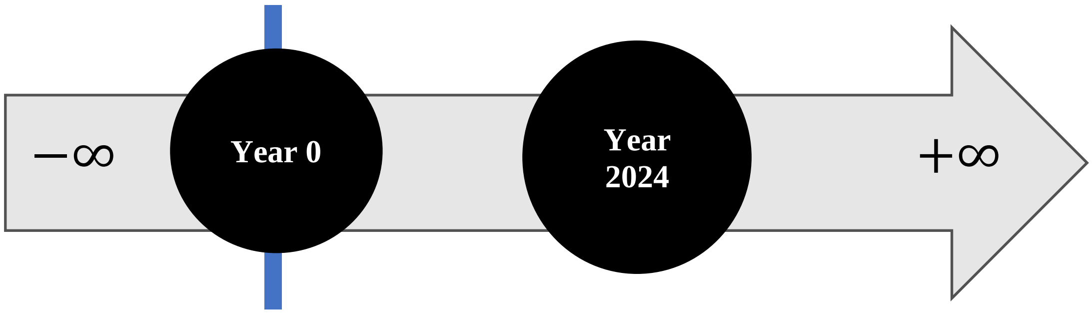


Fig. 5. Absolute time, over which we have no control and which we cannot reverse, pause, or move into the future. This visualization represents the unidirectional nature of time, which flows steadily and cannot be altered, paused, or reversed. The years marked symbolically as "Year 0" and "Year 2024+" represent specific points along the timeline, demonstrating how events are anchored on this uninterrupted axis

4.2. Hypothesis of Relative Time – New Perspectives in Management and Adaptive Technologies

The concept of relative time, formulated by Albert Einstein in 1905 within the framework of the theory of relativity, revolutionized our understanding of time and space in physics. In that context, time is dependent on the speed of objects, leading to a time-dilation effect for objects moving at high speeds relative to a stationary observer. While this concept had profound implications for the natural sciences, its application was primarily limited to cosmic scales and physical phenomena.

The hypothesis of relative time proposed by the author of this work extends this classical concept to the fields of management, production operations, and adaptive technologies. It proposes treating time as a dynamic resource, dependent not only on speed but also on a broad operational, decision-making context, as well as on the subjective experience of process participants. This new interpretation of time finds particular application in management systems and artificial intelligence (AI) algorithms, enabling a more adaptive and precise approach to analysis and optimization.

4.2.1. Key Elements of the New Hypothesis of Relative Time

The hypothesis introduces several foundational elements that expand the classical understanding of time, making it applicable to complex operational contexts.

1) **Multicriteriality and Relativity in the Operational Context**

The hypothesis assumes that the passage of time can be interpreted differently depending on reference points, creating a multicriterial matrix of references (a system of multidimensional references, where various decision-making factors serve as reference points). In this view, time is dynamic and depends on conditions specific to a given situation. For instance, 5 minutes for someone waiting at a cold bus stop will be perceived differently than 5 minutes spent on an intensive task. This relativity forms the basis for more flexible management models, particularly in environments that require rapid decision-making.

2) **Application in Decision-Making and Adaptive Systems**

The author proposes applying this hypothesis in management and adaptive technology systems, where relative time can support decision-making models that adjust to dynamically changing operational conditions. In artificial intelligence (AI) systems, relative time can be treated as a variable that allows for precise resource management and real-time response to changes, which is crucial for enhancing operational efficiency.

3) **Time as a Function of Subjective Experience and Operational Reference Points**

In the new hypothesis, time is defined not only as a linear progression of moments but also as a multidimensional quantity whose perception depends on the subjective experience of process participants and the operational context. The same passage of time can be perceived differently depending on the situation and the reference point, which is significant in management, where subjective perceptions of time influence the quality and efficiency of task execution.

4) **Integration with AI Systems and Forecasting Capabilities**

This hypothesis opens up new perspectives in artificial intelligence, where relative time can be utilized for forecasting and operational optimization. In AI systems, relative time functions as a dynamic factor that adapts algorithms to changing operational conditions, enabling more flexible modeling of future scenarios.

4.2.2. Formulation of the Relative Time Hypothesis

The mathematical model of relative time assumes that the passage of time can be expressed as a function of variable reference points and the operational context:

$$T_w = f\,(t_0, t_1, C) \tag{4}$$

where:
T_w – relative time,
t_0 – initial reference point,
t_1 – final reference point,
C – context vector.

The context vector includes subjective and operational factors such as emotions, environmental conditions, task complexity level, behavioral factors, and others depending on the process. This approach enables precise modeling of relative time by taking into account contextual variability and process specifics, leading to a more nuanced interpretation of time passage.

The formulas below provide the mathematical basis for the relative time hypothesis. Formula 5 defines relative time as the difference between time reference points, while Formula 6 incorporates additional operational factors:

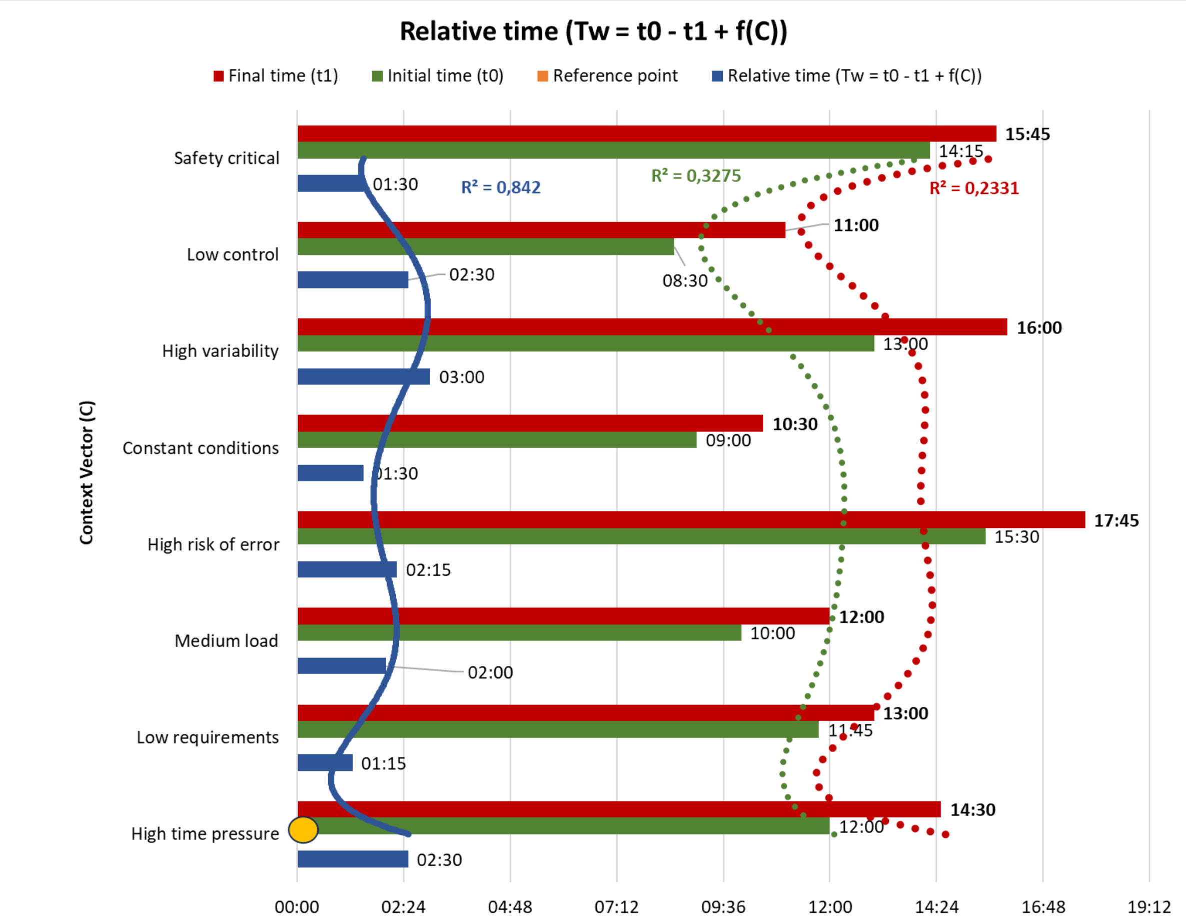
$$T_w = t_0 - t_1 + f\,(C) \tag{5}$$

$$\int_{t_0}^{t_1} T_w dt = \sum_{i=1}^{n} (t_{i+1} - t_i) \cdot C \tag{6}$$

where:
n – denotes the number of reference points,
C – represents the influence of specific process conditions.

Figure 6 depicts dynamic changes in physical parameters such as acceleration and force over time. The graph shows the evolution of these parameters from the initial point t_0 to the final point t_1, illustrating their non-linearity and challenging-to-predict variability. This is an illustration of real-world processes that often exhibit considerable complexity and are sensitive to changes influenced by the operational context. In the context of the relative time hypothesis, this figure emphasizes the importance of forecasting variables in engineering and design processes and highlights the critical need for developing adaptive systems. This allows engineers to design systems that better respond to dynamic environmental changes.

Figure 7 illustrates the multidimensional model of relative time, using the example of vehicles moving along the same route but at different speeds. Each vehicle experiences a distinct operational time, influenced by both internal parameters, such as speed or load, and external conditions, such as traffic density, weather, and traffic management priorities. This figure demonstrates the concept of relative time, which is of particular importance in systems that require rapid decision-making.



	High time pressure	Low requirements	Medium load	High risk of error	Constant conditions	High variability	Low control	Safety critical
Final time (t1)	14:30	13:00	12:00	17:45	10:30	16:00	11:00	15:45
Initial time (t0)	12:00	11:45	10:00	15:30	09:00	13:00	08:30	14:15
Reference point	0	0	0	0	0	0	0	0
Relative time (Tw = t0 - t1 + f(C))	02:30	01:15	02:00	02:15	01:30	03:00	02:30	01:30

Fig. 6. An example illustrating dynamic changes in a process from the initial point (nominally assigned time t_0) to the endpoint (measured time t_1). The chart depicts the multi-criteria and variability of real-world processes, which require flexibility and adaptability within changing operational conditions, described by the Context Vector, presenting an alternative perspective on time across various contexts

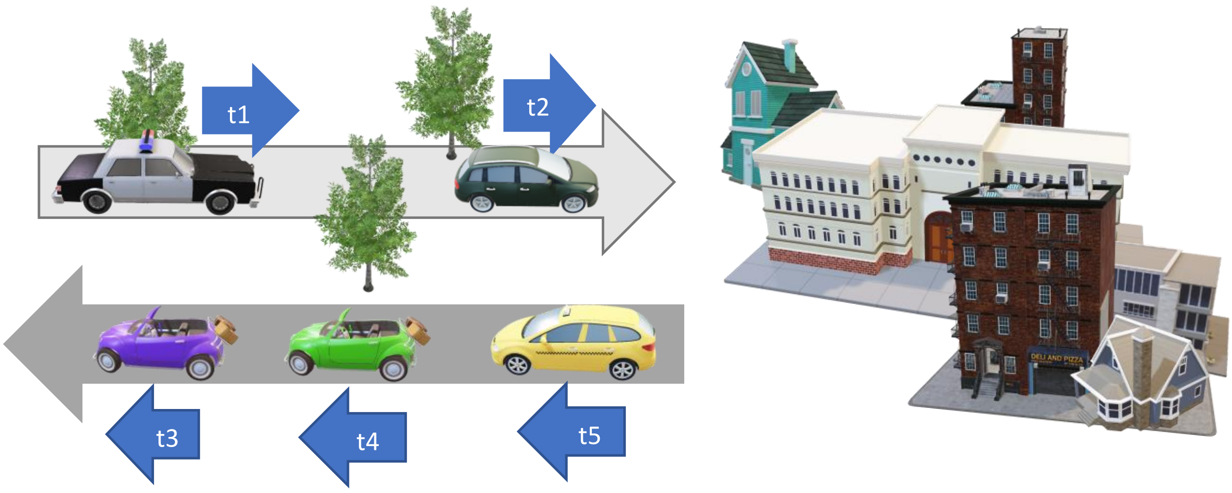


Fig. 7. The diagram illustrates the concept of relative time using the example of vehicles traveling the same route at different speeds. This example demonstrates how the relativity of operational time impacts logistical and operational management in dynamic conditions, which is essential for rapid decision-making and AI system adaptation

4.3. Forecasted Time

Forecasted time refers to phenomena and processes that are subject to influence through the construction and planning of solutions where time is a critical factor, such as machine efficiency, process speed, completion deadlines for various tasks, machine delivery, etc.

When designing a new machine, device, or process, historical indicators from similar solutions can be utilized. This approach allows for the identification of a much-needed reference point, if available, based on staff interviews and archived process records. Based on these sources, a historical indicator of the considered process or operation can be estimated.

$$H_c = \frac{T_c}{T_b} - \frac{(T_1+T_2+T_3+T_4)}{T_b} \tag{7}$$

where:
H_c – historical stoppage indicator for lines and/or processes,
T_C – operating time of similar production lines or other processes under study,
T_1 – registered downtime due to power outage for the historical period (historical information collected and stored in a database),
T_2 – registered downtime caused by preventive and maintenance actions (historical information collected and stored in a database),
T_3 – registered downtimes due to logistical disruptions (historical information collected and stored in a database),
T_4 – time from other causes of production line stoppage (historical information collected and stored in a database),
T_b – absolute time.

To illustrate Equation (7) in a practical example, calculations were performed for a production line based on historical indicators. Suppose we have collected historical data regarding the production process on a similar production line (archived records of all or part of the factors affecting production).

Step 1: Determine the total number of working hours in a year.

A calendar year has 365 days, and the factory operates in a 3-shift system (24 hours a day). However, we need to account for days when production does not occur due to holiday breaks:

a) 2 weeks (14 days) break for Christmas,
b) 2 weeks (14 days) summer break,
c) 1 week (7 days) break for Easter,
d) 3 days break for All Saints' Day.

The number of working days in a year is calculated as follows:

$$365 - (14 + 14 + 7 + 3) = 327 \text{ working days.}$$

The total number of working days in the year is: $327 \cdot 24 = 7\,848$ working hours per year.

Step 2: Division of Working and Downtime by Percentage.

According to the assumptions:

a) 80% of the time is actual production line operating time,
b) 5% is downtime due to failures,
c) 8% is downtime due to logistical issues,
d) 2% is downtime due to major breakdowns,
e) 5% is due to organizational issues, routine maintenance, and other interruptions.

The total percentage must equal 100%. Let's verify:

$$80\%+5\%+8\%+2\%+5\%=100\%$$

Step 3: Calculation of Hours Based on Percentages.

Now, we will calculate the number of hours for each component (effective operation and downtime).

Production Line Operating Time (80%)

$$T_c = 7{,}848 \times 0.80 = 6\,278.4 \text{ godzin.}$$

Downtime Due to Failures (5%)

$$T_1 = 7{,}848 \times 0.05 = 392{,}4 \text{ hours.}$$

Downtime Due to Logistical Issues (8%)

$$T_2 = 7{,}848 \times 0.08 = 627{,}84 \text{ hours.}$$

Downtime Due to Major Breakdowns (2%)

$$T_3 = 7{,}848 \times 0.02 = 156.96 \text{ hours.}$$

Downtime Due to Organizational Issues and Routine Maintenance (5%).

$$T_4 = 7{,}848 \times 0.05 = 392.4 \text{ hours.}$$

Step 4: Calculation of the Historical Line Downtime Indicator (H_c).

We use equation (6) to calculate the historical line downtime indicator (H_c).

$$H_c = \frac{6\,278.4}{7\,848} - \frac{(392.4 + 627.84 + 156.96 + 392.4)}{7\,848}$$

Calculating each term.

$$\frac{6\,278.4}{7\,848} = 0.7999 = 0.8$$

Next, we sum the downtimes:

$$T1+T2+T3+T4 = 392.4+627.84 + 156.96 + 392.4 = $$
$$= 1\,569.6 \text{ hours of downtime.}$$

Now, we calculate the second term of the equation.

$$\frac{1\,569.6}{7\,848} = 0.2$$

Finally, we calculate the historical line downtime indicator (H_c)

$$H_c = 0.8 - 0.2 = 0.6$$

The historical line downtime indicator H_c = 0.6 – indicates that the production line operated efficiently for 60% of the time throughout the year. Therefore, 60% of the operational time was effective, while the remaining 40% accounted for downtimes due to breakdowns, logistical issues, maintenance, and other interruptions.

In summary, in the analyzed example, over the course of the year, the production line operated for 7,848 hours, of which:

1) 6,278.4 hours were effective working time (80%),
2) 1,569.6 hours accounted for total downtime (20%), caused by:
   a) 392.4 hours due to breakdowns,
   b) 627.84 hours due to logistical issues,
   c) 156.96 hours due to major failures,
   d) 392.4 hours due to ongoing maintenance and organizational issues.

The H_c = 0.6 indicator provides a measure of production line efficiency and can guide decisions on optimizing logistics management and machine maintenance.

5. Displacement as the Second Key Parameter Describing Reality and Random Phenomena

Displacement is considered by the author as the second essential parameter describing dynamic reality. Displacement can be viewed as:

a) **Global displacement relative to the Earth** (Figure 8), based on geographic coordinates such as latitude and longitude. These are expressed as angular measures from the geographic coordinate origin, which is the intersection of the Prime Meridian (Greenwich) and the equator.
b) **Displacement relative to a chosen reference point,** illustrated in Figure 9 as a schematic. The design of a displacement mechanism with respect to a chosen reference point is shown in Figure 10. Relative displacement with respect to sequential measurement planes *XY*, *XZ*, and *YZ*.
c) **Combination of multiple movements**, including translational, curvilinear, and rotational, of a selected point within a single body.

Fig. 8. Global displacement relative to the Earth. The zero reference point of the coordinate system can be taken at the intersection of the Prime Meridian and the equator. Here, we assume a theory that divides our planet into four sections, which can also be divided into smaller areas.

One of the proposed methods involves projecting an element (its characteristic points) onto three planes, with an additional measurement of the distance from the zero reference point. As a phenomenon or element changes position, it also shifts the positions of characteristic points on the surfaces of the solid element relative to the origin of the coordinate system.

In summary, we have four variables:

a) the position of points on the *XY* measurement plane,
b) the position of points on the *XZ* measurement plane,
c) the position of points on the ZY measurement plane,
d) the length of the tracking vector *r* – the position of the characteristic points of the solid relative to the origin of the coordinate system.

The characteristic points of this methodology are based on concepts used in CNC machines for machining:

a) Machine zero point,
b) Workpiece zero point,
c) Machine reference point,
d) Tool reference point.

Machining processes have evolved significantly over the past 30 years, and thus, according to the author, they can be treated as predictable, with randomly changing situations rarely occurring. Such situations may include hidden material defects in workpieces and tools, environmental vibrations, breakdowns, temperature fluctuations, power outages, and extreme events such as floods or earthquakes. Experience gained in the field of machine tool construction can and should be used for designing machines in other technological processes, including those with random variability. The dynamics of spindles, cutting tools, and sensors applied are ideal for other industrial applications, such as assembly processes on a single production line for parts of varying shapes and weights, randomly arranged without positioning.

A proprietary construction solution based on the presented theory is shown in Figure 10. The layout of individual sensors in the form of cameras is depicted in Figure 11. This mechanism enables measurement of the change in position of the tested element within the measurement space. It is designed using sliding axes driven by electric motors equipped with high-resolution position sensors and high-frequency data collection on location. This arrangement allows precise and fast adjustment of measurement cameras monitoring specific characteristic points for the spatial solid planes. The displacement radius is measured using a camera mounted on two rotary tables. Using motor-driven tables equipped with position sensors enables precise and rapid repositioning in two axes, allowing it to keep pace with a randomly changing process. The movement directions along individual axes are marked in Figure 12.

The size of the *XY*, *ZY*, and *XZ* planes and the range of the tracking vector r (also referred to by the author as the tracking radius, depending on the process specificity) depends on the size of the displacement area. The measurement space can be divided into smaller sections, called "virtual measurement cubes." The more predictable the process, the larger these virtual measurement cubes can be (fewer cubes required), and conversely, for less predictable processes. The division of the measurement space into virtual measurement cubes is illustrated in Figure 13. By tracking positional changes on individual measurement planes *XY*, *ZY*, *XZ*, using virtual measurement cubes and changes in the length of the tracking vector, we can visualize the path of the object in terms of points, edges, and planes for randomly variable processes.

When a point moves between the measurement planes of the virtual measurement cube, its positional changes can be observed relative to the intersected plane of that cube. To react properly to such changes, software is required that, based on historical data, can determine the direction of the element's movement and predict shifts of the linear actuator carriages in that direction. When it appears that the element changes direction and moves in a different direction than its previous trajectory indicated, the program, based on data from earlier changes, can adapt and adjust the movement path. Consequently, this leads to the determination of the positioning of measurement cameras, which define both the range of movement and the boundaries of the *virtual measurement cube*.

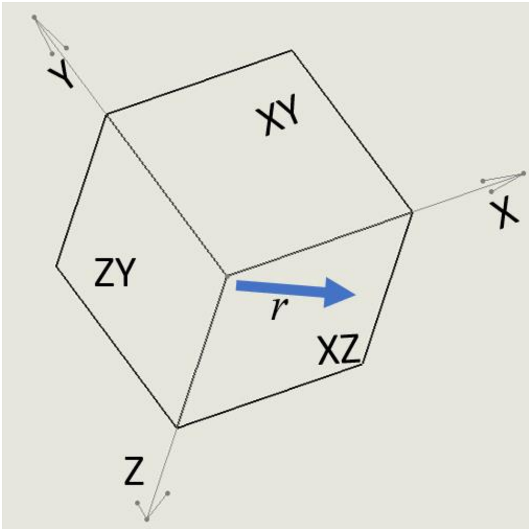


Fig. 9. System of three planes *XY*, *XZ*, *ZY*, projecting the position of the tracking element along with the tracking vector "r"

The following section describes a historical example of position changes and an analysis of using this model, where subsequent movements of objects relative to sensors can be observed. The sensor gathers information on position changes and automatically adjusts the linear or non-linear displacement of the element. Graphical representations of these displacements are shown in Figures 14 and 15, respectively.

