

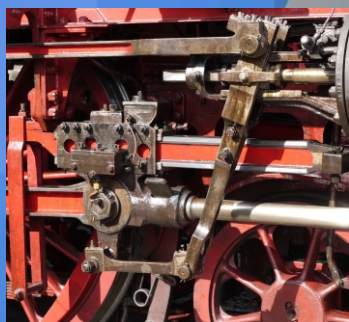
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Determination of the stress-strain state of an aircraft wing twisted around its spar

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Abstract: This article examines the stiffness calculations for a wing pre-twisted relative to its spar. Such wings can be used in experimental aircraft to study changes in their aerodynamic properties during flight testing at various twist angles. Such variable-geometry wings require comprehensive investigation using strength of materials and elasticity theory. This problem is fundamental to the structural mechanics of aircraft.

Keywords: WING, TWIST, DEGREE OF TWIST, LIFT, DISPLACEMENT, SECTION, BENDING MOMENT.

1. Introduction

Efficient flight of any aircraft requires changes in the aerodynamic parameters of the aircraft's performance depending on the mission and flight conditions. The traditional approach to designing new aircraft currently allows only minor (no more than 1–2%) improvements in lift-to-drag ratio and takeoff and landing performance. Wing mechanization, such as simple deflectable leading and trailing edges or sweepback adjustments, does not allow for high maximum lift coefficients to be achieved under varying operating conditions.

Therefore, in recent years, with the development of technical know-how and the emergence of new aviation materials, increasing attention has been paid to improving aircraft aerodynamic performance by altering wing geometry depending on the flight conditions—the use of adaptive wings. Adaptation of the aircraft's lifting system can be achieved by changing the span and sweepback of the wing, as well as the shape and twist of the wing relative to its spar.

In the presented work, the enterprise, based on the application of modern methods of calculating the strength and rigidity in different sections of the wing of such a design, determines the set of those permissible maximum effective in different sections of the wing that can, with high reliability, ensure the required stringent conditions of the customer according to the specified parameters for different stages of flight.

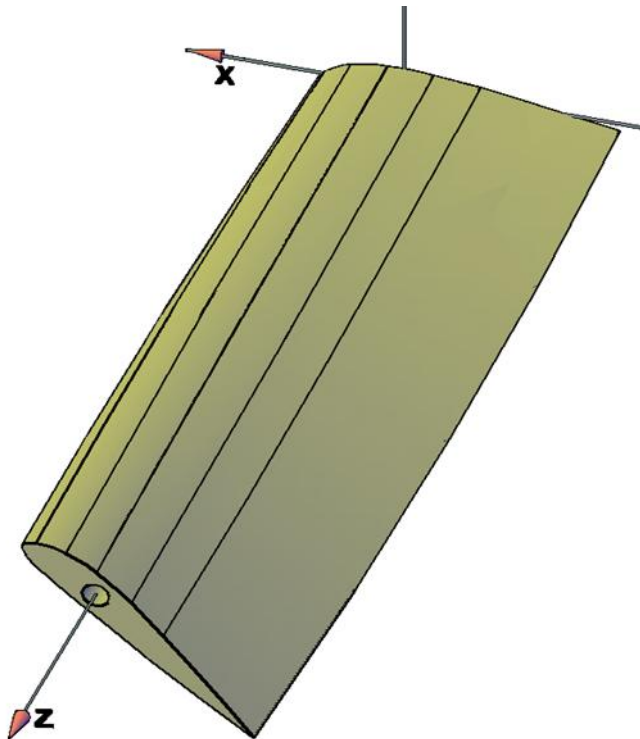


Fig. 1 General appearance of a twisted wing.

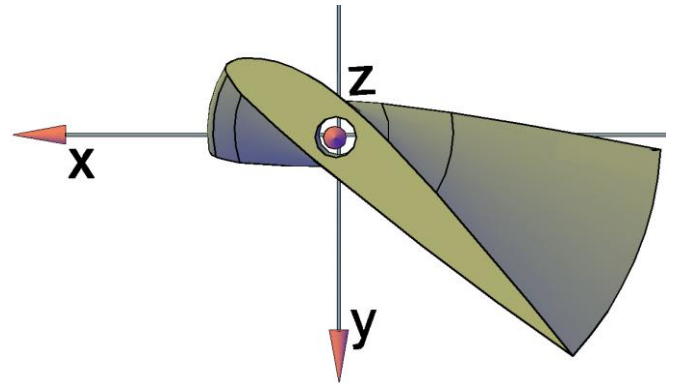


Fig. 2 View of the wing from the free edge.

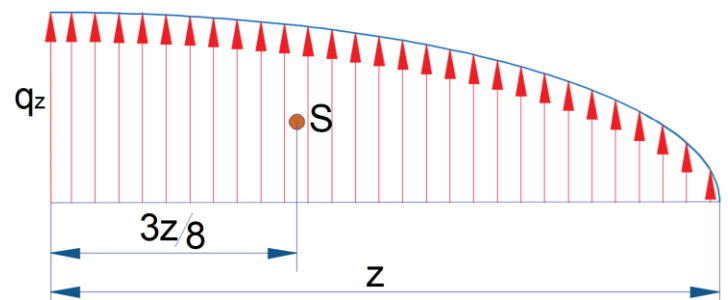


Fig. 3 The type of distributed load acting on the wing, which changes according to a parabolic law.

A twisted wing with a lenticular cross-section (Fig. 1) is loaded along its span by two distributed loads acting in mutually perpendicular planes Oxz and Oyz , which vary according to a parabolic law (Fig. 3). Its geometric shapes and dimensions, as well as the mechanical parameters of its cross-section, are predetermined: I_x , I_y — are the moments of inertia of the section, l is the wing length, E is the modulus of elasticity of the rod material, q_1 is the parabolically distributed load acting in the Oyz plane, and q_2 is the parabolically distributed load acting in the Oxz plane.

To determine the displacements of the twisted wing tip, we use Mohr's formula. First, we obtain the dependences of the bending moments in an arbitrary cross-section on the action of applied parabolically distributed loads q_1 and q_2 and unit forces $F_{1x} = 1N$, $F_{1y} = 1N$ applied to the end section. In an arbitrary cross-section, oblique bending occurs in all loading cases.

The bending moment from a distributed load in an arbitrary cross-section is determined by the formula:

$$M_q = \omega \cdot \frac{3z}{8} = \frac{2qz^{\frac{3}{2}}}{3\sqrt{l}} \cdot \frac{3z}{8} = \frac{qz^{\frac{5}{2}}}{4\sqrt{l}} \quad (1)$$

On the coordinate axes associated with the wing section, the bending moment from the external load acting in this section is projected using the following formulas:

$$\begin{aligned} M_{1x_i} &= M_1 \cdot \cos(90^\circ + \varphi) + M_2 \cdot \cos(180^\circ - \varphi) = \\ &= M_1 \cdot (-\sin\varphi) + M_2 \cdot (-\cos\varphi) = \\ &= \frac{q_1 \cdot z^{\frac{5}{2}}}{4\sqrt{l}} \cdot (-\sin\varphi) + \frac{q_2 \cdot z^{\frac{5}{2}}}{4\sqrt{l}} \cdot (-\cos\varphi) \end{aligned} \quad (2)$$

$$\begin{aligned} M_{y_i} &= M_1 \cdot \cos\varphi + M_2 \cdot (-\sin\varphi) = \frac{q_1 \cdot z^{\frac{5}{2}}}{4\sqrt{l}} \cdot \cos\varphi + \\ &+ \frac{q_2 \cdot z^{\frac{5}{2}}}{4\sqrt{l}} \cdot (-\sin\varphi); \end{aligned} \quad (3)$$

Bending moments from unit loads applied at the end of the wing are projected onto the same axis associated with the section using the following formulas:

$$M_{1x_i}^h = z \cdot (-\sin\varphi); \quad M_{1y_i}^h = z \cdot \cos\varphi; \quad (4)$$

$$M_{1x_i}^v = z \cdot (-\cos\varphi); \quad M_{1y_i}^v = z \cdot (-\sin\varphi); \quad (5)$$

To determine the displacement along the Oy axis, we write Mohr's formula in the following form:

$$\Delta_y = \int_0^l \frac{M_{x_i} M_{1x_i}^h}{EI_{x_i}} dz + \int_0^l \frac{M_{y_i} M_{1y_i}^h}{EI_{y_i}} dz; \quad (6)$$

To solve this expression, the integrals included in it must be solved separately, for which it is necessary to replace the variable according to the following formulas:

$$z = \frac{6l}{\pi} \varphi, \quad dz = \frac{6l}{\pi} d\varphi \quad (7)$$

Since the wing tip rotates by 30° at maximum twist in the case we are considering, the integration limits are taken from 0 to $\pi/6$.