Displacement relative to a selected reference point can be recorded as a multiple integral of the displacement function:

$$p_1 = \iiint f(x, y, z, r) dx\, dy\, dz\, dr \qquad (9)$$

where:
p_1 – displacement of point 1,
f – four-variable displacement function.

Relative displacement with respect to subsequent measurement planes in randomly changing processes for 4 selected points can be expressed as a function in which:
$[x_{11}, y_{11}]$ – represents the coordinates of selected characteristic points describing the measured body on the XY plane. Subscripts denote successive measurements. The notation is applied similarly to all characteristic elements of the measured body,
$\left|\vec{r}_{11}\right|$ – tracking vector length r.

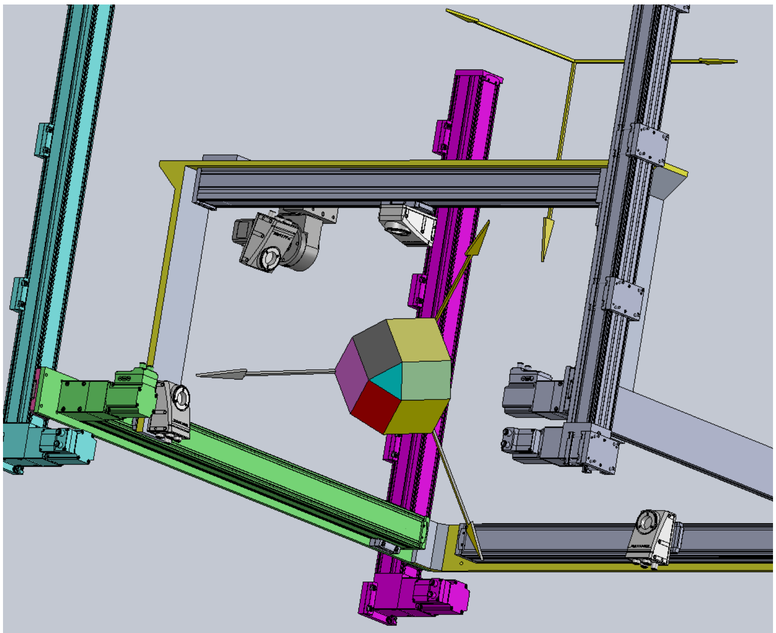


Fig. 10. Mechanism enabling measurements in the planes *XY*, *XZ*, *ZY*, projecting the position of the tracking element along with the tracking vector "*r*"

$$p_1(x,y,z,r) = \begin{cases} [x_{11}, y_{11}] \pm [x_{12}, y_{12}] \pm [x_{13}, y_{13}] \pm [x_{14}, y_{14}] + \cdots [x_{1n}, y_{1n}] \\ [x_{11}, z_{11}] \pm [x_{12}, z_{12}] \pm [x_{13}, z_{13}] \pm [x_{14}, z_{14}] + \cdots [x_{1n}, z_{1n}] \\ [y_{11}, z_{11}] \pm [y_{12}, z_{12}] \pm [y_{13}, z_{13}] \pm [y_{14}, z_{14}] + \cdots [z_{1n}, y_{1n}]\,) \\ \left|\vec{r}_{11}\right| \pm \left|\vec{r}_{12}\right| \pm \left|\vec{r}_{13}\right| \pm \left|\vec{r}_{14}\right| \ldots \pm \left|\vec{r}_{1n}\right| \end{cases}$$

$$p_2(x,y,z,r) = \begin{cases} [x_{21}, y_{21}] \pm [x_{22}, y_{22}] \pm [x_{23}, y_{23}] \pm [x_{24}, y_{24}] + \cdots [x_{2n}, y_{2n}] \\ [x_{21}, z_{21}] \pm [x_{22}, z_{22}] \pm [x_{23}, z_{23}] \pm [x_{24}, z_{24}] + \cdots [x_{2n}, z_{2n}] \\ [y_{21}, z_{21}] \pm [y_{22}, z_{22}] \pm [y_{23}, z_{23}] \pm [y_{24}, z_{24}] + \cdots [z_{2n}, y_{2n}] \\ \left|\vec{r}_{21}\right| \pm \left|\vec{r}_{22}\right| \pm \left|\vec{r}_{23}\right| \pm \left|\vec{r}_{24}\right| \ldots \pm \left|\vec{r}_{2n}\right| \end{cases}$$

$$p_3(x,y,z,r) = \begin{cases} [x_{31}, y_{31}] \pm [x_{32}, y_{32}] \pm [x_{33}, y_{33}] \pm [x_{34}, y_{34}] + \cdots [x_{3n}, y_{3n}] \\ [x_{31}, z_{31}] \pm [x_{32}, z_{32}] \pm [x_{33}, z_{33}] \pm [x_{34}, z_{34}] + \cdots [x_{3n}, z_{3n}] \\ [y_{31}, z_{31}] \pm [y_{32}, z_{32}] \pm [y_{33}, z_{33}] \pm [y_{34}, z_{34}] + \cdots [z_{3n}, y_{3n}] \\ \left|\vec{r}_{31}\right| \pm \left|\vec{r}_{32}\right| \pm \left|\vec{r}_{33}\right| \pm \left|\vec{r}_{34}\right| \ldots \pm \left|\vec{r}_{3n}\right| \end{cases}$$

$$p_4(x,y,z,r) = \begin{cases} [x_{41}, y_{11}] \pm [x_{42}, y_{42}] \pm [x_{43}, y_{43}] \pm [x_{44}, y_{44}] + \cdots [x_{4n}, y_{4n}] \\ [x_{41}, z_{11}] \pm [x_{42}, z_{42}] \pm [x_{43}, z_{43}] \pm [x_{44}, z_{44}] + \cdots [x_{4n}, z_{4n}] \\ [y_{41}, z_{41}] \pm [y_{42}, z_{12}] \pm [y_{43}, z_{43}] \pm [y_{34}, z_{34}] + \cdots [z_{4n}, y_{4n}] \\ \left|\vec{r}_{41}\right| \pm \left|\vec{r}_{42}\right| \pm \left|\vec{r}_{43}\right| \pm \left|\vec{r}_{44}\right| \ldots \pm \left|\vec{r}_{4n}\right| \end{cases}$$

Displacement of a selected point defining the path of movement is recorded as a function of input variables. Assuming that a single point moves through space along a vector

$$\vec{d} = (dx, dy, dz, dr),$$

we can calculate the displacement with respect to all measurement planes XYZ, as well as the initial location. It is assumed that movement occurs in chosen, arbitrary displacement units, which allows precise determination of the new coordinates of each point regardless of the shape of the geometry of the element, e.g., the new position for point A is $A + \vec{d}$.

Continuing, we calculate the new coordinates and *displacement radii r* with respect to the reference systems, enabling precise prediction of linear actuator carriage shifts and adjustment of the motion trajectory relative to changing conditions, where

$$r = \sqrt{x^2 + y^2 + z^2}.$$

In this way, we determine the displacement range, facilitating further prediction of movement and optimization of system operation.

Assume that a solid with 10 faces has 10 vertices initially located within the coordinate system. For simplicity, let's assume that the starting points have coordinates (defined in arbitrary units) as follows:

1. *A* = (1, 1, 0)
2. *B* = (2, 1, 0)
3. *C* = (3, 2, 0)
4. *D* = (3, 2, 0)
5. *E* = (1.5, 3.5, 0)
6. *F* = (0.5, 2.5, 0)
7. *G* = (0, 1.5, 0)
8. *H* = (0.5, 0.5, 0)
9. *I* = (1.5, 0, 0)
10. *J* = 2.5, 0.5, 0)

Assume that the solid moves through space by a vector:

$$\overline{d} = (dx, dy, dz) = (2, 3, 1)$$

Each vertex shifts according to vector $\overline{d}$. We calculate the new coordinates for each point:

1. New coordinates for *A*:

$$A' = A + \overline{d} = (1, 1, 0) + (2, 3, 1) = (3, 4, 1)$$

2. New coordinates for *B*:

$$B' = B + \overline{d} = (2, 1, 0) + (2, 3, 1) = (4, 4, 1)$$

3. New coordinates for *C*:

$$C' = C + \overline{d} = (3, 2, 0) + (2, 3, 1) = (5, 5, 1)$$

4. New coordinates for *D*:

$$D' = D + \overline{d} = (2.5, 3, 0) + (2, 3, 1) = \\ = (4.5, 6, 1)$$

5. New coordinates for *E*:

$$E' = E + \overline{d} = (1.5, 3.5, 0) + (2, 3, 1) = \\ = (3.5, 6.5, 1)$$

6. New coordinates for *F*:

$$F' = F + \overline{d} = (0.5, 2.5, 0) + (2, 3, 1) \\ = (2.5, 5.5, 1)$$

7. New coordinates for *G*:

$$G' = G + \overline{d} = (0, 1.5, 0) + (2, 3, 1) \\ = (2, 4.5, 1)$$

8. New coordinates for *H*:

$$H' = H + \overline{d} = (0.5, 0.5, 0) + (2, 3, 1) \\ = (2.5, 3.5, 1)$$

9. New coordinates for *I*:

$$I' = I + \overline{d} = (1.5, 0, 0) + (2, 3, 1) = (3.5, 3, 1)$$

10. New coordinates for *J*:

$$J' = J + \overline{d} = (2.5, 0.5, 0) + (2, 3, 1) \\ = (4.5, 3.5, 1)$$

Calculate the new radii r relative to the initial reference frame (i.e., the point (0, 0, 0) for each displacement. We use the formula:

$$r = \sqrt{x^2 + y^2 + z^2}$$

1. Radius for A':

$$r_{A'} = \sqrt{3^2 + 4^2 + 1^2} = \sqrt{9 + 16 + 1} = \sqrt{26} \\ \approx 5.1$$

2. Radius for B':

$$r_{B'} = \sqrt{4^2 + 4^2 + 1^2} = \sqrt{16 + 16 + 1} = \sqrt{33} \\ \approx 5.74$$

3. Radius for C':

$$r_{C'} = \sqrt{5^2 + 5^2 + 1^2} = \sqrt{25 + 25 + 1} = \sqrt{51} \\ \approx 7.14$$

4. Radius for D':

$$r_{D'} = \sqrt{4.5^2 + 6^2 + 1^2} = \sqrt{20.25 + 36 + 1} \\ = \sqrt{57.25} \approx 7.57$$

5. Radius for E':

$$r_{E'} = \sqrt{3.5^2 + 6.5^2 + 1^2} = \sqrt{12.25 + 42.25 + 1} \\ = \sqrt{55.5} \approx 7.45$$

6. Radius for F':

$$r_{F'} = \sqrt{2.5^2 + 5.5^2 + 1^2} = \sqrt{6.25 + 30.25 + 1} = \sqrt{37.5} \approx 6.12$$

7. Radius for G':

$$r_{G'} = \sqrt{2^2 + 4.5^2 + 1^2} = \sqrt{4 + 20.25 + 1} = \sqrt{25.25} \approx 5.03$$

8. Radius for H':

$$r_{H'} = \sqrt{2.5^2 + 3.5^2 + 1^2} = \sqrt{6.25 + 12.25 + 1} = \sqrt{19.5} \approx 4.42$$

9. Radius for I':

$$r_{I'} = \sqrt{3.5^2 + 3^2 + 1^2} = \sqrt{12.25 + 9 + 1} = \sqrt{22.25} \approx 4.72$$

10. Promień dla J':

$$r_{J'} = \sqrt{4.5^2 + 3.5^2 + 1^2} = \sqrt{20.25 + 12.25 + 1} = \sqrt{33.5} \approx 5.79$$

Using formula no. 8 to describe displacements:

$$p(x, y, z, r) = \begin{bmatrix} x_{ij} \pm dx & y_{ij} \pm dy & \dots \\ x_{ij} \pm dx & z_{ij} \pm dz & \dots \\ y_{ij} \pm dy & z_{ij} \pm dz & \dots \end{bmatrix}$$

Symbols x_{ij}, y_{ij}, z_{ij} correspond to the initial coordinates of the vertices, and *dx*, *dy*, *dz* represent the displacements. The results are visible in the new positions of the vertices and the calculations of the radii.

Examples of displacement tracking for an irregular solid with 10 faces are illustrated in Figures 11 through 15. These figures demonstrate how characteristic points on a complex geometry are monitored across different measurement planes, allowing precise movement tracking within spatial coordinates. Each face of this solid is paired with specific tracking vectors, highlighting the adaptability of these methods for unconventional geometries. This structured approach enables comprehensive displacement management in dynamic processes, ensuring that even irregular shapes are thoroughly analyzed across relevant planes. To enhance movement speed and zone segmentation, the space has been divided into virtual cubes, as also shown in these figures.

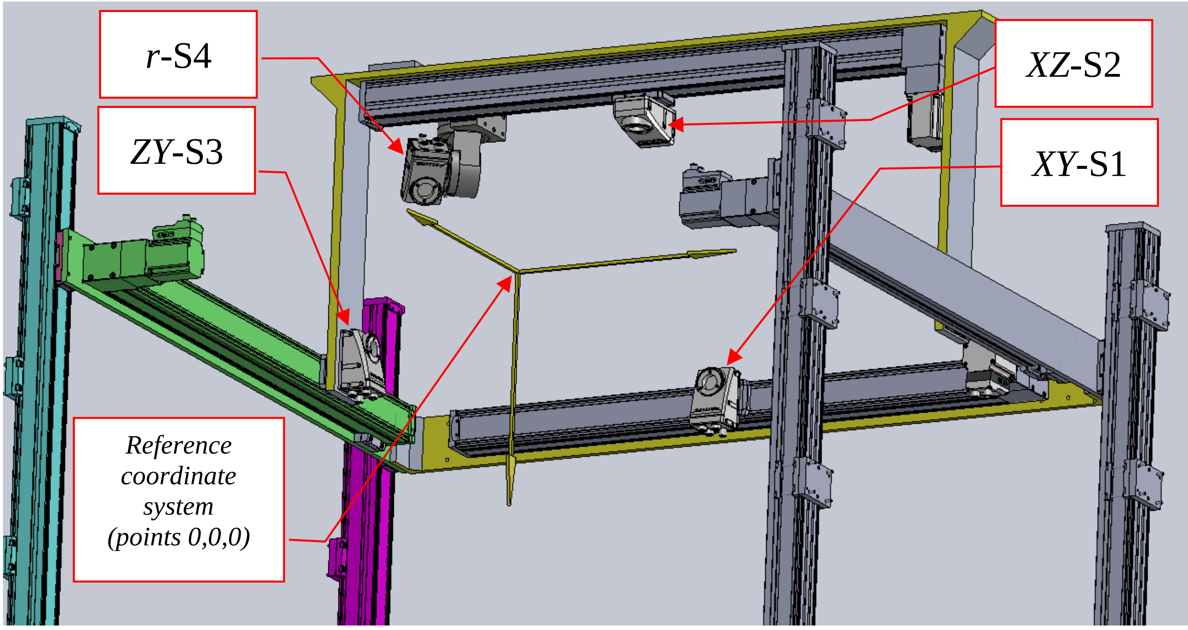


Fig. 11. Structural schematic of the arrangement of measurement cameras within a three-dimensional space. Camera *XY*-S1 monitors movements along the *XY* plane and adjusts on the *Z*-axis, enabling height regulation. Camera *XZ*-S2 controls movements along the *XZ* plane and adjusts on the *Y*-axis, facilitating lateral movement. Camera *ZY*-S3 tracks changes within the *ZY* plane and adjusts on the *X*-axis, allowing precise horizontal movement. Camera *r*-S4, equipped with rotational capabilities, enables 360-degree rotation around the *Y*-axis, providing monitoring of angular changes. This configuration of cameras allows comprehensive analysis of the position and orientation of objects, ensuring high precision in measurement.

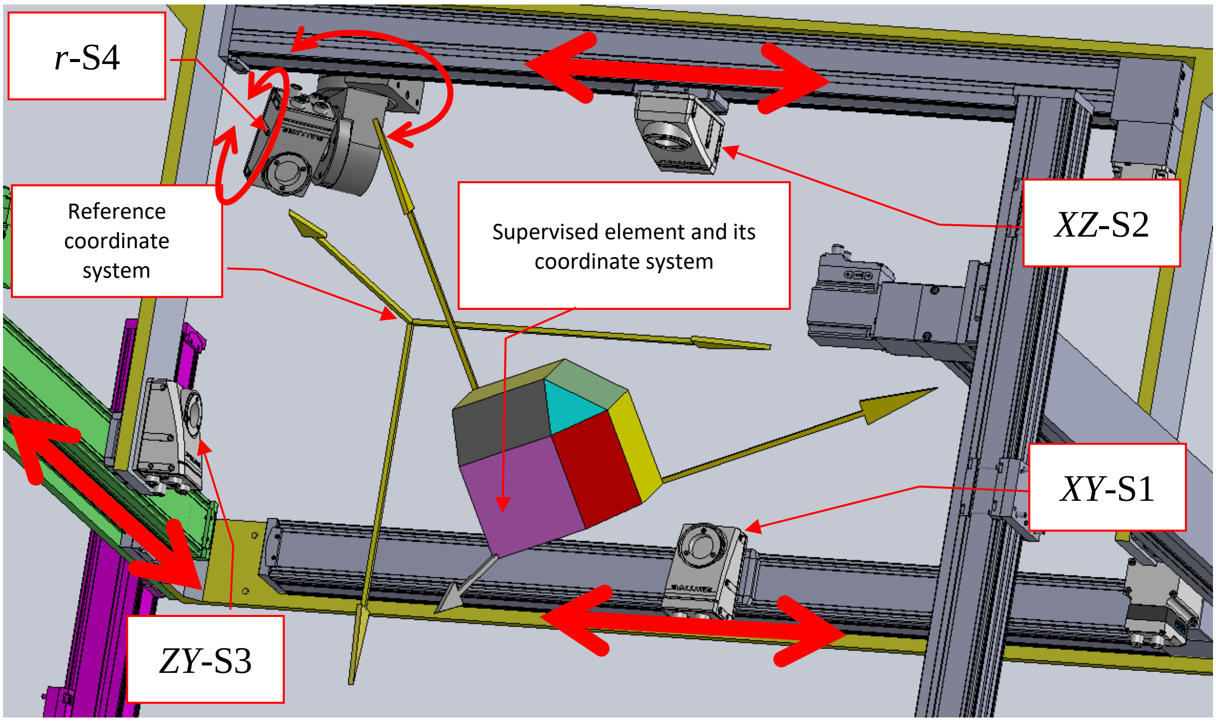


Fig. 12. Spatial configuration of motion and degrees of freedom of measurement cameras. Cameras *XY*-S1, *XZ*-S2, and *ZY*-S3 move along their respective axes: *Z*, *Y*, and *X*, enabling precise positioning of the observed object. Camera *r*-S4 allows full 360-degree rotation around the *Y*-axis, ensuring maximum adaptability and precision in the measurement of object movements. The configuration enables a comprehensive analysis of object orientation within the measurement field, ensuring the reliability of recorded data

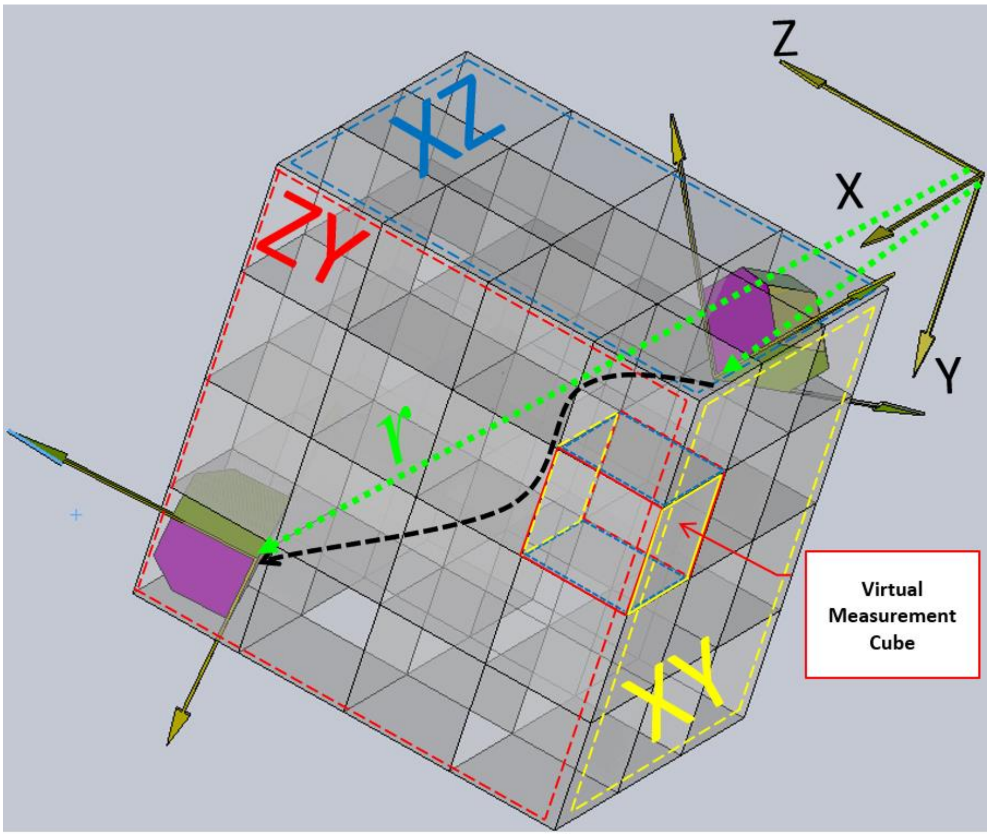


Fig. 13. Division of the measurement space into "virtual cubes," allowing segmentation into smaller measurement areas within the XY, XZ, and ZY planes. Each "cube" corresponds to a specific spatial range, enabling precise tracking of the object's position. Crossing the boundary of one of these areas activates camera movement along the translation axes or its rotation (r), which allows automatic adjustment of camera positions and continuous object tracking. This solution ensures full coverage of the measurement space, enhancing the accuracy and versatility of the measurement process