Then the first integral from expression (6) is calculated as follows:

$$\begin{aligned} \int_0^l \frac{M_{x_i} M_{1x_i}^h}{EI_{x_i}} dz &= \int_0^l \frac{\left[\frac{q_1 \cdot z^{\frac{5}{2}}}{4\sqrt{l}} \cdot (-\sin\varphi) + \frac{q_2 \cdot z^{\frac{5}{2}}}{4\sqrt{l}} \cdot (-\cos\varphi) \right] \cdot z \cdot (-\sin\varphi)}{EI_{x_i}} dz = \\ &= \int_0^l \frac{\frac{q_1 \cdot z^{\frac{7}{2}}}{4\sqrt{l}} \cdot \sin^2 \varphi + \frac{q_2 \cdot z^{\frac{7}{2}}}{4\sqrt{l}} \cdot \cos\varphi \sin\varphi}{EI_{x_i}} dz = \end{aligned}$$

$$\begin{aligned} &= \int_0^{\pi/6} \frac{\left(\frac{6l}{\pi} \varphi \right)^{\frac{7}{2}} \cdot q_1}{4EI_{x_i} \sqrt{l}} \cdot \sin^2 \varphi \cdot \frac{6l}{\pi} d\varphi + \\ &+ \int_0^{\pi/6} \frac{\left(\frac{6l}{\pi} \varphi \right)^{\frac{7}{2}} \cdot q_2}{4EI_{x_i} \sqrt{l}} \cdot \cos\varphi \sin\varphi \cdot \frac{6l}{\pi} d\varphi = \\ &= \int_0^{\pi/6} \frac{\left(\frac{6l}{\pi} \cdot \varphi \right)^{\frac{7}{2}} \cdot q_1}{4EI_{x_i} \sqrt{l}} \cdot \sin^2 \varphi \cdot \frac{6l}{\pi} d\varphi + \\ &+ \int_0^{\pi/6} \frac{\left(\frac{6l}{\pi} \cdot \varphi \right)^{\frac{7}{2}} \cdot q_2}{4EI_{x_i} \sqrt{l}} \cdot \cos\varphi \sin\varphi \cdot \frac{6l}{\pi} d\varphi = \\ &= \int_0^{\pi/6} \frac{\left(\frac{6l}{\pi} \right)^{\frac{9}{2}} \varphi^{\frac{7}{2}} \cdot q_1}{4\pi EI_{x_i} \sqrt{l}} \cdot \sin^2 \varphi d\varphi + \\ &+ \int_0^{\pi/6} \frac{\left(\frac{6l}{\pi} \right)^{\frac{9}{2}} \varphi^{\frac{7}{2}} \cdot q_2}{4\pi EI_{x_i} \sqrt{l}} \cdot \cos\varphi \sin\varphi \cdot d\varphi = \\ &= \frac{\left(\frac{6l}{\pi} \right)^{\frac{9}{2}} \cdot q_1}{4\pi EI_{x_i} \sqrt{l}} \int_0^{\pi/6} \varphi^{\frac{7}{2}} \cdot \sin^2 \varphi d\varphi + \\ &+ \frac{\left(\frac{6l}{\pi} \right)^{\frac{9}{2}} \cdot q_2}{4\pi EI_{x_i} \sqrt{l}} \int_0^{\pi/6} \varphi^{\frac{7}{2}} \cdot \cos\varphi \sin\varphi \cdot d\varphi \end{aligned} \quad (8)$$

The second integral from expression (6) is calculated as follows:

$$\begin{aligned} \int_0^l \frac{M_{y_i} M_{1y_i}^h}{EI_{y_i}} dz &= \int_0^l \frac{\left[\frac{q_1 \cdot z^{\frac{5}{2}}}{4\sqrt{l}} \cdot \cos\varphi + \frac{q_2 \cdot z^{\frac{5}{2}}}{4\sqrt{l}} \cdot (-\sin\varphi) \right] \cdot z \cdot \cos\varphi}{EI_{y_i}} dz = \\ &= \int_0^l \frac{\frac{q_1 \cdot z^{\frac{7}{2}}}{4\sqrt{l}} \cdot \cos^2 \varphi - \frac{q_2 \cdot z^{\frac{5}{2}}}{4\sqrt{l}} \cdot \cos\varphi \sin\varphi}{EI_{y_i}} dz = \\ &= \frac{\left(\frac{6l}{\pi} \right)^{\frac{9}{2}} \cdot q_1}{4\pi EI_{y_i} \sqrt{l}} \int_0^{\pi/6} \varphi^{\frac{7}{2}} \cdot \cos^2 \varphi d\varphi - \end{aligned}$$

$$-\frac{\left(\frac{6l}{\pi}\right)^{\frac{9}{2}} \cdot q_2}{4\pi EI_{y_i} \sqrt{l}} \int_0^{\pi/6} \varphi^{\frac{7}{2}} \cdot \cos\varphi \sin\varphi \cdot d\varphi \quad (9)$$

By summing up the results obtained from these integrals, we obtain an expression for determining the displacement of the end of a twisted wing along the Oy axis:

$$\begin{aligned} \Delta_y &= \int_0^l \frac{M_{x_i} M_{1x_i}^h}{EI_{x_i}} dz + \int_0^l \frac{M_{y_i} M_{1y_i}^h}{EI_{y_i}} dz = \\ &= \frac{\left(\frac{6l}{\pi}\right)^{\frac{9}{2}} \cdot q_1}{4\pi EI_{x_i} \sqrt{l}} \int_0^{\pi/6} \varphi^{\frac{7}{2}} \cdot \sin^2 \varphi d\varphi + \\ &+ \frac{\left(\frac{6l}{\pi}\right)^{\frac{9}{2}} \cdot q_2}{4\pi EI_{x_i} \sqrt{l}} \int_0^{\pi/6} \varphi^{\frac{7}{2}} \cdot \cos\varphi \sin\varphi \cdot d\varphi + \\ &+ \frac{\left(\frac{6l}{\pi}\right)^{\frac{9}{2}} \cdot q_1}{4\pi EI_{y_i} \sqrt{l}} \int_0^{\pi/6} \varphi^{\frac{7}{2}} \cdot \cos^2 \varphi d\varphi - \\ &- \frac{\left(\frac{6l}{\pi}\right)^{\frac{9}{2}} \cdot q_2}{4\pi EI_{y_i} \sqrt{l}} \int_0^{\pi/6} \varphi^{\frac{7}{2}} \cdot \cos\varphi \sin\varphi \cdot d\varphi = \\ &= \frac{\left(\frac{6l}{\pi}\right)^{\frac{9}{2}} \cdot q_1}{4\pi EI_{x_i} \sqrt{l}} 0,0021 + \frac{\left(\frac{6l}{\pi}\right)^{\frac{9}{2}} \cdot q_2}{4\pi EI_{x_i} \sqrt{l}} \cdot 0,0045 + \\ &+ \frac{\left(\frac{6l}{\pi}\right)^{\frac{9}{2}} \cdot q_1}{4\pi EI_{y_i} \sqrt{l}} 0,0099 - \frac{\left(\frac{6l}{\pi}\right)^{\frac{9}{2}} \cdot q_2}{4\pi EI_{y_i} \sqrt{l}} \cdot 0,0045 \end{aligned} \quad (10)$$

To determine the displacement along the Ox-axis, we write Mohr's formula in the following form:

$$\Delta_x = \int_0^l \frac{M_{x_i} M_{1x_i}^v}{EI_{x_i}} dz + \int_0^l \frac{M_{y_i} M_{1y_i}^v}{EI_{y_i}} dz; \quad (11)$$

Proceeding in a similar manner to the previous one, calculations are made for the first integral of the expression:

$$\begin{aligned} \int_0^l \frac{M_{x_i} M_{1x_i}^v}{EI_{x_i}} dz &= \int_0^l \frac{(M_1 \cdot (-\sin\varphi) + M_2 \cdot (-\cos\varphi)) z \cdot (-\cos\varphi)}{EI_{x_i}} dz = \\ &= \int_0^l \frac{q_1 \cdot z^{\frac{7}{2}}}{4\sqrt{l}} \cdot \cos\varphi \sin\varphi + \frac{q_2 \cdot z^{\frac{7}{2}}}{4\sqrt{l}} \cdot \cos^2 \varphi}{EI_{x_i}} dz = \end{aligned}$$

$$\begin{aligned} &= \frac{\left(\frac{6l}{\pi}\right)^{\frac{9}{2}} \cdot q_1}{4\pi EI_{x_i} \sqrt{l}} \int_0^{\pi/6} \varphi^{\frac{7}{2}} \cdot \cos\varphi \sin\varphi d\varphi + \\ &+ \frac{\left(\frac{6l}{\pi}\right)^{\frac{9}{2}} \cdot q_2}{4\pi EI_{x_i} \sqrt{l}} \int_0^{\pi/6} \varphi^{\frac{7}{2}} \cdot \cos^2 \varphi d\varphi \end{aligned} \quad (12)$$

For the second integral of expression (11) we will have:

$$\begin{aligned} \int_0^l \frac{M_{y_i} M_{1y_i}^v}{EI_{y_i}} dz &= \\ &= \int_0^l \frac{[M_1 \cdot \cos\varphi + M_2 \cdot (-\sin\varphi)] \cdot z \cdot (-\sin\varphi)}{EI_{y_i}} dz = \\ &= \int_0^l \frac{q_1 \cdot z^{\frac{7}{2}}}{4\sqrt{l}} \cdot (-\cos\varphi \sin\varphi) + \frac{q_2 \cdot z^{\frac{7}{2}}}{4\sqrt{l}} \cdot \sin^2 \varphi}{EI_{y_i}} dz = \\ &= - \int_0^{\pi/6} \frac{q_1 \cdot z^{\frac{7}{2}}}{4\sqrt{l}} \cdot \cos\varphi \sin\varphi \cdot \frac{6l}{\pi} d\varphi + \\ &+ \int_0^{\pi/6} \frac{\left(\frac{6l}{\pi} \cdot \varphi\right)^3 \cdot q_2}{4 EI_{y_i}} \cdot \sin^2 \varphi \cdot \frac{6l}{\pi} d\varphi = \\ &= - \frac{\left(\frac{6l}{\pi}\right)^{\frac{9}{2}} \cdot q_1}{4\pi EI_{y_i} \sqrt{l}} \int_0^{\pi/6} \varphi^{\frac{7}{2}} \cdot \cos\varphi \sin\varphi d\varphi + \\ &+ \frac{\left(\frac{6l}{\pi}\right)^{\frac{9}{2}} \cdot q_2}{4\pi EI_{y_i} \sqrt{l}} \int_0^{\pi/6} \varphi^{\frac{7}{2}} \cdot \sin^2 \varphi d\varphi \end{aligned} \quad (13)$$

By summing up the results obtained from these integrals, we obtain an expression for determining the displacement of the end of a twisted wing along the Ox axis:

$$\begin{aligned} \Delta_x &= \int_0^l \frac{M_{x_i} M_{1x_i}^v}{EI_{x_i}} dz + \int_0^l \frac{M_{y_i} M_{1y_i}^v}{EI_{y_i}} dz = \\ &= \frac{\left(\frac{6l}{\pi}\right)^{\frac{9}{2}} \cdot q_1}{4\pi EI_{x_i} \sqrt{l}} \int_0^{\pi/6} \varphi^{\frac{7}{2}} \cdot \cos\varphi \sin\varphi d\varphi + \\ &+ \frac{\left(\frac{6l}{\pi}\right)^{\frac{9}{2}} \cdot q_2}{4\pi EI_{x_i} \sqrt{l}} \int_0^{\pi/6} \varphi^{\frac{7}{2}} \cdot \cos^2 \varphi d\varphi - \\ &- \frac{\left(\frac{6l}{\pi}\right)^{\frac{9}{2}} \cdot q_1}{4\pi EI_{y_i} \sqrt{l}} \int_0^{\pi/6} \varphi^{\frac{7}{2}} \cdot \cos\varphi \sin\varphi d\varphi + \end{aligned}$$

$$\begin{aligned}
 & + \frac{\left(\frac{6l}{\pi}\right)^{\frac{9}{2}} \cdot q_2}{4\pi EI_{y_i} \sqrt{l}} \int_0^{\pi/6} \varphi^{\frac{7}{2}} \cdot \sin^2 \varphi d\varphi = \\
 & = \frac{\left(\frac{6l}{\pi}\right)^{\frac{9}{2}} \cdot q_1}{4\pi EI_{x_i} \sqrt{l}} 0,0045 + \frac{\left(\frac{6l}{\pi}\right)^{\frac{9}{2}} \cdot q_2}{4\pi EI_{x_i} \sqrt{l}} \cdot 0,0099 - \\
 & - \frac{\left(\frac{6l}{\pi}\right)^{\frac{9}{2}} \cdot q_1}{4\pi EI_{y_i} \sqrt{l}} 0,0045 + \frac{\left(\frac{6l}{\pi}\right)^{\frac{9}{2}} \cdot q_2}{4\pi EI_{y_i} \sqrt{l}} \cdot 0,0021
 \end{aligned} \quad (14)$$

The total displacement of the end of a twisted wing is obtained by summing the displacements found:

$$\Delta = \sqrt{\Delta_x^2 + \Delta_y^2} \quad (15)$$

To determine the normal stress in any section of the wing in the formulas for bending moments from transverse loads relative to the axes $O_i x_i$ and $O_i y_i$, it is necessary to replace the variable in the following way:

$$z = \frac{6l}{\pi} \varphi; \quad \varphi = \frac{\pi}{6l} z; \quad (16)$$

Relative to the $O_i x_i$ - axis, the bending moment will have the form:

$$\begin{aligned}
 M_{1x_i} &= M_1 \cdot (-\sin \varphi) + M_2 \cdot (-\cos \varphi) = \\
 &= -\frac{q_1 \cdot z^{\frac{5}{2}}}{4\sqrt{l}} \cdot \sin \frac{\pi}{6l} z - \frac{q_2 \cdot z^{\frac{5}{2}}}{4\sqrt{l}} \cdot \cos \frac{\pi}{6l} z
 \end{aligned} \quad (17)$$

The formula determining the moment of inertia of the wing section relative to the axis $O_i x_i$ will be:

$$I_{\text{mp}x_i} = \sum_{i=1}^n F_{\text{imp}} \cdot x_i^2; \quad (18)$$

The formula determining the moment of resistance of the wing section relative to the same axis $O_i x_i$ will be:

$$W_{x_i} = \frac{\sum_{i=1}^n F_{\text{imp}} \cdot x_i^2}{y_{\text{max}}}; \quad (19)$$

The normal stress from this bending moment is found using the formula:

$$\begin{aligned}
 \sigma_{x_i} &= \frac{M_{x_i}}{W_{x_i}} = \frac{-M_1 \cdot \sin \frac{\pi}{6l} z - M_2 \cdot \cos \frac{\pi}{6l} z}{\frac{\sum_{i=1}^n F_{\text{imp}} \cdot x_i^2}{y_{\text{max}}}} = \\
 &= -y_{\text{max}} \cdot \left(\frac{q_1 \cdot z^{\frac{5}{2}}}{4\sqrt{l}} \cdot \sin \frac{\pi}{6l} z + \frac{q_2 \cdot z^{\frac{5}{2}}}{4\sqrt{l}} \cdot \cos \frac{\pi}{6l} z \right) / \sum_{i=1}^n F_{\text{imp}} \cdot x_i^2;
 \end{aligned} \quad (20)$$

Relative to the $O_i y_i$ - axis, the bending moment will have the form:

$$\begin{aligned}
 M_{y_i} &= M_1 \cdot \cos \varphi + M_2 \cdot (-\sin \varphi) = \\
 &= \frac{q_1 \cdot z^{\frac{5}{2}}}{4\sqrt{l}} \cdot \cos \frac{\pi}{6l} z - \frac{q_2 \cdot z^{\frac{5}{2}}}{4\sqrt{l}} \cdot \sin \frac{\pi}{6l} z;
 \end{aligned} \quad (21)$$

The formula determining the moment of inertia of the wing section relative to the $O_i y_i$ axis will be:

$$I_{\text{mp}y_i} = \sum_{i=1}^n F_{\text{imp}} \cdot y_i^2; \quad (22)$$

The formula determining the moment of resistance of the wing section relative to the same axis $O_i y_i$ will be:

$$W_{y_i} = \frac{\sum_{i=1}^n F_{\text{imp}} \cdot y_i^2}{x_{\text{max}}}; \quad (23)$$