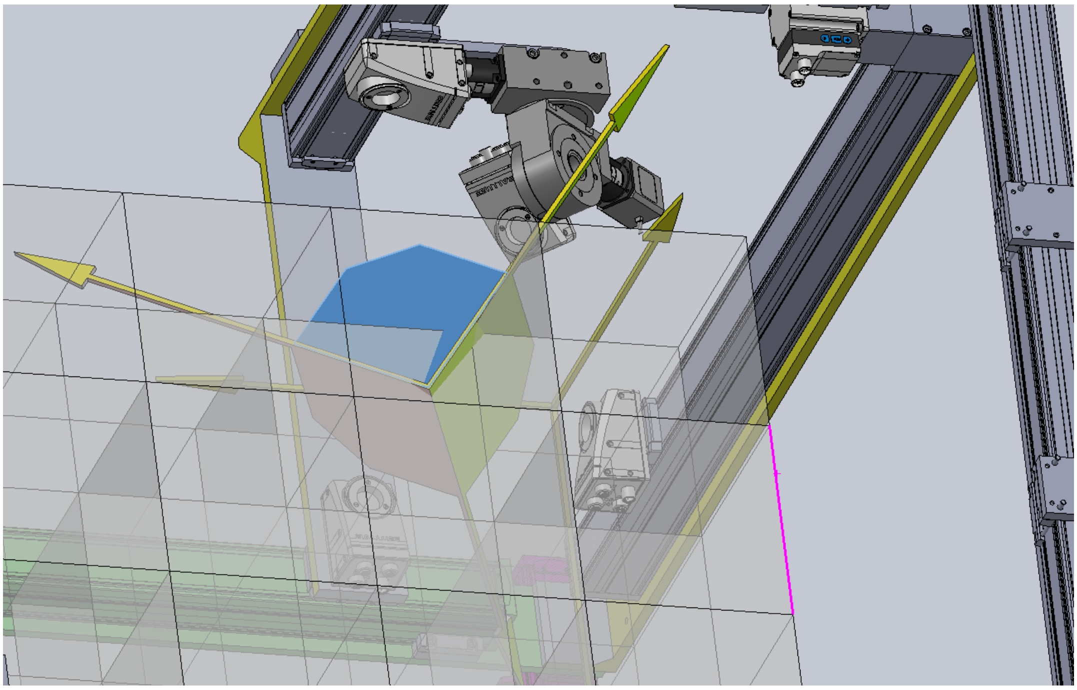


Fig. 14. Illustration of the initial positioning of the measurement system, with the measurement space divided into virtual areas. This setup allows precise tracking of the observed object's position across the XY, XZ, and YZ planes. The system automatically adapts, using dynamic camera positioning to follow the object's movement in all three dimensions. The system is designed for continuous measurement of position changes in high-precision applications

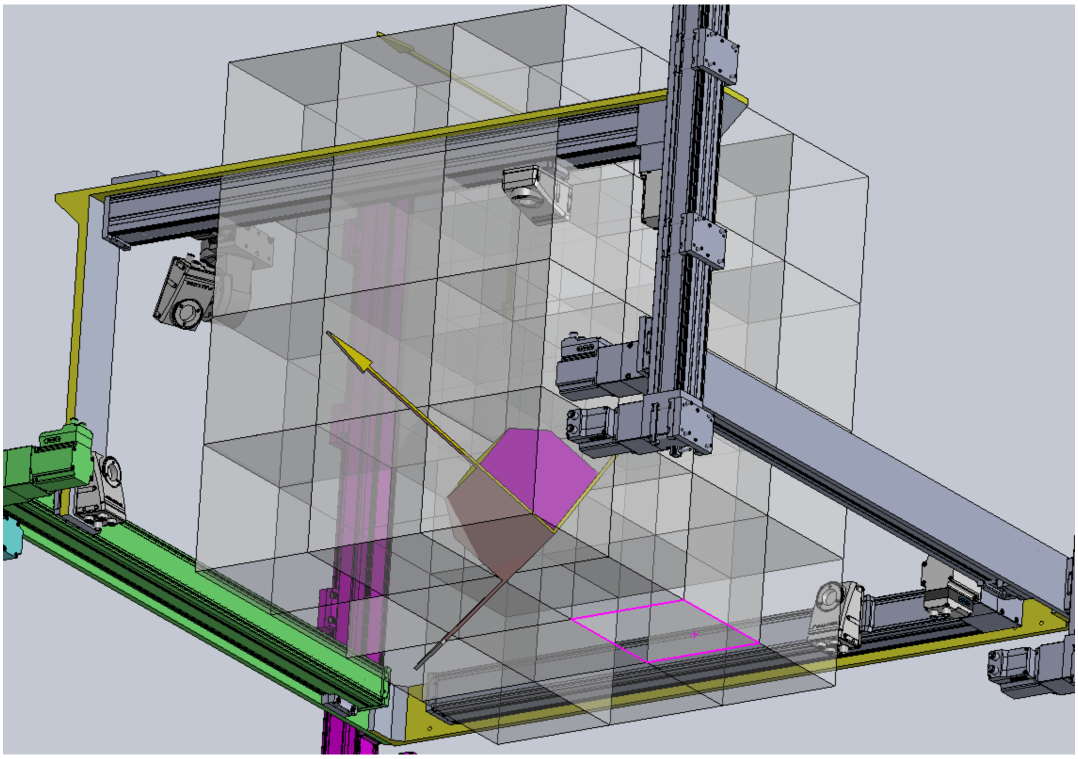


Fig. 15. Continuation of the movement of the measured element shown in Figure 14, depicting the system's state after a certain amount of time. The moving element crosses additional virtual measurement zones, which automatically triggers camera position adjustments. Cameras dynamically reposition along the translation axes and perform necessary rotations to ensure continuous tracking of the object's location. The system precisely follows the movement, which is essential in applications requiring high dynamics and precision in real-time monitoring

6. Proposed New Chapter Title: "Temperature as a Key Parameter in Describing Dynamic Processes and Random Phenomena"

Temperature is a crucial parameter that describes changing reality. For a long time, temperature measurement has been used in the diagnostics of machine health and wear, as well as in the search for missing persons. Temperature can be classified as follows:

a) ambient temperaturę D_o – the temperature of the surrounding environment,
b) Measured temperature relative to a selected reference point T_m – the temperature taken in relation to a specific point,
c) temperature of the examined object on specific measurement planes *XY*, XZ, ZY (T_mXY, T_mXZ, T_mZY) – temperature measurements taken from three sides of the examined object.

Temperature expressed as a difference in temperature, accounting for the specific heat of materials and the amount of heat delivered, according to the formula (Equation 10):

$$\Delta T = \frac{\Delta Q}{m \cdot c} \tag{10}$$

where:
C – specific heat $[\frac{J}{kg \cdot K}]$,
m – mass of the object [kg],
ΔQ – heat delivered [J].

In addition to temperature, similar methodologies can be applied to measure changing volume and indirectly calculate mass and temperature changes occurring on the surface. This approach enables real-time monitoring and control, which is particularly useful in industrial processes involving heating and cooling. By employing this methodology, it is possible to optimize production costs and improve product quality across various industrial sectors.

Depending on the processes, parameters will vary, and each operator aiming to analyze and forecast randomly changing processes must work with a team of specialists to determine which parameters are crucial and relate them to a reference value. The principles for constructing equations to describe additional physical parameters are analogous to those used for time, displacement, and temperature.

In addition to temperature, similar methodologies can be applied to measure changing volume and indirectly calculate mass and surface temperature changes. This approach allows for real-time monitoring and precise control, which is particularly beneficial in industrial processes involving heating and cooling. By employing this methodology, production costs can be optimized, and product quality can be enhanced across numerous sectors of the industry.

7. Historical Data as a Primary Source of Information for Modeling Complex Design Problems in Randomly Changing Technological Processes

History can also be recorded as a function of data changes over time. Anything that occurs outside of this fraction of a second is already history, which can be classified as follows:

1) **absolute history** – events that happen worldwide every day,
2) **documented history** – information recorded on paper,
3) **subjective history** – what people remember and pass on through stories or oral tradition, subject to the imperfections of human senses and vulnerable to suggestions and manipulation,
4) **recorded history** – data registered from measurements of physical and chemical quantities, forming the foundation of science and applicable for predicting randomly changing phenomena.

$$\int_{t_0}^{t_2} \left(\int_{p_{1(t)}}^{p_2(t)} f(p,t)dp \right) dt \tag{11}$$

where:
$f\,(p,\,t)$ – function of documented technological parameters (p) over a selected time interval from t_1 to t_2.

A graphical diagram illustrating the use of historical data and the process of building on historical data analysis and forecasting the probability of future events is shown in Figure 16. The measured operational parameters and the history of phenomena that have historically occurred under similar parameters form the basis for decision-making in the presented methodology. Since 1993, the author has been actively involved in machine design and researching technological processes to implement the best possible solutions for improving worker safety and machine operation, as well as enhancing economic efficiency for businesses by raising the quality of technology.

Figure 16 presents a comprehensive schematic illustrating the data collection and comparison process, along with predictive analysis based on historical trends. This process is designed to optimize decision-making in dynamic and variable technological environments by comparing current data to historical benchmarks.

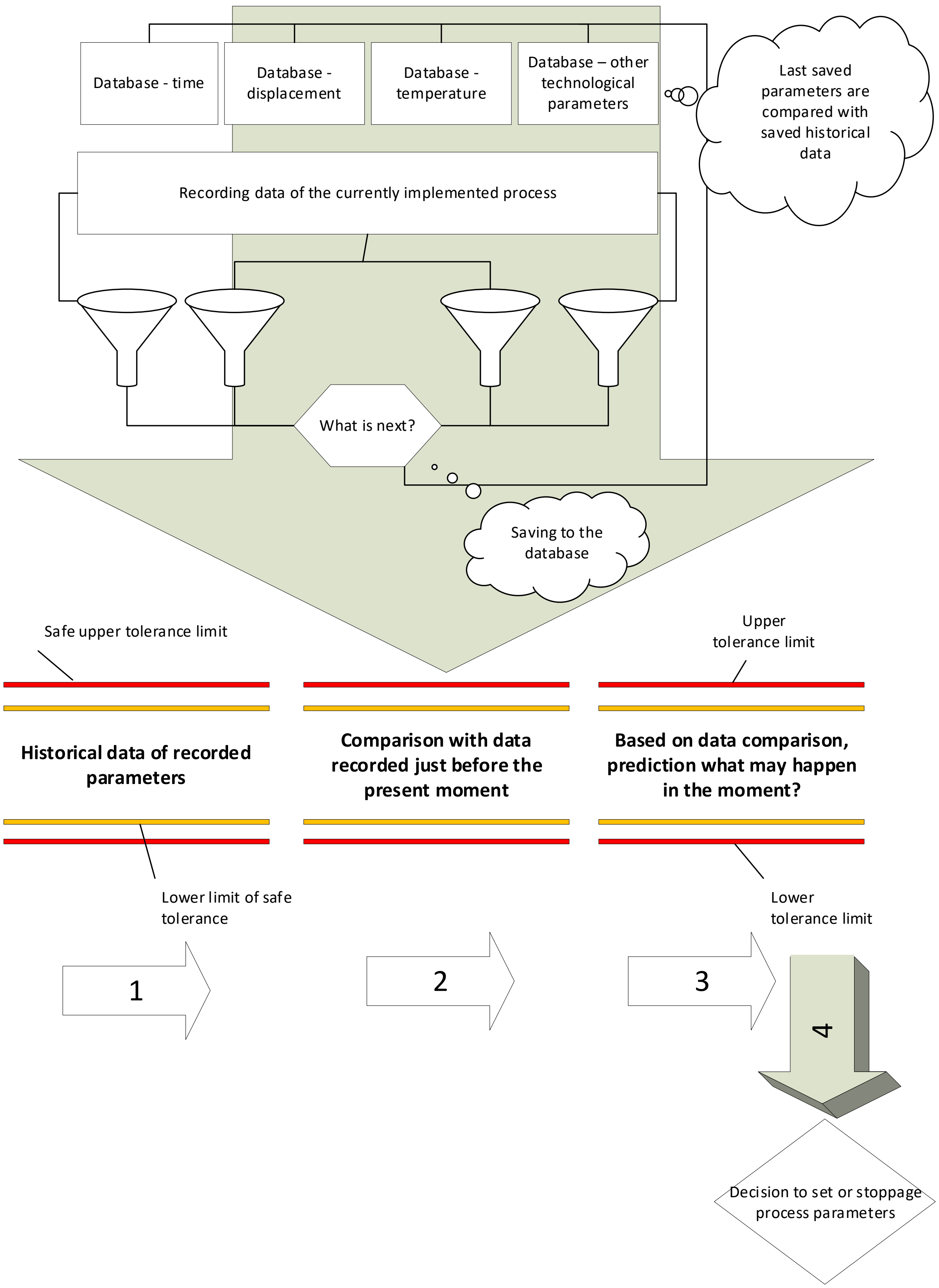


Fig. 16. Graphical representation of the data collection and comparison process with historical events. This system continuously records data related to various operational parameters, such as time, displacement, temperature, and other technological aspects. The recorded data from each moment is compared to historical records to assess deviations and predict upcoming events based on historical trends. This comparison process operates within predefined tolerance limits (upper and lower limits of safe operation) to ensure the system's stability and safety. If the data analysis identifies a potential issue or deviation from safe operational parameters, the system makes an automatic decision to either adjust or halt the process parameters. This predictive approach aids in maintaining optimal functionality and mitigating risks, particularly in dynamic environments where technological changes occur unpredictably

7.1. Diagram Structure and Components:

1. **Data Sources**. The top section shows multiple data sources, each representing different operational parameters (e.g., displacement, temperature, pressure). These sources feed into a central processing unit for data analysis.
2. **Data Recording and Historical Comparison**. Data from ongoing processes are continually recorded and archived in a historical database. This archived data provides a benchmark, capturing typical process fluctuations and tolerance limits.
3. **Comparative Analysis**. The current data is compared with historical data to detect deviations from typical trends. This comparison helps determine whether the present conditions are within the established safe tolerance limits or approaching risky levels.
4. **Predictive Decision-Making**. Based on comparative analysis, predictive algorithms project the likelihood of upcoming changes. If patterns emerge that deviate significantly from safe thresholds, the system triggers alerts or adjustments to prevent errors or inefficiencies.
5. **Tolerance Limits and Adaptive Response**. The lower and upper tolerance limits shown in the diagram represent the operational thresholds. If data indicates a potential breach of these limits, the system adapts by adjusting process parameters to stabilize conditions.

7.2. Using the Diagram for Process Management.

1. **Step 1**: Begin by collecting current data across all relevant operational parameters.
2. **Step 2**: Feed this data into the system, where it is recorded in real time and archived for future reference.
3. **Step 3**: Compare the present data with historical values. Look for trends or anomalies that may indicate a deviation from safe operational conditions.
4. **Step 4**: Use predictive analysis to anticipate future states. If the system predicts a potential breach of safe limits, immediate adjustments should be made to avoid disruptions.

This process ensures that operators maintain optimal control over processes, leveraging historical data and real-time analysis to enhance decision-making.

8. Discussion on the Analysis and Modeling of Design Problems in the Context of Random Technological Changes

8.1. Introduction to the Discussion

The purpose of this discussion is to analyze the results of modeling complex design problems in the context of random technological changes, integrating the author's innovative hypotheses regarding time, displacement, mass, and temperature. This methodology's primary objective is the adaptive management of resources and processes in variable operational environments. The approach combines advanced analytical techniques with dynamic integration of historical data, allowing for enhanced forecasting and adaptation to future technological challenges.

8.2. Application of Time and Displacement Hypotheses in Adaptive Monitoring Systems

Time and displacement are key parameters describing the dynamics of technological reality. The author expands the concept of time by emphasizing its irreversibility and directionality – time progresses unidirectionally and cannot be reversed, forming a foundation for numerous technological processes in which parameters are functions of time. The concept of relative time adds a dynamic aspect to time, making it dependent on operational context and the subjective perception of process participants. Analogous to Einstein's theory of relativity, time in this methodology ceases to be merely a linear flow of moments; it becomes an adaptive resource that enables more flexible management of resources and processes.

Displacement, as the second key parameter, enables precise monitoring of movement and the position of elements in three-dimensional space. The introduction of virtual "measurement cubes" allows dynamic adjustment of these zones' sizes, depending on the object being monitored. This means that for smaller objects, these cubes can achieve microscopic dimensions, while for large objects, such as in military applications, they may span several meters or even kilometers. The segmentation of space into measurement cubes enables detailed tracking of movements, where any deviation or change in position is immediately detected and analyzed, which is crucial in environments that demand high precision and adaptability.

8.3. The Role of Historical and Predictive Data in Process Forecasting and Optimization

A fundamental element of this methodology is using historical data as the foundation for constructing predictive models. The author's core hypothesis suggests that every moment in the past is an information resource for forecasting the future – even a fraction of a second ago is part of history that can be analyzed and used to model future scenarios. This approach supports the systematic collection of operational data, which can be leveraged to precisely model and forecast technological conditions that exhibit randomness.

Integrating historical data with current measurements and using adaptive analytical models enables dynamic adjustments of operational parameters to current conditions. An example of this approach is a real-time monitoring system for temperature and displacement, which adjusts its parameters in response to ongoing conditions, allowing for faster adaptation to changes and minimizing the risk of failure. Thus, the presented methodology is a groundbreaking tool for managing highly dynamic and variable processes, ensuring operational stability and efficiency.

8.4. Integration of Time, Displacement, Mass, and Temperature Parameters

This methodology is based on the interrelationships between four key parameters: time, displacement, mass, and temperature. Each of these parameters plays a crucial role in describing dynamic technological processes, and their integration enables a more comprehensive analysis and control of complex industrial processes.

Temperature, as the third key parameter, is particularly significant in processes involving heating and cooling. Temperature changes are monitored in real-time, enabling precise adjustments to production processes. This approach is invaluable for industry, as temperature control directly impacts the quality of the final product and production costs. Furthermore, the methodology allows for measuring volume changes and the indirect calculation of mass and temperature on surfaces, which can be used to optimize and improve process control..

8.5. Importance of Process Variability and Adaptability

Adaptability is a critical aspect of this methodology, enabling effective management of technological processes characterized by random changes. Variability can be the result of both external factors, such as fluctuations in resource availability or changing market demands, and internal factors, such as equipment failures or unpredictable changes in operational parameters. Integrating historical data with current measurements allows for the identification of patterns and trends, enhancing the system’s ability to forecast and respond rapidly to changes. This approach, therefore, increases operational efficiency and minimizes the risk of downtime and losses.

8.6. Practical Applications and Examples of Process Optimization

The theoretical and empirical investigations demonstrate that real-time adjustment of system parameters is achievable and can significantly enhance operational efficiency. Monitoring systems equipped with proprietary analytical algorithms can detect even minimal deviations and automatically adjust device settings, ensuring continuous process optimization. An example includes the application of these algorithms in industrial processes, where dynamically adjusting operational parameters enables optimized energy and resource consumption, essential for maintaining competitiveness and minimizing costs.

8.7. Summary and Directions for Future Research

In summary, the presented methodology provides a comprehensive and adaptive tool for managing highly variable technological processes. The integration of historical data with dynamic measurements, combined with adaptive predictive models, enables precise modeling of future scenarios and resource optimization. This methodology stands out for its flexibility, allowing adaptation to rapidly changing operational conditions, making it suitable for various industrial sectors.

8.8. Significance of the Author’s "What Next?" Methodology

A central innovation in this work is the "What Next?" methodology, developed by the author as a systematic approach for continuous decision-making, particularly well-suited to environments characterized by random technological changes. This methodology underpins the adaptive framework presented in the study, which is designed to dynamically adjust in response to unpredictable process fluctuations. Unlike traditional methods that rely on fixed-stage planning, the "What Next?" approach introduces an iterative, flexible decision-making model that promotes ongoing assessment and adjustment at every phase of a process. This feature is essential for optimizing responses in environments that require high reactivity and precision.

The core strength of the "What Next?" methodology lies in its structure, which encourages constant evaluation and alignment with real-time data. Each step in the process is not an endpoint but a checkpoint that raises the question of "What Next?" This continuous loop of analysis and decision-making fosters greater adaptability, ensuring that processes remain resilient to unanticipated shifts. By facilitating dynamic recalibration of key parameters like time, displacement, temperature, and mass, the methodology supports a robust approach to maintaining process stability and optimizing operational efficiency.

Moreover, the "What Next?" methodology provides a foundation for implementing advanced predictive models by linking historical data analysis with forward-looking scenario planning. Through this integration, the methodology enables anticipatory adaptation, allowing systems to proactively address potential challenges before they impact performance. This capability is particularly relevant for designing intelligent technological systems and production machines capable of self-adjustment in changing environments.

The significance of this methodology is further underscored by its potential applications in developing technological artificial intelligence (AI) and production machine intelligence. According to the author, technological AI is a system that autonomously optimizes process parameters based on real-time data and predictive modeling, while production machine intelligence refers to self-regulating systems that adjust operational variables in response to environmental fluctuations. Together, these concepts represent the next frontier in industrial automation, where machines and systems autonomously improve performance by continuously analyzing their environment and adapting to new conditions.

8.9. Limitations of the Methodology and Future Research Directions

Despite promising results, this methodology has certain limitations. One of the primary challenges is the significant demand for computational resources and IT infrastructure, which may pose a barrier in environments with limited access to advanced technologies. Another limitation is the dependence on accurate historical data; its absence or inaccuracy can reduce the precision of forecasts and adaptive efficiency. Additionally, this methodology requires advanced real-time monitoring, which may be costly and complex to implement in less advanced environments.

Despite these limitations, this methodology holds great development potential. Future research should focus on optimizing adaptive algorithms to increase their speed and accuracy. Additionally, further development of predictive modeling using more advanced artificial intelligence approaches could significantly enhance responsiveness to changing operational conditions.

9. Conclusions

This study, *"Analysis and Modeling of Design Problems in the Context of Random Technological Changes,"* offers a novel approach to understanding and managing the complexities of design in environments marked by unpredictable technological shifts. The central goal of developing a universal methodology for modeling design challenges in such variable contexts has been successfully achieved, enabling new possibilities for adaptive design management.

The proposed methodology, grounded in four key parameters–time, displacement, mass, and temperature–introduces a cohesive framework that supports the dynamic adaptation of processes to variable operational conditions. A five-axis measurement system was developed to monitor and predict process changes in real time, integrating both relative and absolute time references to enable flexible tracking of fluctuations within segmented "virtual measurement cubes." This arrangement significantly enhances the system's capacity to respond to random process fluctuations with improved accuracy, which is crucial in settings demanding high reactivity and precision.

The hypotheses presented in the study have proven effective in defining these parameters with sufficient breadth and relevance to achieve the study’s objectives. Each parameter’s definition and integration into the framework contribute practically to the model's applicability, reinforcing its utility as an engineering tool. This model facilitates the adaptive management of design processes in dynamically changing conditions, positioning it as a valuable asset for real-world industrial applications. By incorporating multi-criteria decision analysis and integrating historical data systematically, the model not only enriches the understanding of dynamic production processes but also provides a foundation for adaptive systems that can evolve with technological demands.

Moreover, this work introduces two pivotal concepts: *technological artificial intelligence* and *manufacturing machinery artificial intelligence*. Technological artificial intelligence, as conceptualized here, is an adaptive algorithmic system optimized to predict and respond to dynamic technological conditions, while manufacturing machinery artificial intelligence denotes autonomous systems within machinery that monitor, analyze, and adjust production parameters based on real-time and historical data. These definitions establish new research avenues for intelligent, adaptive control systems across various industries, marking a significant theoretical advancement in automated process management.

Future Research Directions, to build upon the theoretical and practical foundation established in this study, the following directions are recommended:

1) **refinement of adaptive algorithms** to further improve real-time responsiveness and precision in fluctuating conditions.

2) **advancement in predictive modeling** to leverage the virtual cube model for more granular forecasting in high-precision environments.
3) **integration with artificial intelligence** to enable autonomous system adjustments informed by both historical data and live feedback, enhancing automation.
4) **validation in industrial settings** to confirm model efficiency and adaptability through iterative testing in real-world conditions.

In conclusion, this study introduces a systematic and forward-looking approach to modeling and managing design processes within unpredictable environments. The proposed framework, designed to facilitate adaptive intelligence, may offer valuable contributions to the field of engineering technology. Its applications suggest promising avenues for enhancing efficiency and adaptability in contemporary production systems and could provide a robust foundation for future advancements in intelligent, adaptive design.

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Original Research

REQUIREMENTS FOR IT SYSTEMS FOR AUTOMATED MARKING OF MECHANICAL PRODUCTS IN ASSEMBLY LINES

WYMAGANIA DLA SYSTEMÓW INFORMATYCZNYCH DO AUTOMATYZOWANEGO ZNAKOWANIA PRODUKTÓW MECHANICZNYCH NA LINIACH MONTAŻOWYCH

Jarosław CHROBOT[1,*]

[1] Wroclaw University of Science and Technology, 27 Wybrzeze Wyspianskiego st., Wroclaw, Poland

* Corresponding author: jaroslaw.chrobot@pwr.edu.pl

Abstract

In many industries there is an obligation to mark the product. In case of mechanical products, such marks are most often applied to products by labelling, as well as mechanical and laser engraving. When marking, employees must remember to change the configuration of the marking machine in case of a change in the type (reference) of the product to be marked. Especially in case of products produced in short production runs, there can be mistakes made by employees and unnecessary time wasted on reconfiguring the marking machine. Therefore, IT applications supporting marking according to the selection of a product from a list or automatically based on the plan of the marked products are gaining importance. This article describes the requirements for computerised systems aimed at supporting the automated marking of mechanical products in assembly lines in companies, which in their case do not see much sense in investing in expensive universal professional software.

Keywords: production, product marking, production data recording, IT systems

Streszczenie

W wielu gałęziach przemysłu istnieje obowiązek nanoszenia oznaczeń na produkt. W przypadku produktów mechanicznych, znaki takie najczęściej nanosi się na produkty za pomocą etykiet, grawerowania mechanicznego i laserowego. Przy znakowaniu pracownicy muszą pamiętać o zmianie konfiguracji urządzenia znakującego w razie zmiany typu (referencji) znakowanego produktu. Zwłaszcza w przypadku wyrobów produkowanych w krótkich seriach produkcyjnych może dochodzić do pomyłek pracowników i niepotrzebnej straty czasu na przekonfigurowanie urządzenia znakującego. Dlatego znaczenia nabierają aplikacje informatyczne wspomagające znakowanie według wyboru produktu z listy lub automatycznie na podstawie planu znakowanych produktów. Niniejszy artykuł opisuje wymagania dla systemów informatycznych, których celem jest wspomaganie automatyzowanego znakowania produktów mechanicznych na liniach montażowych w przypadku firm, które w nie widzą większego sensu inwestowania w drogie profesjonalne uniwersalne oprogramowanie.

Słowa kluczowe: produkcja, znakowanie produktów, rejestracja danych produkcyjnych, systemy informatyczne

1. Introduction

Product marking plays an important role in industry, from production processes to transportation. In many industries, there is an obligation to mark the product. It may result from existing legal regulations, but also from the internal requirements of the company and its customers. Industrial marking must be durable and environmentally resistant in the workplace, as well as must be legible. A permanent mark applied to a product helps to trace the product in the production process, but it is also information for consumers about the characteristics of the item. In case of mechanical products, such marks are most often applied by means

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of sticky labels, mechanical and laser engraving, as well as by attaching radio tags to them. During marking, employees at the final assembly station or quality control must remember to change the configuration of the marking machine in case of a change in the type (reference) of the product to be marked. Especially in case of products produced in short production runs, there can be mistakes made by employees and unnecessary waste of time on reconfiguring the marking machine. Therefore, IT applications supporting marking, according to the selection of a product from a list or automatically, based on an internal plan (list) of marked products, are gaining importance. This article describes the requirements for IT systems aimed at supporting the automated marking of mechanical products at the final assembly station or quality control. The requirements discussed in the paper are based on several years of observation and cooperation with companies, which use marking in assembly lines as well as based on gathering and analysis of companies' requirements.

2. Issues of marking of mechanical products

Currently, it is difficult to imagine logistics, sales or production without various types of detail marking, i.a. descriptions, codes, characters and serial numbers. They enable unambiguous identification of objects, as well as determination of their characteristics. For this purpose, many methods of applying these kinds of marking are used in industry. The choice of marking method is influenced by many factors. One of them is the amount of information necessary to convey, the available surface of the produced part on which it is to be contained, as well as its shape. If there is a need to apply a small amount of data to the object, the engraving method in the form of text or one-dimensional (1D) code can be used. Unfortunately, this technique will be ineffective when more information is required. In this case two-dimensional (2D) codes, like Data Matrix and QR, work well. Another important factor influencing the selection of the marking method may be the influence of the environment, i.e. to what extent it is possible to damage or get dirty the marked surface causing only a fragment of the mark to be read. In such cases, industry also uses 2D codes, which contain redundant information, thanks to which it is possible to read the complete data even when the entire image is not available. It is clearly stated in (Karrach et al., 2022). For example, Data Matrix code and QR code can still be accurately scanned even if up to 30% of its surface area is damaged or obscured. Several publications (Gu at al., 2024, Nguyen et al., 2023) have explored the redundancy and damage resistance of QR codes and other two-dimensional (2D) codes, focusing on their error correction capabilities. These studies provide insights into how QR codes can maintain readability despite physical damage or distortion. The (Dold et al., 2015, Zhang et al., 2019) papers provide an introduction and overview on serialized machine readable code applications as an information source for technical, IT and engineering teams preparing to start with traceability implementation solutions in packaging.

There are already ISO standards, which define the structure, encoding, and specifications for different coding ideas used in various industries:

- one-dimensional (1D) linear barcodes (ISO 15416:2016, 2016),
- two-dimensional (2D) label-based barcodes (ISO 15415:2011, 2011),
- two-dimensional DPM codes (ISO/IEC TR 29158:2011, 2011),
- Data Matrix codes (ISO/IEC 16022:2024, 2024),
- QR codes (ISO/IEC 18004:2015, 2015).

Several publications in journals, like Wall Street Journal and The Guardian, in 2024 discussed the transition from traditional barcodes to QR codes by brands and retailers, aiming to enhance sales and customer engagement. The articles reported on the potential replacement of traditional barcodes with QR-style codes, which can store more detailed information and enhance consumer engagement.

The choice of marking method is also influenced by the way the information is read. Depending on whether the identification process is to be fully automated or performed manually by an employee, different forms of marking are used. In any case, codes used in industry must be resistant to adverse environmental conditions (e.g. extreme temperatures, high dust, painting), as well as the ability to encode a large amount of information while maintaining a small surface area. Direct Part Marking (DPM) technologies ensure that the code is resistant to adverse environmental conditions. The main methods of DPM, in case of mechanical products, are primarily: etching, embossing, milling, laser marking, dot peen marking. 2D codes applied using the DPM method are used in the aviation, space and automotive industries (e.g. for tracking parts during production, tracking engines during services). In case of laser marking, there are now many different methods in practice that can be used to achieve high-quality marking on the produced part in different materials with different shapes. Additive 3D marking (e.g. polyjet) is currently gaining more and more interest, especially in castings (Desavale et al., 2022)

At this point, it is impossible not to mention another, very efficient technology for marking mechanical products, namely RFID (Radio Frequency Identification) technology. It is a method that allows for contactless identification of objects using radio waves. An important feature that distinguishes RFID from optical technologies in the product coding area is the ability to simultaneously scan multiple RFID tags. As a result, this technology allows for object identification without the need for individual scanning, as is the case with optical codes, which is highly helpful when inventorying the warehouse. Industrial companies invest in this technology when the need for rapid identification or automation is a priority, as well as resistance to damage (Unhelkar et al., 2022). There are already ISO standards defined for wireless communication technologies used for identification and data transfer as well, like:

- NFC – Near Field Communication (ISO/IEC 18092:2004, 2004),
- RFID – Radio Frequency Identification (i.a. ISO/IEC 18000-1:2018, 2018).

One shall use RFID technology if long-range tracking (inventory, supply chain, access cards) is needed, from the other side one shall use NFC technology if short-range, secure communication (payments, authentication, automation) is required. In (Thanapal et al., 2017) areas of RFID as well as NFC application and effectiveness for industry were reported. The (Profetto et. al., 2022) scoping review aims to provide readers with an up-to-date picture of the use of RFID technology in health care settings. The (Report, 2022) report provides an in-depth analysis of the RFID technology market, discussing current trends, applications, and future growth prospects across various industries. The (Xin et al., 2021) article points also at disadvantages of the RFID technology for booking inventory in the industry, such as expensive equipment, low accuracy, and high business threshold. The (Kim et. al., 2019, Statler, 2016) articles outline and compare barcodes, QR codes, NFC and RFID, their various functions with regard to consumer marketing and business applications.

3. IT solutions available in industry

To generate codes, 1D or 2D, software is required. The software can convert data into syntax, which is handled by the marking machine. It can be an integral part of the marking machine or be independent. Independent software can be used with any type of marking machine, as long as it is possible to communicate with these devices via communication links (e.g. serial port, TCP/IP network port). The software built into the device is dedicated to a specific type of device. It has an internal logic that can directly generate, m.in, a data-matrix symbol for product labelling. More and more companies decide to implement interfaces in the form of process visualization (operator's panels) due to the versatility of this technology and the possibility of introducing modifications to the software itself without the need to replace the hardware. HMI (Human Machine Interface) is an industrial graphical interface that connects a machine or process with the person who operates it through a physical operator's (control) panel. Such a relationship allows employees responsible for the implementation of tasks to control the course of the process and influence it. One of the most important tasks of the HMI is to provide the operator with real-time information by visualizing the process. It allows for quick and intuitive identification of a possible problem, and thus shortens the employee's response time. "By using online and real-time systems on the HMI, a system can be obtained, that can be controlled and monitored as soon as events occur. With the system integrated HMI, all events can be observed from the monitor screen and can control the system immediately through a computer monitor" (Setiawan et al., 2019). However, HMI may not be enough technology to support more advanced processes. SCADA (Supervisory Control and Data Acquisition), on the other hand, is a computer system that allows to control complex processes and obtain data. It enables their local or remote control through the use of HMIs, which are an important element ensuring communication between devices and the user. In addition, SCADA systems allow to monitor and process the collected data and keep a record of important events and alarms. Appropriate integration of the software allows to connect to external sources of information and transfer data in various formats. "SCADA systems, are widely used in automatic management and control of producing and manufacturing processes throughout the world, reducing manpower and improving production efficiency" (Sinshaw Tamir et al., 2020). "The vast majority of today's Supervisory Control and Data Acquisition (SCADA) systems originate from the leading global manufacturers of industrial equipment characterized by their self-contained ecosystem of proprietary hardware and software solutions" (Šverko et al., 2024).

4. Requirements for the computer application for marking of mechanical products

A computer application, the purpose of which is to support the automated marking of mechanical products, is usually used on a single computer located directly at the assembly final station of a mechanical product, physically connected via a communication link with a marking machine, eventually with other devices (i.e. measurement devices), as well as with remote database. It is best if the application does not absorb the operator too much at the workplace. Only in case of problems, the application can signal to the operator the need for intervention by indicating which procedure to follow. If the employee (the operator) uses other applications, e.g. for reporting, the automatied marking application should run in the background and only occasionally inform about the progress of the marking process. In particular, an IT application supporting automated marking is required to:

- communication with the marking machine in order to carry out the automated marking process (e.g. through the serial port protocol or TCP/IP network protocol),
- reading the data for marking from a file generated e.g. by a measuring device, or from a database, as well as saving the confirmation of the completion of marking to the database or a reporting file,
- enable manual interruption of marking by the workplace operator, e.g. due to incorrect data or other problems that occurred immediately after sending the data to the marking machine,
- enable "acknowledging", i.e. "canceling" or accepting marking errors and resuming the marking process by the user,
- enable usage of built-in procedures so that in case of a problem, one can return to normal operation without the need to restart the application or the computer itself,
- if necessary, provide feedback from external devices, e.g. measuring devices,
- in case of an accumulation of data packages (products) for marking, presentation of the queue in the form of a list, as well as to enable possibility of manipulating this queue (e.g. removal of elements from the queue along with any accompanying information, e.g. files and vice versa – deleting an unnecessary file should remove the item from the list),
- display to the user (on request) chosen process parameters and the status of individual stages of production process,
- generate an event log – in order to record the history of marking, as well as a detailed exchange of information with the marking machine itself, in order to identify possible causes of disruptions in the marking process or the causes of repeated errors,
- enable a configuration of the application by an authorized user in order to, for example, define a communication port or a configurable data chain pattern sent to the marking machine,
- enable testing of communication with the marking machine by directly generating sample marking data, without the need to read files or database content.

In the following subchapters, the main requirements for an IT application supporting the automated marking of mechanical products at final assembly or quality control stations will be discussed.

4.1. Communication with the marking machine

Without computer support, the assembly station operator would have to manually enter the data to be i.e. engraved on the product, and select a marking template. There is then a risk of mistakes, and this process is time-consuming, as well as tedious. The operator must also keep a log of the marking operations performed. The computer application in the field of automated marking of the relevant data performs all operations for the employee. The employee only needs to place the product with the right side under the marking head and confirm the readiness of the marking machine with a physical button.

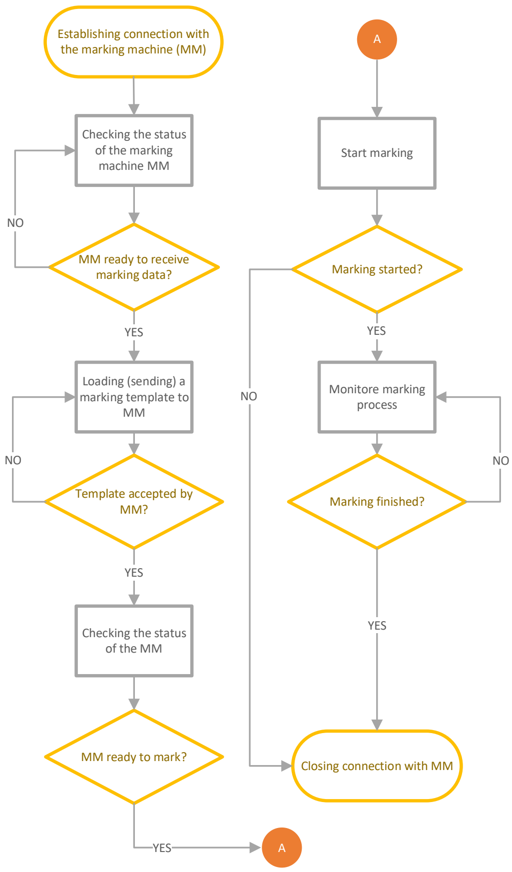

Fig. 1. Procedure of communication with marking machine [source: own development]

The automatic procedure for communicating with the marking machine should include the following steps, which are shown on Fig. 1:

- establishing a connection with the marking machine (logging in, sending a protocol message), often requiring multiple exchange of information,
- checking the status of the marking machine (whether it is ready to accept data) – the marking machine confirms or denies readiness by sending a predetermined message,
- if required, uploading (sending) a template containing texts and variables (assigned in the marking order from the network database) to the marking machine or sending template name only (in case the template is already stored in marking machine's memory),
- assigning values to variables, which are contained in the template sent,
- re-asking the marking machine about the status (whether it is ready for marking),
- starting the marking – marking a string of a fixed format (template) on the mechanical product,
- monitoring progress (receiving subsequent reports from the marking machine, until the marking is completed, or, in case of a trouble, receiving a report on an error).

4.2. Communication with the database

Another requirement is to read the data of the current order from a database installed on a dedicated remote server in the company's computer network, into which the computer with the marking application is connected. Order data can be stored in a relational database table (Table 1).

Table 1. The structure of database table
[source: own development]

ID	VAL	STRING	TEMPL	FINISH
1	0;1;	Text0;Text1;	TEMPL_1	True
2	3;4;	Text3;Text4;	TEMPL_2	False
3	0;2;	Text0;Text2;	TEMPL_3	False

The table row corresponds to the data of the marking order. The example table contains the following fields: ID – row identifier, VAL – identifiers of template variables separated by a semicolon (variables with this name must be previously defined in the marking machine itself and inserted into the template code), STRING – template variable values separated by a semicolon, TEMPL – full template name defined in the marking machine, FINISH – stores the confirmation of the end of the marking (True – completed, False – not finished). To establish the table on the database server and generate database queries, like data retrieving and data saving, the SQL programming language is used. In the case of the discussed table quite simple SQL statements are applied as it is presented on Fig. 2. After the marking process is completed, the application must make a final record in the database of the result of the marking process so that the next order can be read (Fig. 3). The final save in the exemplary database is performed in the FINISH field. If there are more orders to be executed in the table, the application should inform the operator about the number of orders in the queue and allow the operator to display a list of orders that have not yet been executed, so that, if necessary, the operator can set the correct order as the current order or remove an erroneous or invalid order from the queue.

```
-- creation of Orders table; [ID] field is the primary key
CREATE TABLE [dbo].[Orders](
        [ID] [int] NOT NULL,
        [VAL] [nvarchar](50) NULL,
        [STRING] [nvarchar](50) NULL,
        [TEMPL] [nvarchar](50) NULL,
        [FINISH] [bit] NULL,
 CONSTRAINT [PK_Orders] PRIMARY KEY CLUSTERED
(
        [ID] ASC
)WITH (PAD_INDEX = OFF, STATISTICS_NORECOMPUTE = OFF,
IGNORE_DUP_KEY = OFF, ALLOW_ROW_LOCKS = ON, ALLOW_PAGE_LOCKS =
ON) ON [PRIMARY]
) ON [PRIMARY]

-- data retrieving from Orders table
select * from Orders where FINISH = 'False';

-- data saving in the Orders table
update Orders set FINISH = 'True';
```

Fig. 2. Database queries to create table, read and store data
[source: own development]

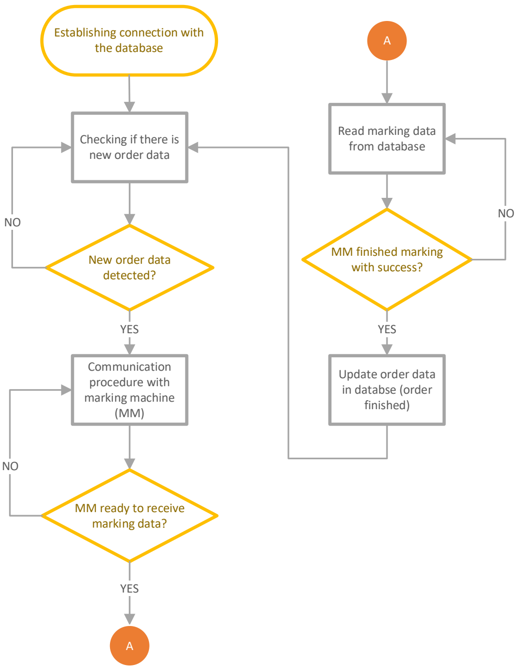

Fig. 3. Procedure of communication with database
[source: own development]

4.3. Reading data from a file

The process of transferring data for marking is based in this case on the automatic generation of a data file by the quality control measuring device. Then the computer application should be able to intercept such a file and read from it the data necessary for product identification and marking. It should also allow the wrong data packets to be removed from the marking queue, which should automatically delete the associated file. In case of reading the data to be marked from the file, the application should generate a marking report containing information on when and what data was applied to the product, what name the measurement file had and what name it was possibly changed to during the archiving process.