The normal stress from this bending moment is found using the formula:

$$\begin{aligned}
 \sigma_{y_i} &= \frac{M_{y_i}}{W_{y_i}} = \frac{M_1 \cdot \cos \frac{\pi}{6l} z - M_2 \cdot \sin \frac{\pi}{6l} z}{\frac{\sum_{i=1}^n F_{\text{imp}} \cdot y_i^2}{x_{\text{max}}}} = \\
 &= \frac{x_{\text{max}} \cdot \left(\frac{q_1 \cdot z^{\frac{5}{2}}}{4\sqrt{l}} \cdot \cos \frac{\pi}{6l} z - \frac{q_2 \cdot z^{\frac{5}{2}}}{4\sqrt{l}} \cdot \sin \frac{\pi}{6l} z \right)}{\sum_{i=1}^n F_{\text{imp}} \cdot y_i^2}
 \end{aligned} \quad (24)$$

The total normal stress acting in an arbitrary section of a twisted wing is obtained by summing the previously obtained stresses:

$$\begin{aligned}
 \sigma_z &= \sigma_{x_i} + \sigma_{y_i} = \frac{M_{x_i}}{W_{x_i}} + \frac{M_{y_i}}{W_{y_i}} = \\
 &= \frac{x_{\text{max}} \cdot \left(\frac{q_1 \cdot z^{\frac{5}{2}}}{4\sqrt{l}} \cdot \cos \frac{\pi}{6l} z - \frac{q_2 \cdot z^{\frac{5}{2}}}{4\sqrt{l}} \cdot \sin \frac{\pi}{6l} z \right) - y_{\text{max}} \cdot \left(\frac{q_1 \cdot z^{\frac{5}{2}}}{4\sqrt{l}} \cdot \sin \frac{\pi}{6l} z + \frac{q_2 \cdot z^{\frac{5}{2}}}{4\sqrt{l}} \cdot \cos \frac{\pi}{6l} z \right)}{\sum_{i=1}^n F_{\text{imp}} \cdot x_i^2 + \sum_{i=1}^n F_{\text{imp}} \cdot y_i^2}
 \end{aligned} \quad (25)$$

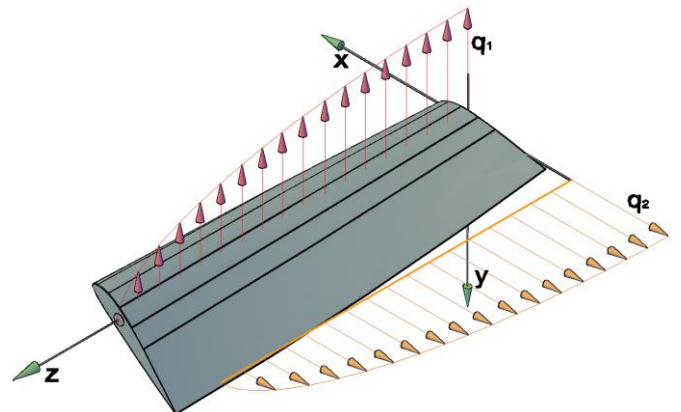


Fig. 4. Distributed loads acting on the wing in mutually perpendicular planes

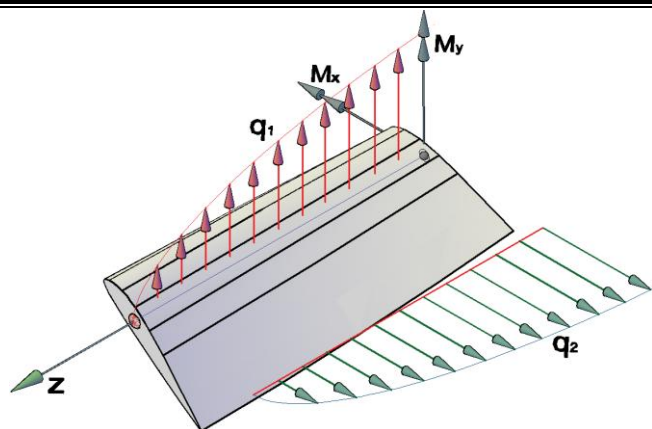


Fig. 5 Loads acting on the left part of the wing after cutting off the right part using a cross section.

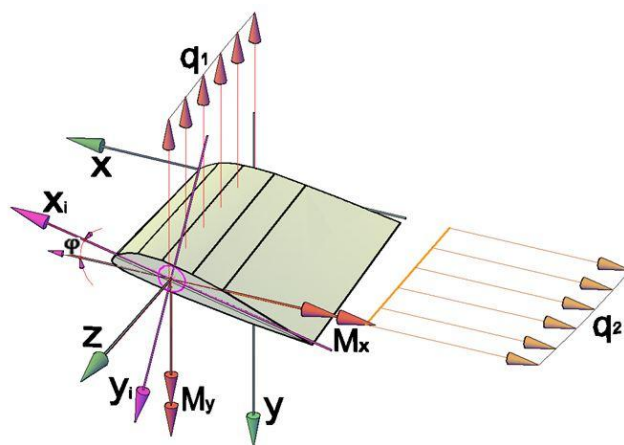


Fig. 6 Loading diagram of the cut-off right part.

Conclusion

Future experimental aircraft may be equipped with variable-geometry wings. The components of such wings operate under conditions of force interaction with other structural components. Such interactions can cause deformations of these components, which in turn can generate additional normal and shear stresses that can exceed permissible values, leading to component failure and wing and, consequently, aircraft failure.

Calculating the strength and rigidity of such wings is a pressing problem in modern mechanics. In this paper, we present one example of a solution to this problem.

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Industry 4.0-Focused Dynamic Tension Control in Wet Wipe Production: Development of Automatic Braking and Accumulation System

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Abstract: In roll-to-roll systems like wet wipe production, the synchronous and smooth unwinding of the web material with constant tension is critical for product quality and production efficiency. Traditional constant belt braking mechanisms cause tension issues due to varying bobbin diameter and friction-induced heating, leading to web undulations, stretching, and breaks in sensitive materials such as wetlace. To overcome these operational challenges, an automatically controlled braking and accumulator system has been developed. The system instantly measures product tension by monitoring web position using a laser ruler and dynamically adjusts the pneumatic brake force via a high-frequency PID algorithm updated every 5 milliseconds. Furthermore, a constant pressure pneumatic piston acts as an accumulator, balancing the web's vertical movements and dampening instantaneous tension variations. This system, compliant with Industry 4.0 principles and based on real-time feedback, solves critical tension control problems, ensures continuity in product quality, and establishes a new concept that is a pioneering example in the global market.

Keywords: DYNAMIC TENSION CONTROL, AUTOMATIC BRAKING SYSTEM, WET WIPE PRODUCTION, INDUSTRY 4.0

1. Introduction

Wet wipe production involves a high-speed, continuous feeding process where achieving stable and precise tension in the raw material web (nonwoven or wetlace) during unwinding is paramount for process stability and product integrity [1]. The efficiency of the roll-to-roll system relies on accurate control of speed, position, and torque, which directly govern web tension [2].

1.1 Challenges in Wet Web Handling

Production lines frequently face challenges during machine start/stop cycles and instantaneous speed variations [3]. These dynamic transitions generate uncontrolled tension fluctuations, resulting in web undulations, stretching, and material breaks.

A. Material Viscoelasticity; The nonwoven and wetlace materials used in this sector exhibit distinct viscoelastic properties, differentiating them from dry paper or film [33, 38]. These materials possess significant internal damping but are also prone to creep and plastic deformation under sustained stress. This makes the tension control problem non-linear; the acceptable tension window is narrow, as over-tensioning causes permanent damage, while under-tensioning leads to wrinkling and steering issues [4].

B. Limitations of Conventional Braking; Existing control systems, typically relying on simple, constant belt braking mechanisms, are insufficient [3]. As the bobbin diameter decreases, the braking pressure must be dynamically reduced to maintain constant torque, a task fixed-mechanisms fail to execute. Furthermore, the resulting excessive friction leads to localized heating, which negatively affects the physical structure and saturation quality of the wet product, further exacerbating material failure [4].

1.2 Research Gaps and Paper Contribution

While extensive research exists on tension control systems using PID and adaptive control [5, 17, 27], a significant gap remains in addressing the combined challenges of: 1) High-frequency disturbance rejection in wet, viscoelastic webs; and 2) Integrating mechanical dampening with dynamic brake control within a single, autonomous Industry 4.0 framework. Previous solutions often relied solely on electrical motor control or simple mechanical dampers without real-time pneumatic actuation [20].

The primary contribution of this study is the development of an automatically controlled braking and accumulator system that uniquely integrates:

Non-Contact Sensing: Real-time, precise tension inference via a laser ruler.

High-Frequency Control: A PID control loop operating at 200 Hz for instantaneous torque adjustment.

Mechanical Filtering: A pneumatically actuated accumulator to isolate the web from transient disturbances.

This integrated approach represents a leap towards autonomous, self-regulating manufacturing systems, fully compliant with Industry 4.0 principles.

1.3 Outline of the Paper

This paper is structured as follows: Section 2 details the System Design and Methodology, focusing on the mathematical justification for the high-frequency control loop and the dynamics of the pneumatic accumulator. Section 3 presents the Results and Discussion, analyzing the system's performance in terms of quality continuity and defect reduction. Section 4 provides the Conclusion and highlights the system's status as a pioneering example in the global wet wipe market.

2. System Design and Methodology

The entire system design is governed by the philosophy of Decentralized Tension Control with Centralized Command, integrating high-frequency sensors, a real-time controller, and dynamic actuators [6]. This approach is mandatory due to the presence of both high-frequency disturbances (mechanical noise, roll eccentricity) and low-frequency transients (speed changes, diameter reduction), which necessitate two distinct control mechanisms: active actuation (Brake Control) and mechanical filtering (Accumulator) [20].

2.1 Dynamic Brake Control Unit (Tension Regulation)

The Control Unit utilizes a cascade control architecture, ensuring stability by continuously compensating for changes in roll diameter, inertia, and pneumatic actuation non-linearities [8, 9].

2.1.1 Real-Time Tension Measurement via Non-Contact Sensing

Web tension is inferred by monitoring the web's out-of-plane position (δ) using a laser ruler (distance sensor) [10, 11]. The primary motivation for using non-contact sensing is the preservation of the fragile, saturated web material [38].

The relationship between web sag (δ) and tension (T) in a horizontal span under the web's own weight per unit length (w) is

often approximated by the catenary equation, although simpler parabolic approximations are used in real-time control:

$$T \cong w L^2 / 8 \delta$$

where L is the span length [25]. The system converts the precise displacement signal (P_{web}) into a tension feedback signal (ΔT) for the controller. The laser's high sampling frequency is crucial to accurately capture the transient vertical oscillations caused by material eccentricity [30].

2.1.2 High-Frequency Adaptive PID Control

The core of the system is the PID control algorithm, which must compensate for the time-varying inertia (J) of the unwinding roll, where $J(R) \propto R^4$ [14].

The control signal $u(t)$ sent to the actuator is generated by the standard PID equation:

$$u(t) = K_p \cdot e(t) + K_i \int e(t) dt + K_d \{ de(t) / dt \}$$

Adaptive Strategy: Since the roll inertia decreases non-linearly, a fixed-gain PID would lead to instability or sluggish response at different diameters. Therefore, a gain-scheduled or adaptive PID strategy is implemented where the gains (K_p , K_i , K_d) are continuously adjusted as a function of the detected roll diameter or roll inertia [17, 27]. This ensures optimal damping and quick settling times throughout the entire unwinding phase [28].

High-Frequency Execution: The control loop executes at 200 Hz (every 5 milliseconds) [5]. This fast execution rate minimizes the phase lag within the control loop, which is critical for Active

Disturbance Rejection against high-frequency tension ripples and mechanical vibrations [14].

2.1.3 Dynamic Pneumatic Brake Actuation

The PID output is mapped directly to the pressure signal regulating the pneumatic brake force [16].

Actuator Modeling: Pneumatic actuators are subject to non-linearities, including dead zones (minimum pressure required to move the caliper) and hysteresis (dependence on the direction of pressure change) [32].

Linearization: The high-frequency controller incorporates a linearization look-up table and dynamic compensation to ensure that the brake's torque output (T_{brake}) is proportional to the command signal from the PID [32]. This meticulous compensation ensures the torque dynamically compensates for the changing radius (R) to maintain constant tension: $T_{brake}(t) = \text{Tension Setpoint} \cdot R(t)$.

2.2 Pneumatic Accumulator Mechanism (Tension Dampening)

The accumulator mechanism acts as a crucial mechanical filter and tension isolation unit, effectively mitigating the disturbances that the brake system cannot instantaneously suppress [19, 20].

2.2.1 Accumulator Dynamics and Isolation Principle

The accumulator is modeled as a second-order mass-spring system, where the pneumatic piston is the spring element [34].

Ideal Tension Equation: Under idealized low-friction conditions, the web tension (T) is determined solely by the pneumatic piston's load (L):

$$T_{ideal} = L / \{2 \cos(\alpha)\}$$

where 2α is the total wrap angle [35]. The continuous operation under constant pressure guarantees a theoretically fixed output tension [22].

Mechanical Buffer: The mechanism utilizes movable rollers opposed by constant pressure pneumatic pistons [21]. This vertical degree of freedom allows the web path length to dynamically absorb or release length, acting as a mechanical buffer against transient forces [42].

2.2.2 Dampening and Disturbance Frequency Filtering: A correctly tuned accumulator's low mechanical resonance frequency ensures it functions as an effective low-pass filter for tension disturbances originating from the unwinder (upstream) [41, 40]. This prevents the propagation of tension noise to the sensitive downstream sections.

Viscoelastic Compensation: The accumulator provides necessary mechanical compliance to manage the viscoelastic nature of the wet web material. It compensates for stress relaxation and creep by adjusting web length dynamically, preventing the material from reaching its plastic deformation limit during high-stress moments [38].

Control Synergy: The accumulator's position provides a secondary, slower feedback signal to the master line speed control, creating a holistic, stabilizing effect across the entire production line [24].

2.3 Instrumentation, Data Flow, and Safety Interlocks

The system's reliability stems from the synchronization of its digital control units and physical actuators, representing a true Cyber-Physical System (CPS) compliant with Industry 4.0 standards.

Data Acquisition (DAQ): The laser ruler sensor outputs its high-frequency position data (analog or digital) to the main Programmable Logic Controller (PLC) or a dedicated Motion Controller [26].

Control Loop Execution: The PID calculation (200 Hz) executes within the motion controller. The output signal (typically 4-20 mA or digital pulse) is sent to the proportional pressure regulator valve that controls the brake.

Actuation Loop: The proportional valve converts the electrical command signal into a precise pneumatic pressure signal, driving the brake calipers. The fast response time of the valve is critical to avoid introducing further phase lag into the 5 ms control loop.

Safety Interlocks: The system includes safety interlocks that monitor both maximum tension (via the laser sensor) and minimum accumulator position. If the accumulator reaches its limit (indicating potential web exhaustion or excessive slack), the system automatically triggers an immediate, controlled line stop to prevent catastrophic web breaks or machine damage.

Schematic views of the developed system, the accumulation system, and the braking system are presented in Figure 1, Figure 2, and Figure 3, respectively

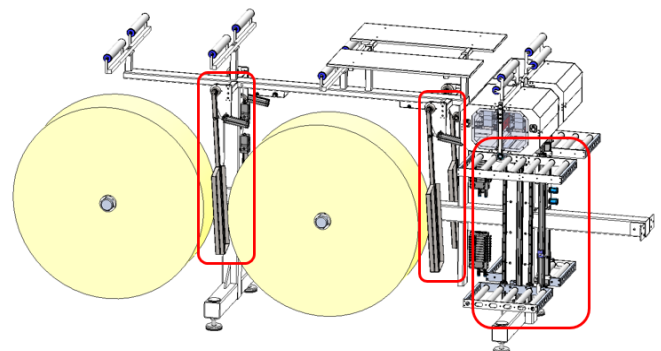


Figure 1. Schematic view of the developed system



Figure 2. The accumulation system



Figure 3. The braking system

3. Results and Discussion

The integrated automatic controlled braking and accumulator system yielded substantial improvements in quality and operational efficiency.

3.1 Continuous Product Quality and Defect Minimization

The system demonstrated superior tension stability compared to fixed systems, eliminating the need for operator input:

Defect Reduction: By maintaining continuous tension stability, the system minimized web undulations, stretching, and achieved a significant reduction in material breaks and production errors across all web materials, including wetlace.

Thermal Control: Elimination of continuous mechanical friction heating solved the problem of heat-induced product damage.