4.4. Procedures in case of problems

In case of problems, the operator at the assembly station of mechanical products should be able to interrupt the marking process, as well as to "acknowledge" (confirm, accept) errors signaled by the marking machine, without the need to restart the application and the marking machine itself. Therefore, there is a requirement for the following additional functions, activated by the user with physical or virtual (software) keys:

- marking interrupt function (funcBREAK) – If the parking machine is in the process of marking, one shall be able to interrupt this process at any time by sending an interrupt command to the marking machine,
- function of acknowledging errors of the marking machine (funcACCEPT) – if the machine shows an error during marking and awaits confirmation of receipt of the error, the error can be confirmed with this function,
- marking resume function (funcCONTINUE) – when the application in the test mode is set to only one marking cycle, or the operator has acknowledged the errors of the marking machine, it is possible to resume a next marking cycle with this function,
- counting the number of errors (funcCOUNT) – if the number of error messages reported by the marking machine is greater than the defined maximum value (made with application configuration interface), the user can use one of the previously discussed functions.

It is important to implement procedures in the application that allow it to return to normal operation without the need to restart the application or restart the computer itself:

- in case of an error reported by the marking machine, the operator should use the funcACCEPT function, and then, after removing the cause of the error, should use the funcCONTINUE function,
- the user interrupts the marking process in the order in which the function is used: first usage of the funcBREAK function, and then, after removing the cause of the error, the funcCONTINUE function,
- the sequence of error acknowledgments and the subsequent resumption of the marking process can be automated by inserting appropriate options in the application configuration user interface, which, when selected, automatically activate the basic problem solving functions.

4.5. Communication with other devices

If the marking data is to be obtained from an external device and provided on the user's interface, the application should provide such a possibility, e.g. communication with a torque screwdriver (to retrieve the results of twisting (torque, angle)) or a leak tester (to receive the test result, e.g. the valve opening pressure value)). In such a case, it is required to save additionally the entire marking text with data obtained from the devices, as well as separately the data obtained from these devices, in the form of a predefined production report, in a database or a in a file,

4.6. Configuring of the application

The marking application should allow the authorized user to configure, in addition to the parameters of communication with devices (i.a. the marking machine), also various access paths (to files, to the database) also in terms of the following main options to choose:

- marking machine communication testing mode – shall allow to test the communication with the marking machine by sending predefined test data, without requiring a database connection or access to input files,
- automatic acceptance of errors – results in acknowledgment of the error reported by the marking machine in automatic way,
- repetition of the marking cycle after an error – allows for automatic resumption of the next marking cycle in case of a positive response from the marking machine to the received error acceptance command,
- marking simulation – causes the marking machine to work in the marking simulation mode (without need for physical marking) for the purpose of testing the data exchange process only,
- restart – allows to reconnect to the marking machine after the marking is complete in case the marking machine closes itself the communication session.

5. Case studies

One of case studies for an application of IT support, built based on the requirements discussed, can be a manufacturing company which engraves serial numbers on metal parts. Employee has to enter data manually and configure engraving device according to type of product. The company wants to automate the process to release the employee from this part of job, which can cause failures in case the employee makes a mistake. The company does not want to buy an extensive, multi-functional software from the market. After implementation, instead of manually entering data, the applied software fetches engraving orders from an SQL database together with other configuration parameters, automatically generates text strings and sends them to the engraving machine without human intervention. It communicates with the engraving device to have the full control over marking preparation process. It confirms the finish of engraving with a feedback update query directly in the database. The system informs the employee in case of problems (for example unknown configuration parameters in the database) and new engraving order.

Another case study can be a manufacturing company of a discrete components. The company engraves a text string on that components. Essential part of data for engraving is to be retrieved from a measurement device. The formatted data has to be sent to engraving machine. The company wants to automate the process, but does not want to pay for a ready market software. The company is interested in dedicated software for this case and handling this one model of engraving machine only. After implementation, the applied software waits for measurement files generated by the measurement device in a chosen folder. Once it detects them, it reads them and prepares a string to send to engraving machine. It builds a list of engraving jobs, which is to be handled by the employee. If the employee does not do any action, the system sends the first job from the list to the engraving machine, communicates with it and, after finish of the engraving process, it removes the job from the list, prepares a report file and make a copy of the measurement file.

6. Marking software on the market

On the market there is offered already professional complex software supporting product marking from design to application on product. One example is Gravostyle, which is a professional engraving and cutting software developed by Gravotech. It is designed for rotary, laser, and hybrid engraving machines. It provides a wide range of CAD/CAM functions tailored for professional engravers. Another example is EngraveLab, which is a professional engraving software developed by CADlink Technology Corp., widely used for trophy engraving, signage, industrial marking, and personalization, tailored for both laser and rotary engraving systems. Both packages offer necessary functionality:

- design and import – enable creation intricate designs, manage text, and process images directly within the software,
- machine control – work with laser, rotary, dot peen and scribing engraving machines,
- variable data engraving and database integration, making it suitable for automated workflows,
- auto-start engraving based on database updates – when new data is added to the database, the software can automatically trigger engraving jobs,
- remote job control – engraving jobs can be queued and processed remotely using a networked database system.

There are also less equipped IT systems like i.e. Lightburn, which does not have built-in database connectivity features like SQL or external database integration, however, one can manage and store settings, such as material libraries and cut settings, which function like a simple internal database.

The second case study from the chapter 5 shows a specific case, which needs individual treatment. The commercial complex marking software offered on the market requires users to adapt their entrance data. Entry data files have to be adapted – formatted and ordered as result of prior search, analyses and mathematical operations, for example to find an average value. Other issue is a timing – once an entry file is ready, the user has to point at it and manually start fetching data. If there is no file yet, the user has to wait for it and in this way is engaged by the system longer that it would be necessary. Either way, not all cases will be handled with such systems and sooner or later IT support will be needed to develop an IT module to integrate input with output within a given special case.

7. Summary and conclusions

This article describes the requirements for information systems aimed at supporting the automated marking of mechanical products in assembly lines. The described requirements for the application are primarily related to reading input data, automatic recording of production data, product marking, which contains the recorded data, as well as handling procedures so that in case of a problem, normal operation can be resumed. The workplace operator is relieved then of the activity of data recording and programming of the marking machine by entering data for marking, as well as assigning it an executive program. From the point of view that on the market there are already some mature complex and complete IT systems supporting automated product marking, the requirements presented in the paper rather regard IT integrators in smaller companies. Such companies do not see much sense in investing in expensive professional software, have limited budget, and want rather to program communication itself, based on documentation delivered by a producer of the marking device. So this paper could be a valuable set of ideas and possible requirements for such dedicated integration jobs.

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Original Research

THE WAY OF DETECTING LEAKS IN PNEUMATIC ACTUATORS ON THE EXAMPLE OF A SELECTED PRODUCTION SYSTEM

SPOSÓB DETEKCJI NIESZCZELNOŚCI SIŁOWNIKÓW PNEUMATYCZNYCH NA PRZYKŁADZIE WYBRANEGO SYSTEMU PRODUKCYJNEGO

Artur MACHA[1], Andrzej LOSKA[1,*]

[1] Department of Fundamentals of Machinery Design, Faculty of Mechanical Engineering, Silesian University of Technology, Konarskiego 18a, Gliwice, Poland

* Corresponding author: Andrzej.Loska@polsl.pl

Abstract

Compressed air is a very important energy medium in industrial processes. Leaks in pneumatic systems, inappropriate pressure, improper use of components, etc. are responsible for losses of produced compressed air. Pneumatic actuators, which are key in this respect, are exposed to internal and external leaks, which leads to an increase in their extension and retraction time, a decrease in the force achieved on the piston rod, and in the case of large leaks - to their stopping, causing a failure and necessary downtime of the machine or the entire production line. The article addresses the problem of leaks in pneumatic actuators used within automated production systems. The specificity of operation of pneumatic actuators, problems with their leaks, and available methods of their detection are discussed. For the needs of the tested production system, an original way for detecting leaks in pneumatic actuators was developed, the operation of which was verified using a simulation model in the Simulink environment. This way involves measuring the pressure value in individual pneumatic actuator supply lines with the compressed air supply from the source cut off. The pressure drop in the system and the position of the piston rod indicate the size of the leak and its location. The proposed solution allows for testing actuator leaks on the entire valve island using a single measurement point. The performed simulation analysis allowed to confirm the correctness of the developed way.

Keywords: pneumatic actuators, leak detection, simulation methods, Simulink

Streszczenie

Sprężone powietrze to bardzo ważne medium energetyczne w procesach przemysłowych. Nieszczelności w układach pneumatycznych, nieodpowiednie ciśnienie, niewłaściwe użycie elementów, itp. odpowiadają za straty wyprodukowanego sprężonego powietrza. Kluczowe w tym zakresie siłowniki pneumatyczne, narażone są na wycieki wewnętrzne i zewnętrzne, co prowadzi do zwiększenia czasu ich wysuwania i wsuwania, zmniejszenia siły osiąganej na tłoczysku, a w przypadku dużych wycieków - do zatrzymania ich pracy, powodując awarię i konieczny przestój maszyny czy całej linii produkcyjnej. W artykule podjęto problem nieszczelności siłowników pneumatycznych eksploatowanych w ramach zautomatyzowanych systemów produkcyjnych. Omówiono specyfikę działania siłowników pneumatycznych, problemy ich nieszczelności, a także dostępne metody ich detekcji. Dla potrzeb badanego systemu produkcyjnego, opracowan został autorski sposób detekcji nieszczelności siłowników pneumatycznych, którego działanie zweryfikowano przy użyciu modelu symulacyjnego w środowisku Simulink. Sposób ten polega na pomiarze wartości ciśnienia w poszczególnych nitkach zasilania siłownika pneumatycznego przy odciętym dopływie sprężonego powietrza ze źródła. Spadek ciśnienia w układzie i pozycja tłoczyska, świadczy o wielkości wycieku i jego lokalizacji. Zaproponowane rozwiązanie pozwala na badanie nieszczelności siłowników na całej wyspie zaworowej przy użyciu jednego punktu pomiarowego. Przeprowadzona analiza symulacyjna pozwoliła potwierdzić poprawność opracowanej metody.

Słowa kluczowe: siłowniki pneumatyczne, detekcja nieszczelności, metody symulacyjne, Simulink

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1. Introduction

Compressed air is a colorless and odorless medium, so its leaks are difficult to notice. Air leakage is characterized by the generation of high-frequency sound, but the noise of other components of production machines effectively masks the acoustic effect.

About 75% of the cost of compressed air production is energy costs. The remaining costs are the costs of purchasing the compressor, dryer and other components (about 10-15%) and operating costs, which include spare parts, periodic services and repairs (about 10-15%). Leaks in pneumatic systems, inadequate pressure, improper use of components, etc. are responsible for losses of produced compressed air in the region of 20-30%, and in some systems even up to 60% (Whitlam, 2021). In the European Union, compressed air production is 10% - 30% of the total electricity consumption in industry (Radgen et al., 2001).

Pneumatic actuators, which are key in this respect are exposed to internal and external leaks, and this leads to an increase in the time of their extension and retraction, a decrease in the force achieved on the piston rod, and in the case of large leaks - to their work being stopped. The consequence of such a phenomenon could be a failure and necessary downtime of the machine or the entire production line. Incorrect operation of actuators may in some cases, cause product defects (Kalisch et al., 2014).

Effective leak detection of pneumatic actuators influences the systematic planning and implementation of preventive actions, shortening the time of unplanned downtime, reducing the consumption of compressed air and reducing the costs of electricity. Currently, there are being developed various methods and tools allowing for leak detection, However, implementing them in industrial practice requires making major changes to existing systems or purchasing expensive devices, the cost of which often exceeds the possible benefits for the company.

Taking into account the above arguments, the authors of this article presented the results of research on the problems of leaks in pneumatic actuators used in production systems. The effect of undertaken and completed works is developed original way of leak detection. The correctness of the developed way was verified in computer simulation conditions based on a model built for this purpose and data sets originating from a real production system.

The first part of the article presents the pneumatic specificity of double-acting actuators, as well as a review of leak detection methods used in industrial practice. Then, the research object – pallet loading station – Is presented. The main part of the article includes a description of the author's way of detecting leaks in the tested system, followed by an analysis of the correct operation based on a simulation model developed for this purpose. The article ends with conclusions concerning both the problem of leaks in pneumatic actuators and the developed way of detection.

2. Operation specificity of double-acting industrial pneumatic actuators

A pneumatic actuator is a device that converts the energy of compressed air into linear mechanical force and movement. It is a key component in both robotics and industrial automation thanks to the availability of compressed air in most industrial plants (Hu et al., 2018, Szenajch 2016). Pneumatic actuators differ in their design, ability to exert forces, force change during operation, number of positions, type of movement and connection of the driving element with the driven element (International, 2018, Kurmyshev et al., 2020). A typical pneumatic actuator consists of a cylinder with a moving element inside, i.e. a piston and a piston rod (Tomasiak, 2001).

Each cycle of operation of a double-acting pneumatic actuator consists of two movements – the extension of the piston rod and the retraction of the piston rod (Mahmoud et al., 2018; Fracczak et al., 2021, Parr, 2011). Fig. 1 shows the air flow paths during piston rod extension movement.

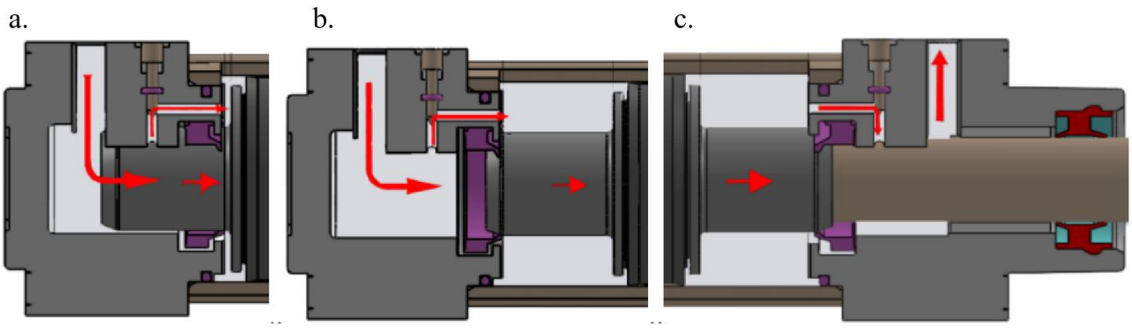

Fig. 1. Air flow during piston rod extension: a. piston start of movement, b. piston leaving the damping phase, c. damping phase start (Mahmoud et al., 2018)

During the extension of the piston rod, the valve is overdriven, which supplies air to the actuator port in its rear cover. Air passes through the return valve into the chamber, where the rear part of the piston is located. In the initial phase, called the damping phase, air first passes through the throttle valve into the compartment between the rear of the piston and the rubber ring, in the rear cover. Once the minimum required pressure is reached, which varies depending on the size and type of actuator, the piston begins to be pushed. When the piston moves back enough to be no longer sealed by the ring, air enters through the gap and its speed increases. Once a certain position is reached, the piston is sealed by a rubber ring in the front cover and air from the second compartment flows only through the throttle valve, causing a slow final movement and starting the next damping phase. During the entire movement, the air that previously filled the second compartment is discharged through the actuator connection in its front cover. After all the air has been pushed out, the piston reaches its final position and the piston rod is in its most extended position (Mahmoud et al., 2018; Fracczak et al., 2021, Parr, 2011).

Fig. 2 shows a stepwise diagram of the piston rod retraction movement.

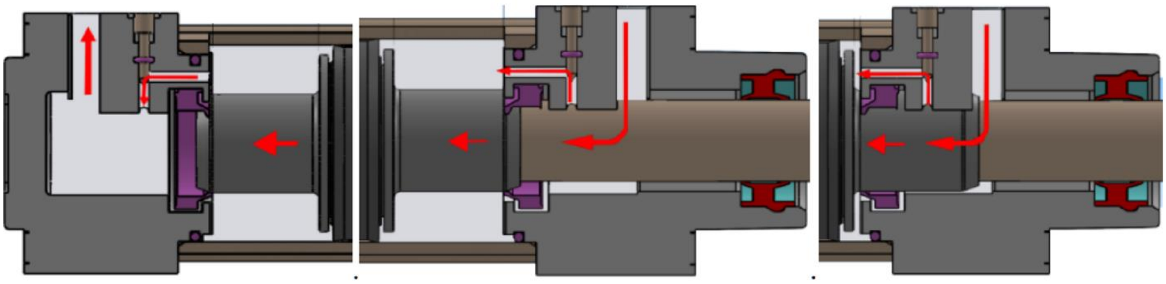

Fig. 2. Air flow during piston rod retraction: a. start of damping phase, b. piston leaving damping phase, c. start of piston movement (Mahmoud et al., 2018)

In order to retract the piston rod, air is supplied to the cylinder port in its front cover. The entire movement pattern is identical to that of extension, but the air flow is in the opposite direction. Once the appropriate pressure is reached in the front compartment, the damping phase begins and the air flowing through the throttle valve causes the piston to slowly move towards the rear cover. When the piston leaves the damping area, a rapid retracting movement of the piston rod begins, and after reaching the second damping area, a slow retracting movement of the piston rod occurs. After all the air has been pushed out of the second compartment, the piston reaches its final position and the piston rod is in the most retracted position.

To control the operation of a double-acting actuator, a two- or three-position five-way valve is required. The valve controls the direction of the compressed air flow and thus forces the appropriate movement of the actuator's piston rod. In the case of three-position valves, it is also possible to stop the piston rod in any middle position, however, due to the high compressibility of air, this position has low repeatability. Three-position valves are often used to protect against piston rod movement in the event of a safety circuit being interrupted, for example by opening a machine door. The valve is controlled by applying a digital signal to the appropriate solenoid valve coil, which causes air flow between the individual connections.

In each cycle of the actuator's work, there are two main forces – the pushing force and the pulling force. The values of these forces differ from each other, therefore the required forces must be determined appropriately so that the selected actuator meets the assumptions of the designed system.

$$F_{tc} = P \cdot \pi \cdot R^2 \quad (1)$$

$$F_{tr} = P \cdot \pi \cdot (R^2 - r^2) \quad (2)$$

where:
F_{tc} – theoretical pushing force [N],
F_{tr} – theoretical pulling force [N],
P – compressed air pressure [bar],
R – radius of piston [mm],
r – radius of piston rod [mm].

From formulas (1) and (2) it follows, that the pulling force of a double-acting actuator is less than the pushing force of this actuator. If the same pressure is applied to both compartments of the actuator at the same time, the piston rod will extend, because the pushing force will be greater. However, the useful force on the piston rod is different from the theoretical one. This is influenced by pressure changes during filling and emptying of the actuator compartments and friction forces occurring in the seals.

3. Leaks in pneumatic actuators – characteristics and methods of detection

Leaks are the basic and largest group of causes of pneumatic actuator failures. They occur most often at the sealing points of the connections between the elements in the pneumatic system. Seal damage causes leaks which affect the incorrect operation of the actuator itself, as well as increased compressed air consumption. Air leakage is uncontrolled, accidental and always undesirable. They can be eliminated by cyclical replacement of seals combined with early detection of air leaks (Jaafar et al., 2024; Loska et al., 2016, Sun et al., 2021).

Typical locations of air leaks during the piston rod retraction and extension phases are shown in Fig. 3.

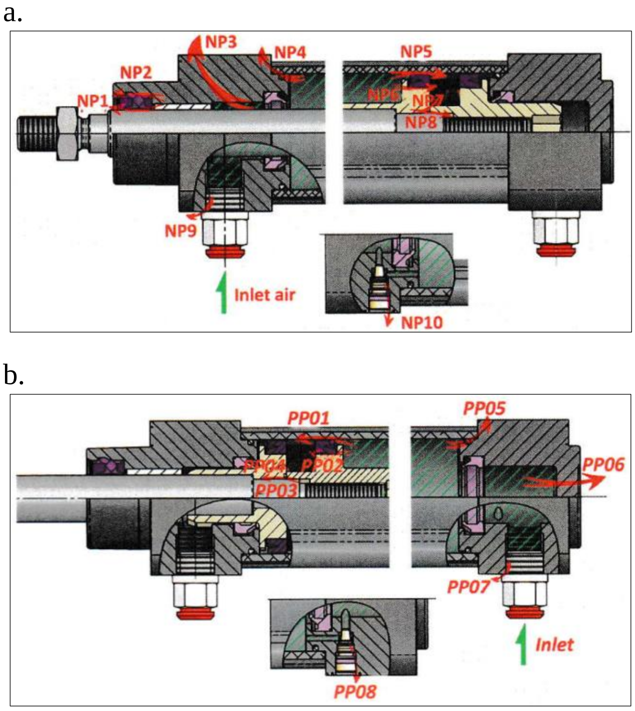

Fig. 3. Location of air leakage points during operation of the pneumatic actuator: a) the piston rod retraction phase, b) the piston rod extension phase (Parr, 2011)

Defects during the piston rod retraction were marked with the appropriate number and the letters NP (Fig. 3a), while defects during the extension were marked with the letters PP (Fig. 3b). Possible leak locations are due to the construction of the actuators.

Because of the large number of actuator seals, leaks can occur in different places and each of them has a different effect on the actuator's operation. At first, these leaks are small and have no visible effect on the actuator's operation, but they will increase over time. In order to maintain the set operating parameters of the actuator, the compressed air flow throttling adjustment is performed at the actuator output. This allows the actuator to work longer, but air losses will be greater and may ultimately lead to complete its damage and unplanned downtime of the machine caused by a failure. Depending on the type and construction of the actuator, as well as the nature of the damage, it is possible to regenerate pneumatic actuators by replacing the seals, repairing the moving parts, or replacing the piston rods. Excessive wear of the actuator may result in irreversible mechanical damage. Regeneration is not always cost-effective, so it is important to consider the ratio of repair costs to the cost of a new device (Zhu et al., 2023; Abela et al., 2022).