3.2 Industry 4.0 Compliance and Technological Advancement

The project successfully delivered a fully automatic and digitally controlled solution, achieving compliance with Industry 4.0 standards.

Autonomous Operation: The high-frequency PID core acts as an autonomous decision-making mechanism, ensuring consistent performance.

Efficiency Gains: The reduction in friction heating improved energy efficiency, and the elimination of breaks minimized raw material waste (scrap).

Market Leadership: The combination of control precision and high automation established the system as a pioneering example in the global market, validating the benefits of advanced control methodologies.

4. Conclusion

This study successfully developed and validated an integrated automatic braking and pneumatic accumulator system to solve dynamic tension control issues in high-speed wet wipe production.

The system's core novelty lies in its 5-millisecond responsive PID control, which dynamically modulates the pneumatic brake, coupled with a piston-based accumulator mechanism that mechanically dampens transients. This Industry 4.0-compliant solution guarantees continuous and stable web tension, irrespective of machine speed or bobbin size variations.

The project validates that the application of high-frequency sensing and control methodologies can fundamentally solve endemic web handling problems, enhancing the technological competitiveness and operational reliability of modern continuous manufacturing processes.

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Integrated hybrid photovoltaic system for production, storage and use of electricity for energy-intensive processes

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Abstract: In today's global industrial environment, the need for sustainable, efficient, and energy-saving solutions for energy supply is more significant than ever and every enterprise that has adopted the policy of a green and low-carbon economy must seek such solutions. Enterprises must analyze their largest energy consumers and look for alternative options for generating and using "green energy". Photovoltaic systems are among the most common solutions, but their dependence on weather conditions requires integration with energy storage systems. This report presents a model and analysis of an integrated hybrid photovoltaic system with battery storage, designed to provide electricity for energy-intensive production processes under the conditions of the Bulgarian climate and electricity market.

Keywords: SUSTAINABLE DEVELOPMENT, SUSTAINABLE DEVELOPMENT GOALS, PHOTOVOLTAIC SYSTEM, ALTERNATIVE ENERGY

1. Introduction

Sustainable development implies achieving an integrated balance between the three interrelated pillars of development – economic, social and environmental. In this context, sustainable development is seen as a process of harmonizing economic growth, social equality and the conservation of natural resources, with the aim of ensuring the long-term sustainability of human societies and ecosystems.

The growing urgency of climate change challenges, combined with the simultaneous need for energy security and economic stability, has raised heightened concerns about the future of energy sources.[6]

The use of renewable energy sources is becoming an increasingly important and responsible part of the fight against global challenges related to climate change, depletion of available natural resources and energy security both globally and in particular for manufacturing enterprises. Renewable energy sources such as solar, wind and hydroelectric energy provide sustainable alternative solutions to traditional coal and oil sources, which are the main generators of greenhouse emissions. Traditional energy sources must have a decreasing function and use at the expense of energy obtained from renewable energy sources. High-quality software solutions for monitoring energy consumption and, accordingly, planning energy consumption are also increasingly a priority part of the policies of modern enterprises. One of the priorities of the European Commission - the European Green Deal is the basis of this study in relation to the use of energy from alternative sources.[1] Business organizations are challenged to identify their environmental impacts in order to address environmental sustainability issues. [8]

By integrating alternative energy sources into energy systems, businesses can not only reduce their carbon footprint, but also increase energy independence and create new jobs in the field of green technologies. The wise use of alternative sources also helps to stabilize energy prices on international exchanges and to ensure access to electricity in remote and underserved areas, which is particularly important for economic development and social well-being. In the context of growing electricity consumption, the transition to sustainable use of alternative energy sources is becoming an indispensable part of energy production.

2. Purpose of the study

To develop and analyze a model of a hybrid photovoltaic-battery system, optimized to minimize energy losses and increase the efficiency of energy supply in industrial conditions in Bulgaria.

3. Research methodology

To achieve the goal of scientific research, it is necessary to solve the following research tasks:

- 1) To analyze the energy profile of a typical energy-intensive Bulgarian enterprise.
- 2) To determine the main sources of energy losses when using photovoltaic systems without storage.
- 3) To model a hybrid Photovoltaic battery (PV-battery) system with different combinations of parameters:
 - Photovoltaic generator power,
 - Battery capacity,
 - Control algorithm.
- 4) To perform an energy and economic analysis to determine the optimal ratio between production capacity, investment and return.
- 5) To derive recommendations for parameterization and implementation of such systems in Bulgarian industrial enterprises.

To solve the tasks set to achieve the goal, literature review, engineering design and technical and economic analysis were used as research methods.

4. Economic, environmental and social advantages of using alternative energy

In 2015, United Nations (UN) Member States adopted 17 Sustainable Development Goals (SDGs) as part of the 15-year 2030 Agenda. They represent a blueprint for a better and more sustainable future, aimed at combating poverty, inequality, environmental problems and promoting peace and justice.[9], [11]

2025 marks the 10th anniversary of the adoption of the SDGs and the 10th edition of the Sustainable Development Report [9]. Produced by the SDG Transformation Center of Sustainable Development Solutions Network SDSN's, This report examines the progress made each year on the SDGs since their adoption by the 193 UN Member States and contains detailed country profiles, graphs, maps and analysis on each of the 17 goals. According to the Sustainable Development Report 2025, Bulgaria has an overall SDG index of 76.3/100, which places it in the middle of the EU ranking. (Fig. 1 and Fig. 2)



Fig. 1. Overall Performance and Average Performance by SDG. [9].



Fig. 2. SDG Dashboard and Trends. [9].

The report shows that Bulgaria has a solid foundation and a full electricity supply, but the transition to clean energy and a low-carbon economy is too slow. Although the share of renewable energy sources is growing, the pace is not sufficient to reach the 2030 targets without accelerating the pace.

As countries around the world strive to achieve the 17 Sustainable Development Goals, society expects businesses to actively strengthen their sustainable practices and contribute to achieving net zero emissions.

The use of alternative energy in manufacturing plants is becoming increasingly relevant in the context of global efforts for sustainable development and minimizing carbon emissions. The use of "green" energy has some key advantages that are important for any enterprise:

- **Reducing energy costs** - Investing in alternative energy permanently reduces the cost of electricity, as the sources are free after the initial investment;
- **Cost optimization:** Alternative energy sources offer protection from fluctuations in traditional fuel prices and the electricity market, allowing businesses to more accurately plan electricity costs;
- **Reducing the carbon footprint** - Using alternative energy significantly reduces greenhouse gas emissions, which contributes to environmental protection and helps businesses prove their "green" policy of operating their organization;
- **Trust** - Businesses that implement sustainable energy practices build a better reputation and trust with their partners, customers and other related individuals and organizations;
- **Creating technological innovations** - Investing in the production and use of alternative energy stimulates innovation and the implementation of new technologies and software solutions.
- **Creating a competitive advantage:** Businesses that develop the use of alternative energy sources can be more attractive in the market to customers looking for sustainable solutions.
- **Use of external grant funding** - Companies have the opportunity to apply for various national programs for co-financing the production and storage of energy from renewable energy sources.

The use of alternative energy in manufacturing plants not only generates economic benefits, but also helps protect the environment and improves the image of companies in society. Businesses that invest in sustainable solutions will not only benefit from economic advantages, but will also play an active role in creating a cleaner and safer planet for future generations.

Electrical energy storage is recognized as a major technology with great potential for storing energy in a specific state, depending on the technology used. [4]

Financial profitability analysis is an essential topic for preliminary research and a key decision criterion in the design and construction of a photovoltaic system. [5]

5. Working principle of hybrid photovoltaic systems

Solar photovoltaic systems have become a reliable and sustainable energy source that meets the growing demand for electricity worldwide. The growing demand for clean energy has

made this type of system an attractive option for electricity generation. [10]

Incorporating energy storage systems with solar photovoltaic systems is generating significant interest due to its ability to improve system flexibility, provide more reliable power supply, and optimize energy usage. [3], [6], [4] The use of solar energy, in particular by manufacturing enterprises, is the most affordable from an economic point of view. The technology for extracting and storing electrical energy from solar radiation is the most widespread and, accordingly, its price has been significantly reduced in recent years and is increasingly affordable for enterprises..

Photovoltaic technology is a method of directly converting sunlight into electricity using semiconductor materials. Solar panels, composed of photovoltaic cells, use sunlight to produce electrical energy. [4], [2]

Photovoltaic systems (PV- systems) with battery storage are increasingly being deployed in industrial plants with high energy consumption to reduce costs and increase energy independence. However, the efficiency of these systems depends on many parameters – installed power, battery capacity, inverter configuration, climatic conditions, load profile and control algorithm.