There are many leak detection methods used in industrial practice, and the key ones are those that can be used in their places of work and do not require construction and structural changes in the pneumatic system. In this area, it is necessary to mention leak detection sprays, ultrasonic leak detectors, thermal imaging cameras, acoustic emission method and measurement of air flow, pressure and exergy.

Each of the analyzed leak detection methods has its advantages and disadvantages, not all of them are suitable for every pneumatic system. Also important are the organizational and economic circumstances and conditions, which often makes it necessary to individually select the method to suit the technical system requirements and process constraints.

Leak detection sprays can detect even very small leaks. They are very easy to use and one spray can be used to detect leaks in many places in the technical system.

However, they are limited to external leaks, do not allow the detection of internal leaks in pneumatic actuators. It cannot be automated – its use and results must be verified by a trained operator. To ensure the operator's safety, it is necessary to stop the machine when detecting leaks using this method near moving parts. This method is a good solution, if you notice problems with the actuator and you expect confirmation that the source of these problems is an external leak (Whitlam, 2021).

Ultrasonic leak detectors allow for quick analysis of leaks in a large area of the machine. Testing the system for leaks using this method may require stopping the machine in order to safely access its individual components. The ultrasound method is only useful for external leaks, and can be partially automated. It is a good solution in case of necessity of comprehensive machine check for quick location of the leak source (Guenther et al., 2016; Rottländer et al, 2016).

Thermal imaging cameras are the basic equipment of the maintenance department due to their versatility in diagnostic use. This method is used to quickly confirm external leaks in pneumatic actuators, with the possibility of partial automation. Depending on the design of the machine, it may be necessary to stop it. The measurement results may be influenced by heat emitted by other components of the machine (Kroll et al., 2009; Dudić et al., 2012).

The acoustic emission method is a fully automated method for testing leaks in pneumatic actuators. It allows for early and accurate detection of internal and external leaks and testing of pneumatic actuator parameters during operation. The implementation of the acoustic emission method in a specific technical system requires performing tests in order to select appropriate alarm thresholds depending on the actuator model. The method requires considerable resources and the cost of application depends on the number of actuators tested (Kucharski et al., 2023; Nazarchuk et al., 2017).

Testing for leaks in pneumatic actuators by measuring air flow, pressure and exergy allows for automatic measurements to be taken while the actuators are operating. It is possible to detect internal and external leaks. This method allows for the analysis of the operation of several actuators from one measurement point, which reduces the number of necessary changes in the existing system, but requires many tests to be performed in order to accurately train the neural network. The method requires financial outlays related not only to the cost of sensors, but also to computer equipment with appropriate specifications, allowing for the analysis of the obtained data and drawing conclusions based on neural network models (Zhu et al., 2023).

Industry solutions are most often automatic detection systems. Available products are characterized by high accuracy and full technical support from the manufacturer, which allows for the process of implementing such devices into existing systems to be simplified. Some methods and tools also require a monthly subscription fee to access individual options (SMC, 2024a; SMC, 2024b).

4. Description of the research object

The selected research object is the pallet loading station. It is the subsystem of the machine responsible for loading elements onto pallets for transport to further stages of the production process. The key and analyzed components of this subsystem include three gates operated by pneumatic actuators. Fig. 4 shows a top view of the station with pallets placed inside.

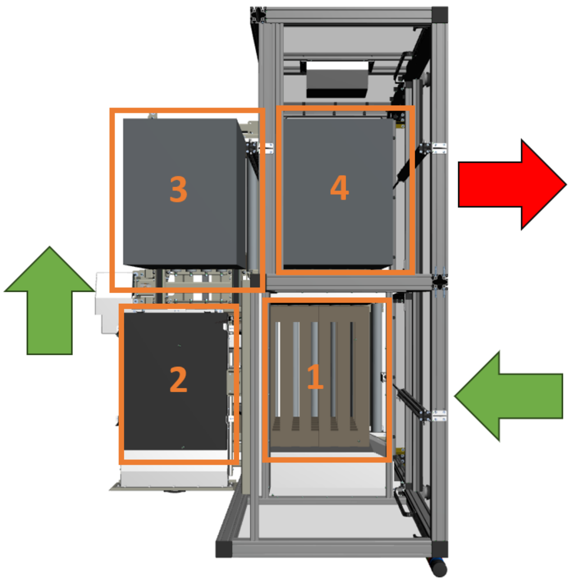

Fig. 4. Research object – pallet loading station

The numbers 1 to 4 indicate the appropriate zones, and the arrows indicate the direction of pallet movement. In zone 1 there is a storage, where pallets inserted by the operator are stored. Access to zone 1 is separated by a gate. In zone 2 there is a storage for spacers used to separate layers of products stored on the pallet. There is no gate between zones 1 and 2, and the pallets move on a chain conveyor under the spacer storage. In zone 3, the pallets stop and then the products are loaded using an industrial robot. Once the pallet is full, the gate between zones 3 and 4 opens and the pallet moves to zone 4. Removing the full pallet from zone 4 is possible after opening the gate located between zone 4 and the exit from the machine.

Each gate is operated by one of the double-acting actuators. They are controlled by 5/3 directional control valves mounted on one valve island. The movement of the gate to the open/closed position is signalled by inductive sensors, which are components of the machine's safety system.

The machine software does not allow the control of the sluice gate when the second gate of this sluice is not closed. In a situation where none of the gates has confirmation of closing, the machine is stopped with an alarm from the safety system. A similar case may occur if the gate did not close or open within the specified time. Additionally, each gate is equipped with an safety edge strip protecting it from collision with an incorrectly inserted pallet or with the operator.

Leaks in pneumatic actuators in the tested system significantly affect the consumption of compressed air and may pose a health risk to machine operators. Initially, they are unnoticeable and may not have a major impact on the machine's operation. Therefore, it is necessary to use appropriate detection systems to prevent them and continuously monitor the wear of pneumatic actuators. In the following sections of the article, it will be presented an original way of testing leaks in pneumatic actuators, which consists of description of the system structure, leakage testing way and simulation analysis of its implementation. Simulation evaluation is currently a flexible and universal form of verifying the structure and operation of pneumatic actuator systems and is the subject of both scientific research (Feng et al., 2013; He et al., 2011), and practical applications.

5. Construction and operation of the leak detection system for pneumatic actuators

The development of the leak detection way was preceded by the formulation of assumptions. It was assumed, that the leak detection system:

- should be applied in an existing pneumatic system,
- should be characterized by a limited number of elements and low cost of implementation,
- should enable leak detection on multiple actuators using a single measurement point,
- should be able to function automatically for preventive leak detection.

Additionally, the test duration should be short enough not to cause production to stop.

The diagram of the pneumatic system with the developed leak testing solution is shown in Fig. 5. The red rectangle indicates the proposed and implemented additions.

The analyzed solution is part of the pneumatic system of the entire machine. Compressed air is supplied to a valve island consisting of 3 monostable solenoid valves 5/3: V1, V2 i V3. Each valve controls the extension or retraction of the cylinder piston rods A1, A2 i A3. The speed of individual movements of the cylinder piston rods can be regulated using throttle-check valves supplying air to the cylinder connections. All cylinders are equipped with pneumatic cushioning allowing for damping of the final movements of the piston rods in order to limit sudden stops in the end positions. The working medium within the entire system is supplied and distributed using flexible pneumatic hoses with an outer diameter of 8 (mm) and an inner diameter of 6 (mm).

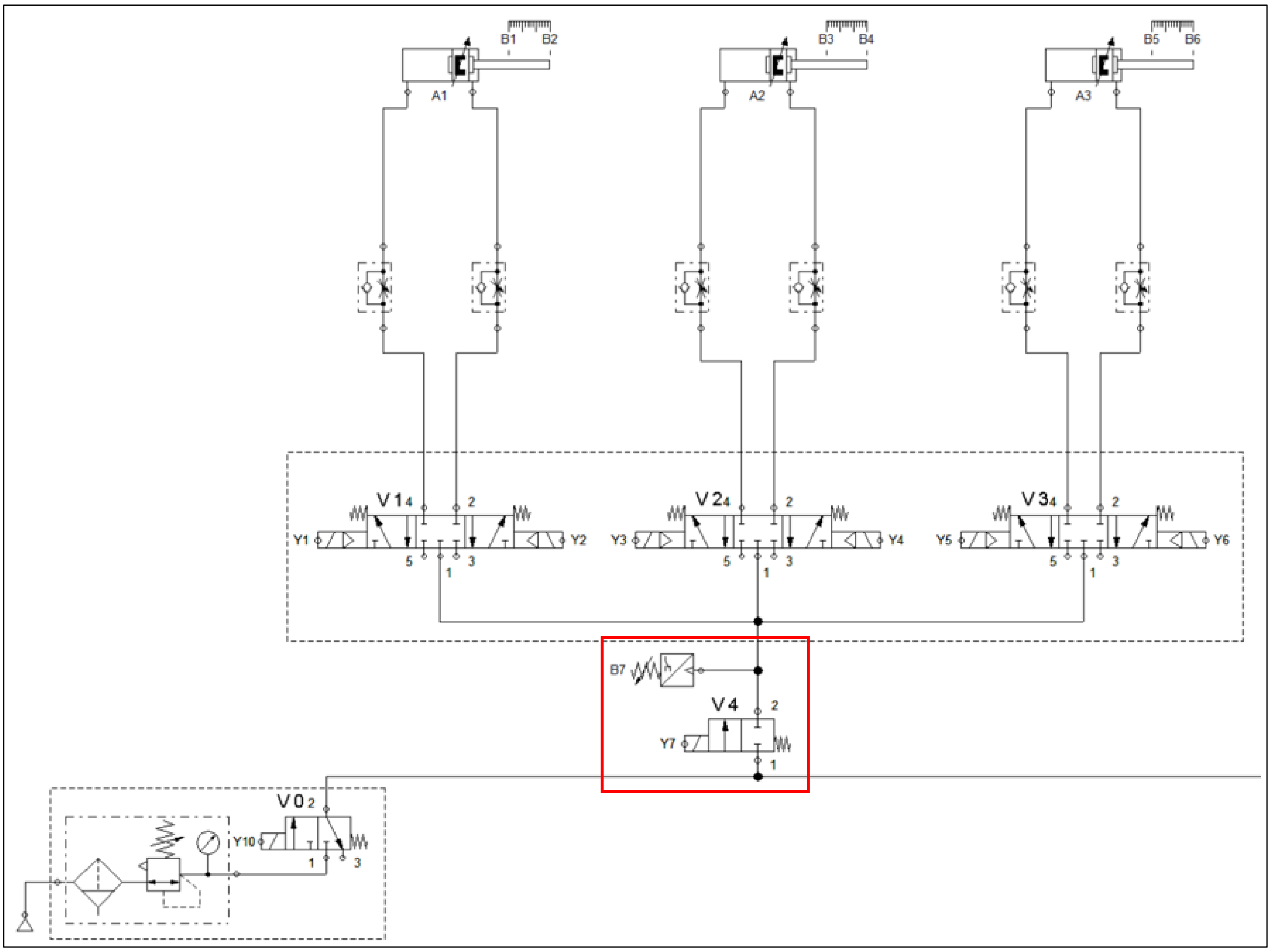

Fig. 5. Diagram of the pneumatic system including the developed leak test solution

The operation of the developed solution consists in monitoring the pressure drop of compressed air in particular pipes supplying the working medium to the actuators. In this case, all valves in the monitored valve island are three-position valves, so there is no need to replace the solenoid valves controlling the individual actuators. The key element of the system is the 2/2 shut-off solenoid valve, located before the valve island. This solenoid valve, controlled by an electric signal, allows for quick shut-off of the air flow from the source to the system, which is important for monitoring the pressure in the system. An electronic adjustable pressure switch was placed between the shut-off valve and the analyzed valve island, allowing data to be sent to the PLC controller. A shut-off valve marked with the symbol V4 and an electronic adjustable pressure switch marked with the symbol B7 were installed before the valve island. These are the only changes that need to be made in the analyzed system.

Compressed air is supplied to the system from the plant's compressed air network and goes to the MSB4-1/4:C3:J1:D14-WP compressed air preparation unit from Festo. The compressed air flow in the system is controlled by five-way, three-position solenoid valves with central exhaust SY5400-5U1 from SMC, marked in the diagram with symbols V1, V2 and V3. Fig. 6 shows the valve terminal used in the system.

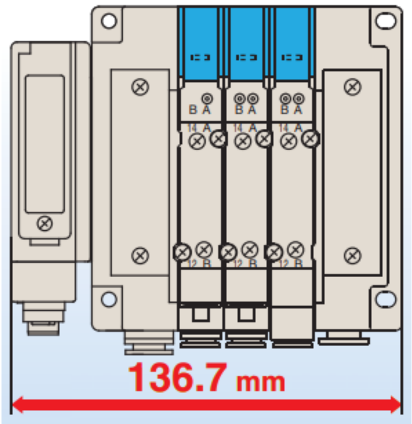

Fig. 6. The EX260 valve island from SMC used in the system

The plate solenoid valves are mounted on a valve island type EX260 from SMC containing 3 stations, controlled by means of a CC-Link communication module. In the diagram (Fig. 5), this island is marked with a rectangle of dashed lines.

For the purpose of cutting off the compressed air supply in the tested part of the system, the M21424V=-EL solenoid valve from PNEUER was used. This valve is marked in Fig. 6 with the symbol V4. To detect the position of the piston rod, there are used magnetic safety switches from ifm electronics MN508S–MN44008-AKOA/-H/US/8P. The sensors are attached to the machine structure and the actuators are mounted at the bottom of the gate. The main contacts of the switch are connected to the machine's safety system, and the auxiliary contacts are used to send information about the piston rod position to the PLC controller. The sensors are marked in the Fig. 5 with symbols B1-B6. A digital precision pressure sensor with a two-color display ISE30A-01-E from SMC is used to monitor the pressure value in the tested part of the system. The adjustable pressure switch is marked in the Fig. 5 with symbol B7. All electronic components are powered by 24V DC, and the pressure used in the system is within the working pressure range of all the elements used.

As part of the developed way, the leakage test of each actuator from a given valve island is carried out individually. When one of the actuators is tested, the solenoid valves of the other actuators should be in the initial position so as not to affect the measurement results.

A pressure drop in a given line will indicate a leak in the actuator, its connections, the line itself or the solenoid valve, in particular:

- a pressure drop in the fully retracted position will indicate an external leak and/or internal leak of the actuator,
- a pressure drop in the fully extended position will indicate an internal leak in the actuator,
- an equal pressure drop in both positions will indicate an internal leak in the actuator,
- a pressure drop in the fully retracted position greater than in the fully extended position will indicate an external leak and an internal leak of the actuator.

6. Simulation model of the leak testing system for pneumatic actuators

The verification of the developed leak detection way was based on the built simulation model of the system. It was used to carry out analytical part of the research. The model was prepared in the Matlab Simulink environment using the Simscape module and pneumatic system components. The created simulation model based on the pneumatic diagram from Fig. 5 is presented in Fig. 7.

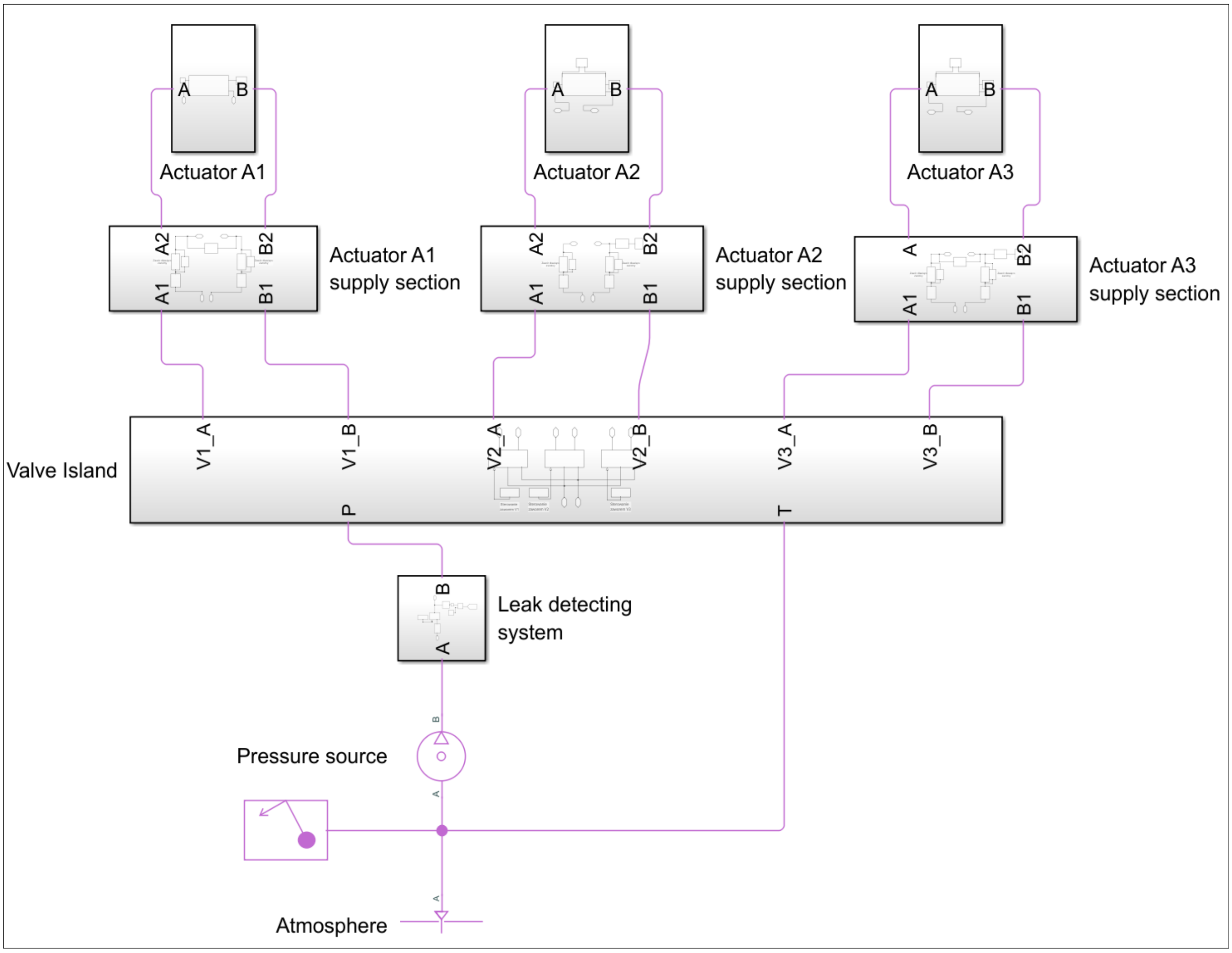

Fig. 7. Simulation model of the pneumatic actuator leak detection system

The model has been divided into 8 subsystems. The order of the subsystems is consistent with the flow of compressed air in the system: first, air is taken from the environment and compressed in the compressor, then it flows through the leak testing system to the valve island from where it is delivered to the appropriate actuators via their supply lines. Selected subsystems of the model are shown in Fig. 8.

The model was developed with the following parameters:

- pressure of compressed air: 4,2 (bar),
- diameters of connections and outer diameters of pneumatic pipes 8 (mm),
- internal diameters of pneumatic pipes 6 (mm),
- mounting of actuators in a vertical position with the piston rod pointing downwards,
- weight of each gate 14,5 (kg),
- the lengths of particular pneumatic lines: for the actuator A1: 5,5 (m) and 6,8 (m), for the actuator A2: 5 (m) and 6,3 (m) for the actuator A3: 4,5 (m) and 5,3 (m),
- the lengths of the pipes before the valve island have been omitted,
- pneumatic actuators: with a stroke 1300 (mm), piston diameter 32 (mm) and piston rod diameter 16 (mm).

Simulation analysis using the developed model requires identification of the position of the actuator control valve slide, the position of the shut-off valve slide, the position of the actuator piston rods and the pressure value in the system before the valve island after the shut-off valve. Additionally, a graph of the displacements of all actuators during the simulation is generated. The diagram of data acquisition and collection from the simulation process is shown in Fig. 9.