The main research problem is to identify the optimal parameters of the PV-battery system that minimize energy losses and maximize the usability of the produced energy under the conditions of the Bulgarian climate and industrial energy profiles..

On this basis, a local energy production system can be connected to existing infrastructure to become an energy generator.[7]

The hybrid photovoltaic system (Fig. 3) combines three main components:

- Photovoltaic generator (PV array) – converts solar radiation into electrical energy.
- Inverter-control unit – converts direct current (DC) into alternating current (AC) and manages the energy flows between the PV system, the battery and the grid.
- Storage system (battery module) – accumulates excess energy and provides power in the absence of sunlight or peak load.

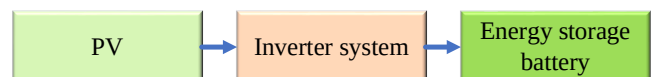


Fig. 3. Hybrid photovoltaic system

However, the size of the optimal system depends on many factors, such as meteorological data, load profile, battery size and price, feed-in tariffs, etc. [5]

A hybrid system can operate in several modes:

- Production and direct consumption – when there is sufficient solar radiation.
- Energy storage – when there is excess electricity production.
- Battery transfer to the load – during peak load or night mode.
- Grid exchange – when there is a shortage or excess of energy.

The integrated hybrid photovoltaic system with battery storage is an efficient and sustainable solution for providing electricity for energy-intensive production processes. The main advantages include:

- increased energy independence;
- stable power supply during peak loads;
- long-term economic and environmental benefits.

6. Development of a conceptual design for an integrated hybrid photovoltaic system

The development was made for the needs of a Bulgarian manufacturing company that manufactures metal structures and parts thereof.

The study examined a concrete case of providing an energy-intensive annealing process in the production of reinforcing steel wire to achieve greater elasticity of the material. This is a process of heating and controlled cooling of steel to reduce internal stresses, increase ductility, and improve the structure of the metal. This is done using an industrial electric furnace with top loading and a nominal power of 100 [kW/h].

Fig. 4 shows the schematic diagram of the wire annealing furnace. The company has undertaken to implement a program for maximum solar energy supply of the production process with this technology and for this purpose will use the available photovoltaic power plant with a capacity of 300 [kW/h] to meet the needs of this process. For this purpose, it has been calculated that the annealing system needs about 250 [kW] of electricity for the normal operation of the process.

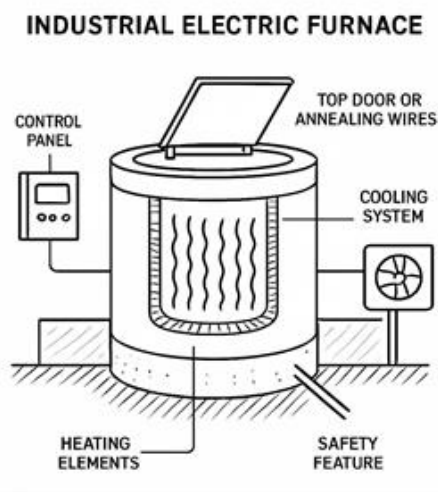


Fig. 4. Industrial annealing furnace

Table 1 shows the technological sequence of the process with data on the consumption of electricity for annealing wires with a material diameter of up to 4 [mm]. The table also shows that about 250 [kW] of electricity are required for one cycle. The company has built a photovoltaic power plant for electricity production with a capacity of 500 [kW/h]. This plant serves the entire production. In order to ensure the annealing process, the following work scheme has been made. Wire production is calculated in 6 working days and one day of maintenance. On the maintenance day, it is planned to temper the produced production that will be annealing. For this purpose, a hybrid system for storing electricity with digital control is being built, which is synchronized with the main inverter of the plant via software. It is planned that the batteries for wire production with a capacity of 300 [kW] will be charged with priority in order to ensure this production. The daily cost of wire production is between 200-300 [kW]. The hybrid system for the production, storage and consumption of photovoltaic energy takes into account the advantage of always keeping the batteries powered for wire production and then redirecting energy to other productions.

Table 1: Wire annealing technology up to 4[mm] thick.

Process	Temperature (°C)	Time (hours)	Energy consumed [kW/h]
Heating	до 800	2	180
Maintaining temperatures	800 - 900	1,00	60
Cooling	less than 100	1,00	10

As seen in Fig. 5, the photovoltaic installation can be used to support the overall energy system of the enterprise, both locally and with priority to individual nodes for planned energy consumption.

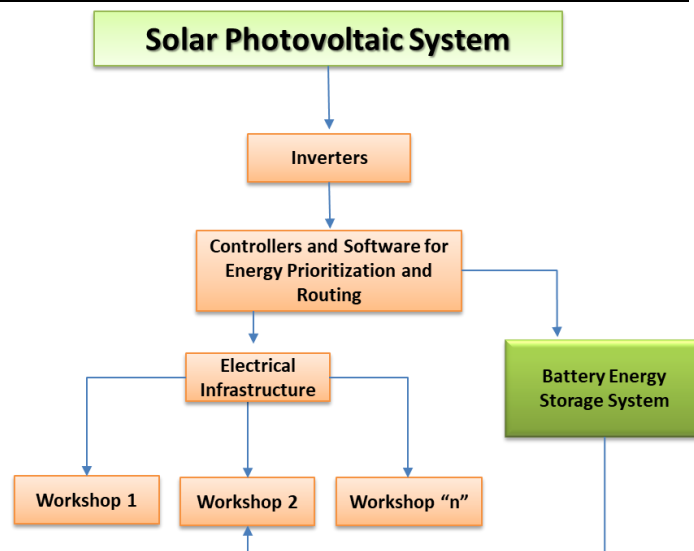


Fig. 5. Block diagram of photovoltaic infrastructure

The company plans to install a 500 [kW] photovoltaic power plant to cover part of its needs. In the first phase of the project, the installation of 303,3 [kW] photovoltaic panels is planned, and it will subsequently be upgraded to 500 [kW]. From an analysis of a 100 [kW] photovoltaic power plant in another base of the company, data on electricity production for one calendar year amounting to 106,875 [kW] is extracted. From this information, electricity production with a 300 [kW] power plant amounting to 320,000 [kW/year] is assumed. The average monthly yield is between 12,000 and 42,000 [kW] with a clear seasonality. This makes a daily yield between 400 and 1,400 [kW] on days with minimal sunlight and poor meteorological conditions and days with perfect conditions for solar energy production.

A battery system for electricity storage is also being designed for this system, to cover the production of wires and fibers. The batteries will have a total capacity of 303,08 [kWh].

7. Main components of the integrated hybrid photovoltaic system

Photovoltaic power plant with capacity 300,3 [kW] built from a photovoltaic panel SUN 66M-H8N – 550w, panel type - TOPCon HALF-CELL MONO PV MODULE

Inverters – Three Phase Hybrid Inverter+ Deye SUN- 50kw K-SG01HP3-EU – 6 pieces;

Total power battery system 303,08 [kWh]

Energy storage batteries - UZ Energy Power Lite 51.2V - 5.12kWh –59 pieces;

8. Investment costs for project implementation

Based on the current average price per kW of electricity consumed on the free market of 0,35 BGN excluding VAT, the following calculation can be made:

With an annual production of 320,000 kW x price of 0,35 BGN excluding VAT = 112,000 BGN per year, not taking into account the trend towards increasing electricity prices.

The price for delivery, installation and commissioning of the entire system is 450,000 BGN excluding VAT.

9. Return on investment

Return on investment: 440,000 / 112,000 = 3.93 years.

If the market price of electricity increases, which has been a constant trend in the last 2 reporting years, a return can be expected within 3,5 years.

The warranty period of the panels is 15 years, with the manufacturer giving 88% efficiency after 30 years.

The warranty period of the batteries is 10 years.

The warranty period of the inverters – 10 years.

The long warranty period of the system elements guarantees sustainable consumption of alternative energy.