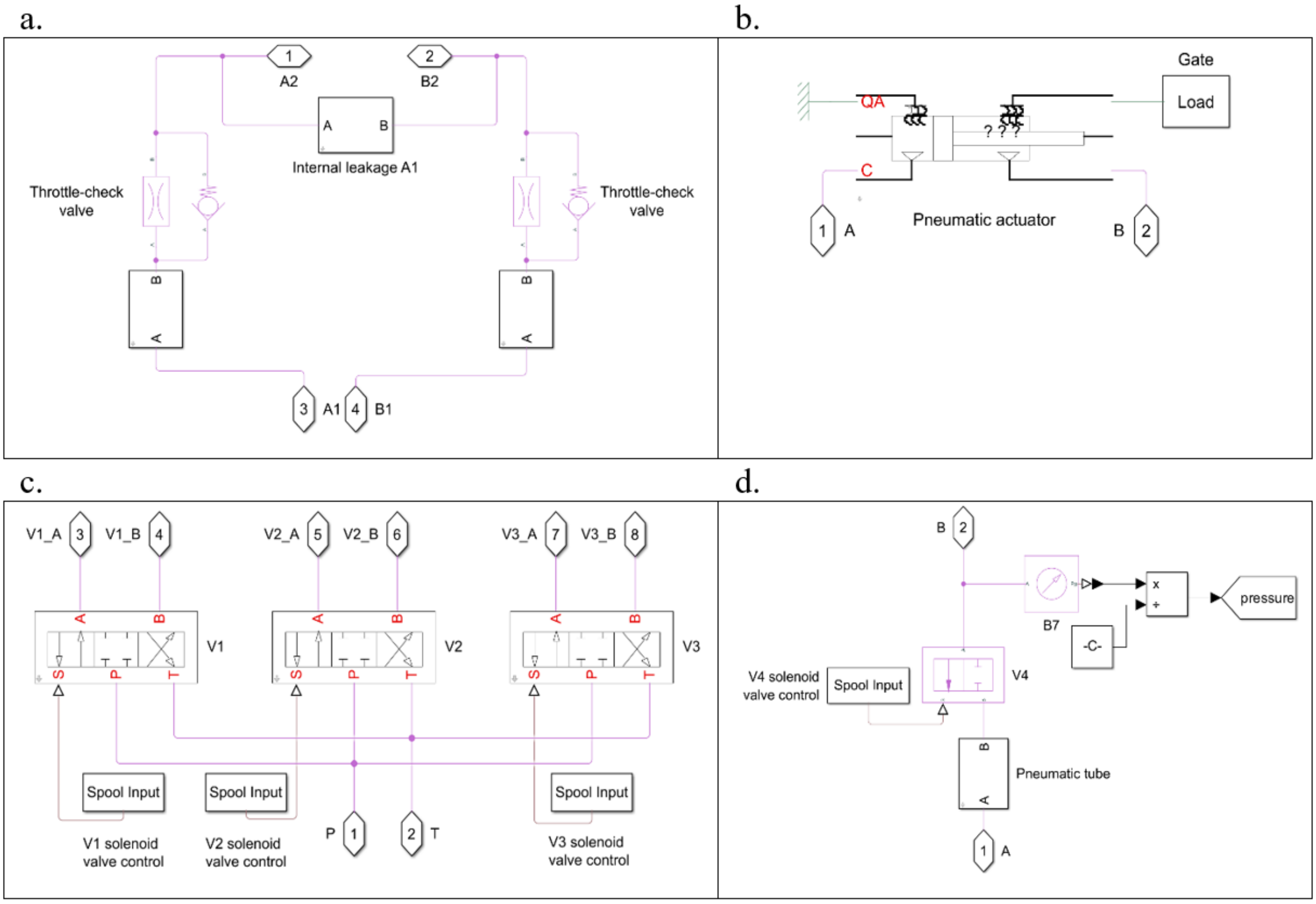

Fig. 8. Selected subsystems of the pneumatic actuator leak detection system: A1 actuator power supply subsystem, b. A1 pneumatic actuator subsystem, c. valve island subsystem, d. leak testing subsystem

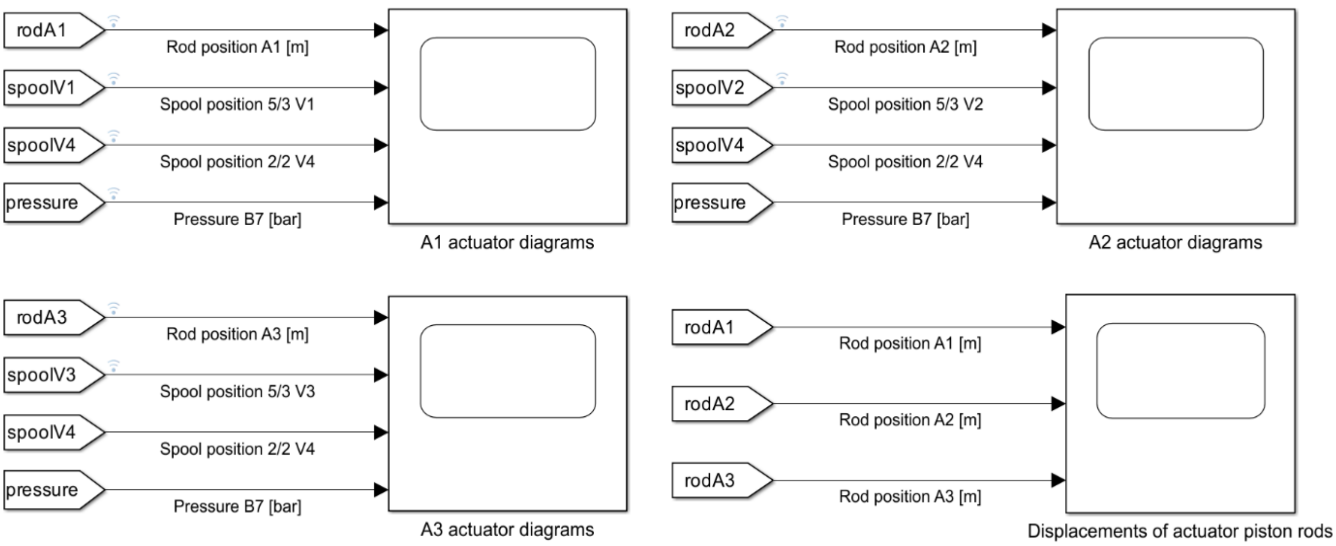

Fig. 9. The scheme of acquiring and collecting data from the simulation process

A Gantt chart showing the leak testing procedure for one actuator is shown in Fig. 10.

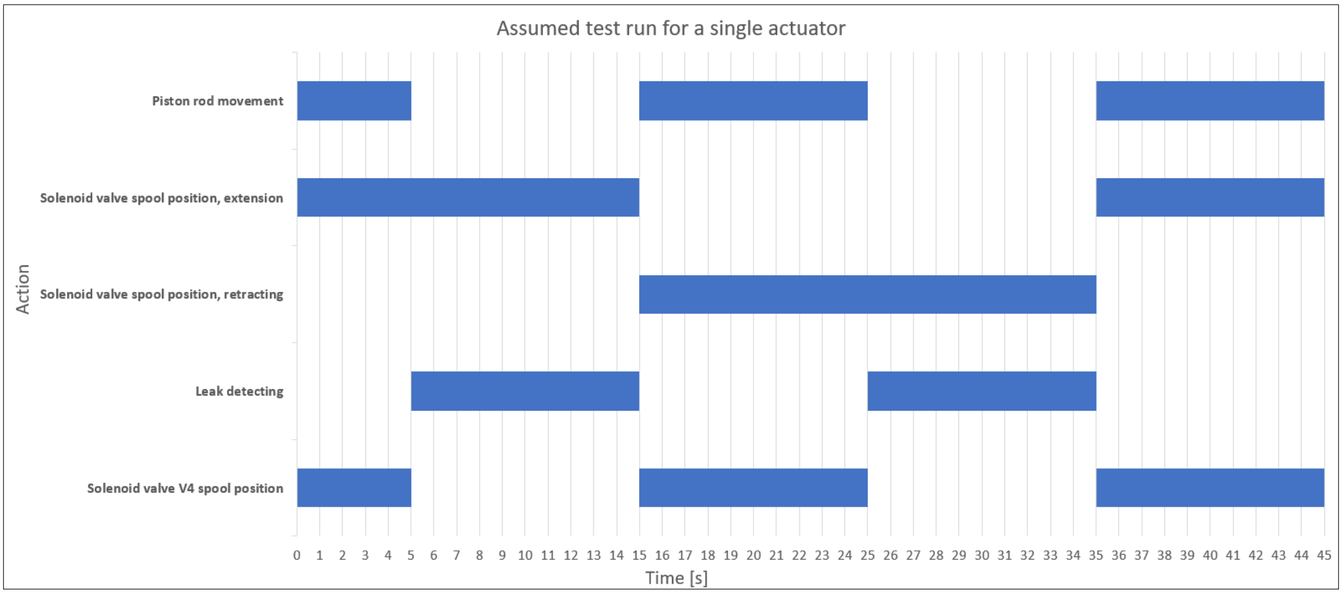

Fig. 10. Gantt chart of the leak test of one actuator

During the analysis, it was assumed that a leak requiring intervention by trained personnel was signalized by a pressure drop of 0.2 (bar) during the 10 (s) test period. After completing the test of one actuator, the described cycle was repeated for the next actuator. The total test time was 135 (s).

The visualization of selected results of the simulations is presented in Fig. 11.

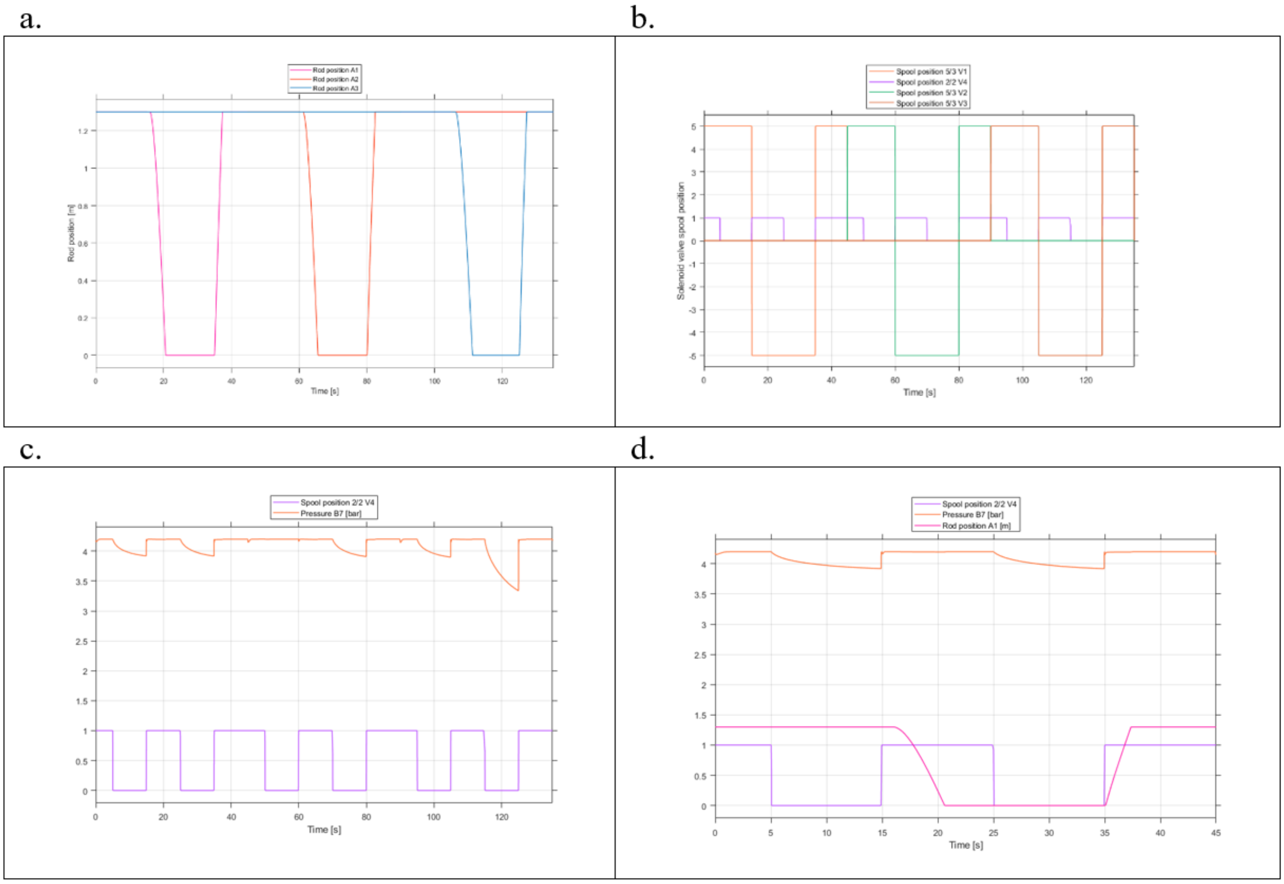

Fig. 11. Visualization of selected results of the simulation process

The values of the obtained pressure drops for each actuator in a given position are presented in Table 1. The leak diameter is one of the basic geometric measures of the size of a leak. It defines the reference diameter value of a circular surface corresponding to the surface of the real leak.

Table 1. The values of pressure drops of the actuators for individual leak diameters

Actuator	Pressure drop in the fully extended position [bar]				Pressure drop in the fully retracted position [bar]			
	Leak diameter [mm]							
	0,2	0,3	0,4	0,5	0,2	0,3	0,4	0,5
A1	0,01	0,03	0,11	0,28	0,01	0,03	0,11	0,28
A2	0,00	0,00	0,00	0,00	0,01	0,03	0,11	0,29
A3	0,01	0,03	0,11	0,30	0,02	0,11	0,38	0,86

The results obtained in the analysis are consistent with the assumptions, in particular:

- the pressure drop for actuator A1 was equal in both positions, which indicates an internal leak,
- the pressure drop for the A2 actuator was only in the extended position, which indicates an external leak,
- the pressure drop for the A3 actuator was greater in the extended position than in the retracted position, which indicates internal and external leakage.

7. Conclusions

The aim of the research conducted and presented in the article was to develop a way for detecting leaks in pneumatic actuators operating in production systems. The task was carried out on the example of a pallet loading station, where pneumatic actuators are used to open and close three gates through which pallets pass. These actuators are responsible for the operator's safety, and their failures are time-consuming due to the way they are installed.

The formulated goal was achieved through simulation studies based on the developed way and model prepared in the Matlab Simulink environment. A series of simulations were carried out for different sizes of internal and external leaks of the three tested pneumatic actuators. The obtained results allowed to confirm the operation of the developed leak detection system.

Leaks in actuators are a very common cause of their damage. Leaks in pneumatic cylinders do not always affect their cycle length, but they significantly affect the consumption of compressed air on the machine. Internal and external seals are the most sensitive elements in the construction of pneumatic actuators. Internal and external seals are the most sensitive elements in the construction of pneumatic actuators.

The developed leak detection way involves in measuring the pressure value in individual pneumatic actuator supply threads with the compressed air supply from the source cut off. The pressure drop in the system, its magnitude and the position of the piston rod in which it was detected, indicates the size of the leak and its location. The proposed solution allows for testing actuator leaks on the entire valve island using a single measurement point.

The duration of the test depends on the assumed accuracy of the detected leak. The longer the tightness is checked in a given part of the pneumatic system, the smaller the leak can be located. The disadvantage and at the same time the advantage of the presented concept is the fact that the detected leaks will be located not only in the actuator itself, but also at its connections, on pneumatic lines, throttle-return valves and solenoid valves themselves. Therefore, the exact location of this leak cannot be determined using this way, but it will allow to limit this place to a specific part of the pneumatic system. The duration of the test can be significantly reduced by testing several actuators simultaneously, provided that they can operate at the same time. If no pressure drop is detected, it can be assumed that there are no compressed air leaks in any of the tested locations in the system. Detection of a pressure drop during such a test may require testing of individual actuators individually or, for example, only half of the actuators. It should be taken into account that in the case of small leaks on several actuators, they may be detected by the system when testing multiple actuators at once, while when testing individual actuators, this drop may be small and may not be detected.

The pressure drops depend on the amount of air in the system. The analyzed actuators have a stroke of 1300 (mm), therefore the amount of air in the chamber is large and a small leak will cause a smaller pressure drop than in the case of the same leak in a smaller actuator.

The development of the solution is also possible by recording the collected data. Analysis of historical data will allow for determining the rate of wear of seals, as well as determining the pressure drop values at which failure occurs. Determining the limit pressure difference will allow for preventive replacement of actuators before the machine stops due to failure. The use of learning algorithms will also allow for faster data analysis and faster selection of alarm thresholds in the case of installation in other pneumatic systems.

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Original Research

ARTIFICIAL INTELLIGENCE-BASED DESIGN OF ASSEMBLIES IN THE FREECAD SOFTWARE

PROJEKTOWANIE ZŁOŻEŃ Z ZASTOSOWANIEM SZTUCZNEJ INTELIGENCJI W PROGRAMIE FREECAD

Roman WDOWIK[1,*], **Artur BEŁZO**[1]

[1] Department of Manufacturing Processes and Production Engineering, Rzeszów University of Technology, al. Powstańców Warszawy 12, Rzeszów, Poland

* Corresponding author: rwdowik@prz.edu.pl

Abstract

The article presents application of the FreeCAD software and generative artificial intelligence (AI) in the design process regarding exemplary mechanical engineering-related assemblies. Authors have studied how to support a product development and computer-aided (CAD) design phase by the use of generative pre-trained transformer (GPT). Prompting process, that lead to Python language-based code creation in the ChatGPT™ by OpenAI company, was studied from the perspective of 3D assemblies creation in the FreeCAD software. Moreover, authors studied how to improve the basic 3D models by the use of text-based prompts and CAD user improvements of the solid models and discussed the general effectiveness of this approach. It was also separately studied how to automate creation of many parts of the same type by the use of the AI, and apply such CAD libraries in the developed assemblies. The performed research presented selected possibilities of AI-based design process, challenges of the design process and future areas of investigation of AI-based assembly development resulting from the usage of existing GPTs.

Keywords: artificial intelligence, assembly development, fixtures, manufacturing, CAD

Streszczenie

Artykuł przedstawia zastosowanie programu FreeCAD oraz generatywnej sztucznej inteligencji (SI) w procesie opracowywania przykładowych złożeń. Autorzy badali jak wspierać etap projektowania części w zakresie modelowania wspomaganego komputerowo (CAD), wykorzystując do tego celu generatywny wstępnie wyuczony model językowy (GPT). Zbadano proces tworzenia promptów w usłudze ChatGPT™ firmy OpenAI prowadzący do wygenerowania w tym środowisku kodu w języku Python dla potrzeb generowania złożeń 3D w programie FreeCAD. Analizowano także jak ulepszyć bazowe modele 3D przez zastosowanie dodatkowych promptów oraz bezpośrednich zmian wykonanych przez użytkownika z zastosowaniem istniejących narzędzi CAD oraz ogólną efektywność takiego podejścia. Omówiono także oddzielnie jak zautomatyzować opracowywanie wielu części tego samego typu przez zastosowanie sztucznej inteligencji oraz jak wykorzystać takie biblioteki CAD w rozwijanych złożeniach. Wykonane prace uwidoczniły wybrane możliwości modelowania wspomaganego sztuczną inteligencją, wyzwania tego procesu i przyszłe kierunki badań dotyczących projektowania złożeń przez zastosowanie istniejących modeli językowych sztucznej inteligencji.

Słowa kluczowe: sztuczna inteligencja, projektowanie złożeń, uchwyty, wytwarzanie, CAD

1. Introduction

The design process of various fixtures such as chucks, vises, clamps, etc. plays a crucial role in modern manufacturing environments. The fixtures are designed to secure a machined part during the manufacturing process that generates forces which must be transferred by the fixture in order to protect a part from unnecessary displacements. The above-mentioned design process requires designer's skills,

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appropriate design tools and technological knowledge. Nowadays, the most of the design activities are performed by the use of the 3D CAD software (three-dimensional computer-aided design software) tools which are available for manufacturing firms. The developments in the area of software have changed the design techniques a lot. For instance drawing boards, being utilized in the past, have been replaced by the abovementioned CAD software. Most of them are commercial tools licensed for the final users but also some open-access (free of charge) tools are available. The fixture design requires an analysis of factors linked to the quality of clamped and manufactured parts, cost effective fixture manufacturing process planning and fixture designing and other crucial factors influencing the effectiveness of the entire manufacturing process. In this context, authors selected an open-access software such as FreeCAD stable version 1 (FreeCAD, 2024) to discuss the artificial intelligence (AI) selected applications in the product development process. Accessibility of the Python console in the FreeCAD software and the great progress regarding that software capabilities convinced authors to focus on the presented study.

Nowadays, AI and AI-based tools are becoming very popular among scientists and they promise a game changing perspective in the area of production challenges such as Industry 4.0 challenges (Sarker, 2024). Large Language Models (LLMs) using generative pre-trained transformer (GPT) such as ChatGPT™ by OpenAI (ChatGPT, 2024) or Copilot™ by Microsoft (Copilot, 2024) or Gemini™ by Google (Gemini, 2024) enable to redefine selected design approaches and develop methodologies improving the overall design process in CAD environments. The FreeCAD software offers the abovementioned tool available for a user that enables to create a Python language-based code which can be directly used for the solid models design needs. The tool implemented in the software is a Python console activated from the main menu: *View\Panels*. If that tool is combined with existing generative artificial intelligence-based tools such as text chats enabling to create Python code, the design process has a potential to be aided, however, the methodology of such design process, difficulties linked to it have not been studied so far.

In this context, authors decided to study selected areas linked to the AI-based assembly creation in the FreeCAD software that may contribute to design process improvements and gaining new knowledge in that area.

Currently literature analysis linked to that approach is limited as it was mentioned above, however, several authors tried to initiate the academic discussion in that area. For instance, Badagabettu et al. in their work (Badagabettu et al., 2024) presented Query2CAD, a novel architecture that returns a CAD model similar to the user's prompt. Deng et al. (Deng et al., 2024) from Cranfield University tested LLM for creation of CAD models (simple assemblies of gears) in OpenSCAD software. Hunde and Woldeyohannes (Hunde and Woldeyohannes, 2024) discussed perspectives of implementation AI into CAD environments. Moreover, Kapsalis (Kapsalis, 2024) demonstrated Natural Language Processing for 3D Modelling to Enhance Computer-Aided Design Workflows. In addition, Li and co-authors (Li et al., 2024) presented Multi-Modal Large Language Models for 3D Computer-Aided Design Generation.

In this context, the proposed topic of the paper is an actual research problem in authors' opinion and methodology of AI-based fixture design and analysis of exemplary results shall be indicated as main areas of the study.

2. Methodology of AI-based fixture design in the FreeCAD

This chapter presents the methodology behind the 3D assembly design by the use of the ChatGPT™ and the FreeCAD software having implemented the Python console. Moreover it presents and discusses the basic methodology on how to implement the changes required to adjust the basic 3D models to the design and technological requirements.

The AI-based modelling is supported by the text prompting, Python language-based code creation by the ChatGPT™ and its final running in the FreeCAD software that starts the adjustment processes using available CAD tools. The chapter is divided into a design testing phase and a design improvement phase.

2.1. Testing phase

The first attempts concerned creation of simple prompts in order to verify how detailed are existing knowledge and capabilities of the text LLM about the typical construction details of selected assemblies. This phase is important in authors opinion because it reveals the general problems related to CAD modelling automation by the use of AI.

In this context, only a general request was send to the chat to generate simple assemblies such as a three-jaw chuck having application on turning machines and also for clamping axisymmetric parts on other types of machine tools, a turning tool holder that is applied to clamp a turning insert that cuts material, screw-nut-wrench assembly as a typical assembly, assembly of two gears and vise (Figure 1).

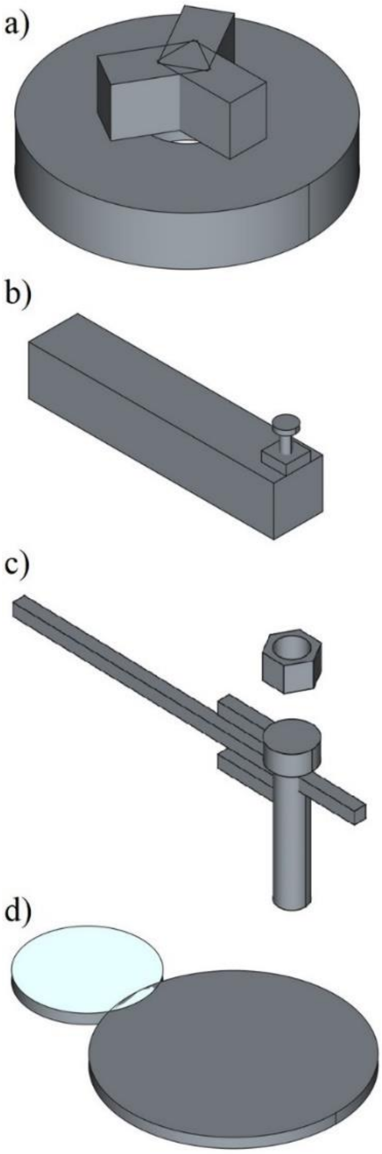

Fig. 1. Selected assemblies created on the basis of simple prompts and the ChatGPT™ text responses – print screens captured in the FreeCAD environment: a) 3-jaw chuck, b) turning tool holder, c) wrench-screw-nut, d) pair of gears

For example, an exemplary simple prompt regarding tool holder was created and run in the ChatGPT™ from the developed text (prompts were tested in Polish language):

Create a lathe tool consisting of a holder, an insert and a mounting screw.

This text request of authors (and similar requests regarding other assemblies) triggered the LLM and generated a Python language-based code.

In some cases (e.g. in the case of screw-nut-wrench assembly) authors requested some small changes such as an additional request (reprompting) regarding improvement to the hexagonal shape of the nut.

The results were recorded as **.FCstd* files – default format of the FreeCAD software. The abovementioned exemplary CAD 3D models generated in the FreeCAD software are presented here without any further changes as print screens saved in the working area of the FreeCAD environment.

It is clearly visible in the Figure 1 that only a few similarities can be indicated if the obtained visual result of the abovementioned parts is compared to the real objects known in the manufacturing environments. For instance, a jaw chuck (Figure 1a) has a correct general shape of its body (real jaw chucks which are used e.g. in lathes have cylindrical bodies) and general orientation of jaws is also correct in that case. In the case of tool holder (Figure 1b) the shapes and locations of elements are correct but they have no detailed geometrical features. Also, a screw-nut and a wrench models (Figure 1c) have some similarities to the real objects, however, the worst result was obtained in the case of a wrench geometry in authors' opinion which is not sufficiently similar to the real wrenches and also there is no thread generated on the screw, and the screw's head has only a general shape correctly generated. The gear wheels (Figure 1d) have a cylindrical shape which corresponds to the real gears and their position (one to the other) is correctly generated but there is no details such as teeth, central hole necessary to place a wheel on a shaft, etc.

The testing phase indicated that at this stage of LLM models development chats are able to create FreeCAD-related Python code that can generate simple objects but their correctness may depend on the prompting phase and still cannot propose very detailed and production-ready CAD models.

In the next stage of the research authors decided to create more structured prompts in order to ask about more detailed geometrical and functional properties of the generated solid models.

The Table 1 was designed to provide the detailed description of each assembly. The indicators presented in the Table 1 were developed to create the final more detailed prompt. Each prompt linked to one assembly contained descriptions from all the rows in the column entitled *Description.* They were copied to the ChatGPT™ in order to obtain the Python language-based code. The codes, similarly to the previous attempts were run in the FreeCAD. At this stage authors focused on three different assemblies: a vise, a screw-nut assembly and a jaw chuck assembly.

Table 1. Indicators involved in the prompts

Designation	Indicator name	Description
D	Dimensions	Dimensions of parts and assembly such and length. height, thickness, etc.
L	Layout and constraints	Description of location of parts within the assembly, e.g. how one part is placed within the assembly.
N	Number of elements	Number of single elements, mainly if the number of similar parts is greater than 1.
G	Geometry of elements	Description of geometry such as its shape.
F	Functionalities	Description of functionalities such as how single parts influence the exploitation of the entire assembly, for instance: description of movements of parts or the applications linked to specific machined parts, etc.

The following paragraphs present the prompts developed on the basis of indicators in the table and used to generate 3D models. In some cases correcting prompts were also sent to the ChatGPT™ to achieve a better result compared to the result obtained on the basis of the first prompt. These correcting prompts are also presented in the subchapter.

Exemplary prompt for a vise

Generate a code which will be used in the Python console in the FreeCAD software and will help to create an assembly of the vise.
(D) *The vise shall have a length of 200 mm, a width of 80 mm and a total height of 80 mm.*
(L) *The vise shall have a base element to which 1 stationary and 1 movable jaw are fixed. The stationary jaw is secured by the use of screws on one side of the base, while the movable jaw is guided by the use of guides located on the base and on the jaw. Moreover, a screw is fixed to the movable jaw at one of screw sides and this screw goes through a nut which is fixed to the base on the opposite side (opposite to the stationary jaw location) of the base.*
(N) *5 solid models are included within the assembly in total.*
(G) *The base has a shape of a cuboid – a block. The jaws have the same shape as the base. The nut has a shape of a block with a threaded hole parallel to the screw axis. The screw has a shape of a cylinder.*
(F) *The jaws shall secure a machined part. The screw rotation around its axis shall move the movable jaw along the base of the vise, however, the nut is a stationary element.*

Correcting prompt: *The screw shall go through the center of the nut, be parallel to the longer side of the base. The nut shall have a threaded hole.*

The result obtained in the FreeCAD software is presented in the Figure 2.

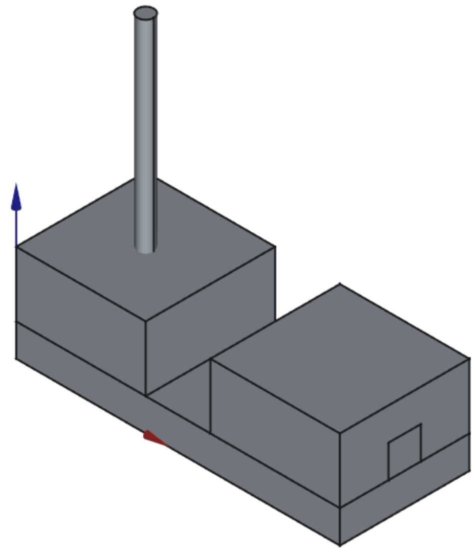

Fig. 2. An AI-supported vise model obtained in the FreeCAD software

Exemplary prompt for a screw-nut assembly

Generate a code which will be used in the Python console in the FreeCAD software and will help to create a screw-nut assembly.
(D) *The screw-nut assembly shall have a length of 100 mm in total (total length of the screw including its head). A diameter of the screw shall be 12 mm. The same diameter shall be created for threaded hole of the nut. The head of the screw shall have a height of 10 mm.*
(L) *The nut shall be screwed onto the screw.*
(N) *Number of solid models equals two – the first one is the screw model and the nut model is the second one.*
(G) *The head of the screw shall have the shape of a regular hexagonal prism. The nut shall also have the shape of a regular hexagonal prism.*
(F) *The final model represents the screw-nut assembly. The screw is screwed onto the nut.*

Correcting prompt 1: *Nut and screw shall be separate parts.*
Correcting prompt 2: *Nut shall be located in the center of the screw.*
Correcting prompt 3: *Nut shall have thicker wall.*

The Figure 3 presents the result obtained in the FreeCAD software.

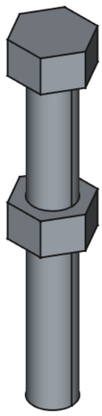

Fig. 3. An AI-supported screw-nut assembly obtained in the FreeCAD software

Prompt for a 3-jaw chuck

Generate a code which will be used in the Python console in the FreeCAD software and will help to create a 3-jaw chuck assembly.
(D) *A chuck diameter is 150 mm and its height is 80 mm. Each of three jaws has a length of 40 mm, a height of 20 mm and a width of 20 mm.*
(L) *The three jaws lay on the face of a cylinder representing the chuck body. They are placed every 120 degrees around the axis of the chuck.*
(N) *The number of solid models in the assembly is four – body and three jaws.*
(G) *The body of the chuck is a cylinder. The jaws are cuboids.*
(F) *The jaws may be translated to the axis of the chuck. This enables to clamp a machined part.*

The Figure 4 presents the result. In fact, after sending a few correcting prompts (6 in total) that were following the abovementioned main prompt, the result presented in the Figure 4 was the best one compared to the 3-jaw chucks existing in the real manufacturing environments.

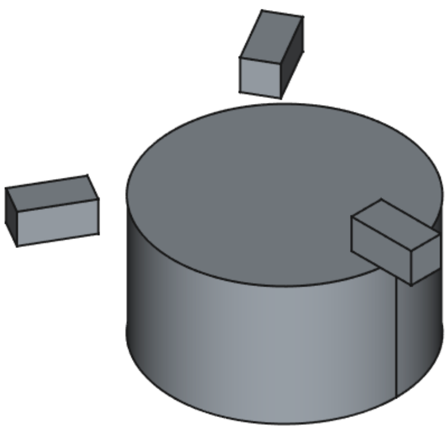

Fig. 4. An AI-supported 3-jaw chuck model obtained in the FreeCAD software

It can be stated now that a fully correct result of AI-aided modelling is still not reached. Only in the case of the screw-nut assembly the correct result was reached (please refer to the Figure 3).

The entire testing phase proved that some very general shapes and dimensions are generated according to designer's needs and ideas. In this context further improvements are necessary to be added. Authors also verified generated models' dimensions required in the prompts by using existing measure tool of the CAD environment and it can be stated that they were generated correctly as requested in the prompts.

In the conclusion of this subchapter, it can be stated that the required general shapes of separate elements in the assemblies are generated correctly, and the dimensions are also properly created, however, the position of elements or features (e.g. the threaded hole in the case of the nut of the vise) should be improved. Moreover, no detailed features (e.g. thread on the screw) were generated. In fact a person who writes a prompt does not know the result that will be created by the ChatGPT™ and this is quite disappointing for a designer but clear from the scientific point of view. In authors opinion this observation may define the nature of human and artificial intelligence collaboration concept. In this context, the final results (final outputs) of any intelligence work cannot be precisely predicted even if they are expected. However, AI-created (or human) outputs may be improved by other designers or other AI-based tools.

The currently verified concept presented in the previous sentence, proposed after completion of the studied examples during the testing phase, shifted the research to the next step that is focused on further improvement of initial results.

2.2. Improvement phase

This subchapter presents further methodology on the steps that can be completed in order to obtain the detailed models that meet requirements of designers.

Several possible approaches are possible to be applied and tested:

1. Further correcting prompts designing and expecting the better final results after a text-based talk with the ChatGPT™.
2. Manual (based on a designer actions) correction of the Python language-based code.
3. Manual correction of the best of all obtained 3D models using existing CAD tools in the FreeCAD or another CAD software.

Authors selected one type of the part (3 jaw chuck) and presented how a designer can proceed. Similar approaches can be applied in the case of other assemblies.

2.2.1. Further correcting prompts application

Further correcting prompts may lead to selected improvements of models geometry. Authors requested the ChatGPT™ for further improvements such as creation of T slots or more detailed geometry of the jaws. However, they found it very difficult to obtain the detailed final model efficiently. A designer shall consider if an effort put into the design by the use of prompts is effective or maybe another approach can be used. One of the results obtained after the correcting prompts application is presented in the Figure 5. It can be stated that positioning of geometrical features is reachable, however, it also requires additional workload which can be replaced by the direct modelling using CAD tools.

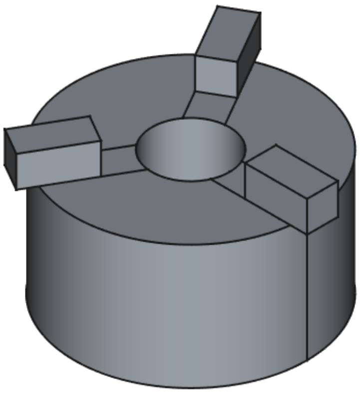

Fig. 5. An AI-supported 3 jaw chuck CAD model improved by the use of correcting prompts

2.2.2. Manual correction of Python language-based code

Manual correction of the Python code seems to be another possible solution. Nevertheless, looking from the perspective of a CAD tool accessibility and workload for a designer, in authors' opinion, the better results can be reached easily by the use of approach presented in point 2.2.3. However, in some cases selected values or single rows of the Python code may be changed to improve the result. There is also a good practice to ask in the prompt for additional comments to understand better and faster how every single command works. From the perspective of improvement phase, if a designer decides to rewrite the entire Python code because the basic one does not meet requirements, it means that there is a necessity to design the part from the beginning using the Python nomenclature.

2.2.3. Manual correction of 3D models in CAD environment

This approach enabled to complete detailed changes and the final obtained result is probably the best if a model is compared to chucks existing in the real manufacturing environments. In this case the AI helped to obtain simple cylinder and a block that were redesigned by the use of CAD tools. The final result is presented in the Figure 6. Authors have not implemented all the details, however, they presented that manual redesign is easier to be implemented in the case of detailed part's features. In this context, existing (traditional) CAD design methodology and tools still are very efficient.

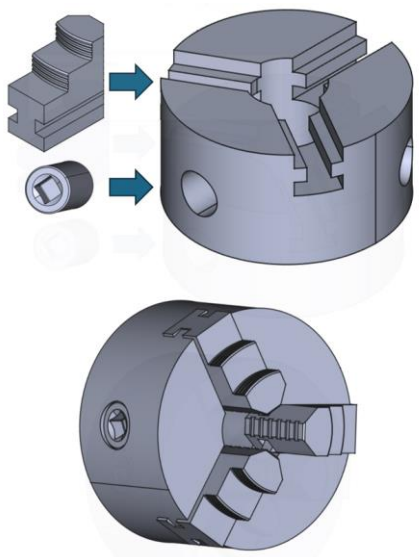

Fig. 6. A 3 jaw chuck CAD assembly model improved manually by a designer by the use of traditional CAD tools

3. Automated design of simple parts of the same type

The usage of part libraries in modern CAD environments is a standard procedure leading to faster creation of complex assemblies by using standard parts such as bearings, screws, rings, etc. Due to the best results (previously verified) regarding AI-aided creation of simple geometries such as a screw-nut assembly, authors developed that concept and studied if the ChatGPT™ can create a useful Python-based code that can be applied in the FreeCAD environment in order to generate a set of simple solid models in the chosen folder saved on the PC hard drive.

The basic prompt was as follows:

Generate code for the FreeCAD software Python console that will create hexagonal head screws having thread diameter of 12 mm. Length of the screws shall start from 10 mm to 500 mm long, in 10 mm increments. In total 50 screws shall be created. Let each solid model be saved in a folder entitled 'screws' created on the D drive of the PC.

Figure 7 presents the screw having the total length of 500 mm displayed in the FreeCAD environment after implementation of the Python code generated by the ChatGPT™ and selected from the created library. Verification of requested dimensions (requested by authors) by the use of existing CAD tools has also a positive output. Both length and diameter of screw were correctly generated. The Figure 8 presents the final code generated in the ChatGPT™ environment that is a result of the basic (first) and the second prompt. The first attempt caused an error and the ChatGPT™ explained that App.pi and related trigonometric functions (cosine and sine) were incorrectly referenced. The second attempt ended up correctly and 50 solid models were saved in the indicated folder on the drive of used PC.

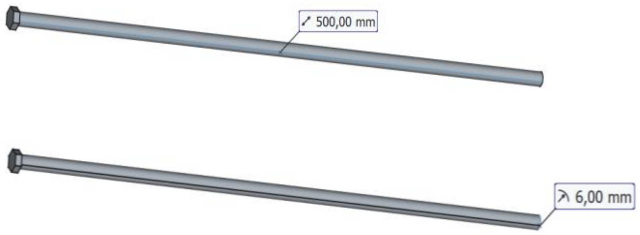

Fig. 7. Exemplary screw having length of 500 mm and diameter (2 x radius) of 12 mm – FreeCAD preview

The code enabled to create 50 solid models in 'screw' folder located on local drive. It is presented in Figure 9. Authors decided to generate by the ChatGPT™ support also 10 additional nuts having different heights ranging from 5 to 55 mm. The final result of prompting and generated Python code implementation in the FreeCAD environment is presented in the Figure 10 (An exemplary nut having diameter of threaded hole 12 mm and total length of 55 mm is presented).

These two examples indicated that using the ChatGPT™ in the case of libraries that consist of simple 3D models at this stage of LLM development can be successfully applied in the CAD libraries development and applications. It shall be also stated that the verified libraries of standard parts are also a very reliable solution when special parts are assembled in CAD environments and AI-support may play a significant role in that area.

```python
import FreeCAD as App
import Part
import os

# Create the folder to store screws
output_folder = "D:/screws"
os.makedirs(output_folder, exist_ok=True)

def create_hexagonal_head_screw(thread_diameter, length):
    # Create a new document
    doc = App.newDocument()

    # Create the shaft of the screw
    shaft = Part.makeCylinder(thread_diameter / 2, length)

    # Create the hexagonal head
    hex_radius = thread_diameter * 0.75
    hex_thickness = thread_diameter * 0.5
    hexagon = Part.makePolygon([
        App.Vector(hex_radius * cos(angle), hex_radius * sin(angle), length)
        for angle in [i * 2 * App.pi / 6 for i in range(7)]
    ])
    hexagon_face = Part.Face(hexagon)
    hexagon_solid = hexagon_face.extrude(App.Vector(0, 0, hex_thickness))

    # Combine shaft and hexagonal head
    screw = shaft.fuse(hexagon_solid)

    # Add the screw to the document
    doc.addObject("Part::Feature", "Screw").Shape = screw
    doc.recompute()

    return doc

# Parameters
thread_diameter = 12  # mm
min_length = 10  # mm
max_length = 500  # mm
step_length = 10  # mm

# Generate screws
for length in range(min_length, max_length + 1, step_length):
    doc = create_hexagonal_head_screw(thread_diameter, length)
    file_path = os.path.join(output_folder, f"hex_screw_{length}mm.FCStd")
    doc.saveAs(file_path)
    print(f"Saved: {file_path}")

print("All screws generated and saved.")
```

Fig. 8. The final Python code used for screw library development created by the ChatGPT™ on the basis of prompt

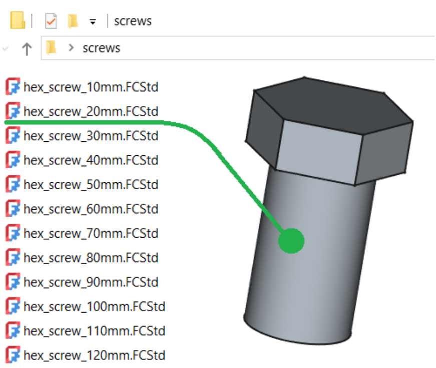

Fig. 9. Print screen of screw library in folder on the D drive of PC (Folder in Windows 10™ by Microsoft operating system)

Fig. 10. Exemplary nut – FreeCAD preview

4. Conclusions

The study focused on the analysis of CAD design of assemblies supported by the use of artificial intelligence. In authors opinion, the AI-based modelling of fixture assemblies is a promising approach having a great potential in the future of manufacturing. Automation of such design processes will probably help to decrease the overall design time. However, at this stage of AI developments there is still a need for improving LLM models in order to obtain better output code. Authors share a similar opinion often presented by researchers and top developers in the area of AI indicating that there is a need for prompting research. However, the analysis presented possibilities of the FreeCAD software combined with the ChatGPT™ by OpenAI and helped to obtain general information about the expected complexity of models that could be generated by the use of AI in a way that requires only minor changes to the basic CAD models. It also presented that a quite simple geometries can be correctly generated at this stage.

Moreover, creating 3D CAD models libraries is a very promising concept that can be simply and directly implemented in CAD designers work.

The work presented the results that extend an overall knowledge in the area of assembly design and possible applications of LLM models for CAD design at this stage of their development.

General attempts (based on authors observation) that have been made to make a quantitative comparison of research results by comparing the time of generating CAD models using AI and traditional methods are strongly linked to the authors skills. The effectiveness of using AI depends on the details of the prompts too. Authors suppose that the more accurate they are, the greater the efficiency of generating CAD models. The problem concerns their proper formulation and a lack of knowledge regarding their interpretation by the LLM. For this reason, in authors opinion, it is difficult to determine the time it will take to build a CAD model using AI. In the case of manual (traditional) modelling it mostly depends on CAD software and also on a CAD user skills. The study has shown that AI can support designer's work regarding creation of large number of repeatable solids, with simple and similar shapes. It definitely saves designer's time. Manual modelling in this case would certainly be time-consuming. While prompting methods are being improved and LLMs too, the designers should expect better LLMs efficiency and accuracy of AI-generated models. This will be the subject of further research together with application of other software tools (e.g. Python-based environments using dedicated Python libraries without the typical CAD software usage) and implementation in the real CAD project. Moreover, the results obtained in various chats may also be compared and discussed.

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Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the Foundation for the Development of the Education System. Neither the European Union nor the Foundation for the Development of the Education System can be held responsible for them.

The results of this paper will be used in the international trainings for students developed within the abovementioned project. They also contribute the research-based education.

Artificial intelligence (AI) usage statement

The generative AI (ChatGPT™ by OpenAI) was used only to generate a Python code on the basis of prompts created by authors. Generated Python code lines were run in the FreeCAD software. All sentences in the paper were developed by authors without AI assistance, excluding the fact that we checked "a" and "the" articles in authors' prompts and translated a few words from Polish into English by the use of the ChatGPT™.

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