10. Ecological effect

The implementation of a hybrid system with a photovoltaic installation and a battery group for energy storage has numerous positive environmental effects that would contribute to the sustainable development and implementation of a successful "green" practice in the company's energy management, such as:

- **Reduction of carbon emissions** - The use of solar energy instead of traditional fossil fuels significantly reduces emissions of CO₂ and other greenhouse gases;

- **Sustainable resource management** - Solar energy is a renewable resource that is practically inexhaustible;

- **Efficient use of energy** - Batteries allow the storage of excess energy generated during sunny days, which ensures a stable and reliable supply during days with worse meteorological conditions;

- **Reduction of noise pollution** - Photovoltaic systems operate silently, compared to traditional generators operating on liquid, gaseous fuels and wind facilities, which create noise pollution;

- **Locations** – photovoltaic panels are located on a pitched roof and do not affect soils and biodiversity in any way.

11. Conclusion

The use of renewable energy sources and the implementation of hybrid energy systems to provide power at different stages of the production process represent a strategic step towards increasing the energy independence and environmental sustainability of enterprises. This approach creates the prerequisites for the production of products with "green production" certificates, which in turn improves the corporate image, increases competitiveness and provides access to new market segments in which consumers and business partners set high requirements for the use of energy produced entirely from renewable sources..

In recent years, there has been a growing trend towards the mass deployment of photovoltaic systems for electricity generation, which is an important step in the energy transformation process. The next stage in this transition is the effective management and integration of these systems through modern software solutions that allow for weather monitoring, energy consumption optimization, intelligent storage and use of accumulated energy at times of high market prices. This leads to better cost control, increased efficiency and a lower carbon footprint of production activities.

In a broader context, such technological and organizational solutions are fully consistent with Goal 7 of the UN Sustainable Development Goals – "Ensure access to affordable, reliable, sustainable and modern energy for all". They contribute both to increasing the share of energy from renewable sources and to improving the energy efficiency and sustainability of the industrial sector. The implementation of such systems not only supports the achievement of national and European goals for green transformation, but also strengthens the role of enterprises as active participants in the transition to a low-carbon and sustainable economy. In this sense, integrated energy management is a key tool for implementing the principles of sustainable development in the practice of modern industry. Despite the higher initial investment, the system is economically justified and guarantees a significant reduction in the carbon footprint of industrial production.

This publication presents the results of an actual scientific and practical study conducted within the framework of a scientific doctoral project PD9/2025, funded by the state budget - 2025 at the Technical University - Varna "Innovative solutions for sustainable

business development in Bulgaria in the transition to a circular and low-carbon economy".

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Surface Characterization of 2D Layers for Sensor Applications using SEM and 3D Laser Microscopy

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Abstract: Two-dimensional (2D) materials such as graphene and tungsten disulfide (WS_2) are promising candidates for gas sensors due to their unique electrical and surface properties. Graphene exhibits high conductivity and mechanical strength, while its oxidized or functionalized forms enhance chemical reactivity and gas adsorption. WS_2 , a semiconducting transition metal dichalcogenide, shows strong surface interactions with gases, enabling sensitive detection even at room temperature.

In this work, graphene and WS_2 thin films were characterized to evaluate surface morphology, uniformity, and structural quality. Graphene films were prepared by chemical vapor deposition (CVD) and transferred onto SiO_2/Si substrates, while WS_2 films with thicknesses of 20 nm and 50 nm were obtained via CVD and sputtering. Surface analysis using scanning electron microscopy (SEM) and 3D laser microscopy revealed that graphene films are highly uniform and smooth, whereas WS_2 films exhibit thickness-dependent surface roughness and texture. These findings provide insights into the relationship between film morphology and gas sensing performance, highlighting the potential of both materials for sensor applications.

Keywords: 2D MATERIALS, GRAPHENE, TUNGSTEN DISULFIDE, SENSOR APPLICATIONS

1. Introduction

Graphene [1] is a two-dimensional material made of a single layer of carbon atoms arranged in a hexagonal lattice. It possesses exceptional physical properties – such as very high electrical and thermal conductivity, mechanical strength, and permeability. Due to its structure, it serves as a basic building block for derivatives like graphene oxide (GO), which results from the chemical oxidation of graphene.

While pure graphene is chemically inert, oxidation introduces oxygen functional groups (e.g., hydroxyl, epoxy, carboxyl) into its structure, which significantly change its properties – reducing conductivity but increasing reactivity and the ability to bind molecules. It is these modifications that make graphene oxide a suitable material for applications in sensor technology [2], biomedicine, electrochemistry, and catalysis. Graphene is therefore a starting material and its structure and purity fundamentally influence the quality and properties of the subsequently prepared graphene oxide.

The authors mentioned in [2] were among the first to demonstrate the use of graphene as a starting material for gas sensors. They point out that graphene can detect individual gas molecules through measurable changes in electrical resistance, indicating its potential for the development of ultra-sensitive gas sensors operating at room temperature. In their experiment, the authors used graphene with naturally occurring defects that enabled gas adsorption. In practice, GO or functionalized graphene is often used to increase sensitivity, as pure graphene is chemically inert.

Currently, surface functionalization with palladium (Pd), which can adsorb H_2 molecules and alter the electrical properties of the graphene channel, is used to enhance the sensitivity of graphene sensors to hydrogen. Theoretical studies confirm that palladium-functionalized graphene undergoes significant changes in its electronic structure when interacting with hydrogen [3].

Another promising material for gas sensors is tungsten disulfide (WS_2), which is part of the two-dimensional TMDC (transition metal dichalcogenides) materials. It has a layered structure similar to graphene but with notably different electrical properties. WS_2 is a semiconductor with a direct band gap in its monolayer form, making it ideal for use in electronics and sensors. According to a study by Minezaki et al. [4], WS_2 shows a significant response to hydrogen molecules due to surface interactions and alterations in its electronic structure, confirming its potential in the field of gas sensors.

When used in gas sensors, WS_2 shows high sensitivity to gases like NO_2 , NH_3 , H_2S , and H_2 , mainly because of its large surface area and ability to adsorb gas molecules. The interaction of gases with the WS_2 surface causes a change in electrical resistance, which can serve as a sensor signal. The sensitivity of the WS_2 layer depends on several factors: the number of layers (monolayer WS_2 has higher sensitivity than multilayer WS_2), the presence of defects and edges, doping with metal nanoparticles (e.g., Pd, Pt), as well as the quality of the substrate and the layer's morphology [4].

Unlike graphene, WS_2 naturally has higher chemical reactivity and can interact with gas molecules without needing prior oxidation. These features make WS_2 an attractive material for developing low-voltage, flexible, and miniature sensors that operate at room temperature.

When comparing both materials, it can be concluded that graphene is an excellent conductor, but it requires modifications – such as oxidation or functionalization – to enhance its sensitivity to gases. WS_2 has a natural semiconducting property and higher surface reactivity, making it suitable for gas sensors even without additional modifications. The choice of material depends on the needed selectivity, operating temperature, and type of gas being analyzed [5].

2. Experimental Part

Thorough characterization of 2D thin films is crucial for understanding their structural, morphological, optical, and electrical properties, which directly affect the performance of sensors. In this study, we examine the morphology and structure of graphene and WS_2 thin films using scanning electron microscopy (SEM) and 3D laser scanning microscope (KEYENCE VK-X3050 Series). The goal is to analyze surface topology, grain size, layer uniformity, and surface defects based on high-resolution micrographs.

We studied two 2D materials – graphene and WS_2 – that were prepared using different methods.

Graphene

A sensor chip with a graphene-based field-effect transistor (GFET) array (MSE PRO GFET, MSE Supplies, USA) was employed to examine the surface morphology and structural properties of the graphene layer. The circuit features a single-layer graphene channel deposited on a SiO_2/Si substrate, with interdigital contacts prepared by the lift-off method from a 50 nm thick gold layer mounted above. This type of circuit is ideal for detecting gases and volatile compounds. All circuits share the same

channel length (1 mm), but have different electrode widths and gaps.

A full-area graphene monolayer was first synthesized by chemical vapor deposition (CVD) and then transferred onto a 90 nm SiO₂ /Si substrate using a polymer-assisted transfer method. Layer thickness: 6-8 nm.

WS₂ layer for gas sensors

For tungsten disulfide (WS₂), thin films with thicknesses of 20 nm and 50 nm were prepared by magnetron sputtering, and their surface morphology was examined.

The WS₂ layer was formed as a thin film using a physical deposition technique – sputtering from a WS₂ target. The process occurred in a controlled atmosphere chamber at low pressure, where the deposition rate and layer thickness were managed. Silicon dioxide on silicon (SiO₂ /Si) served as the substrate, providing good electrical insulation and compatibility with microelectronic structures [6].

After deposition, the layer was annealed in an inert atmosphere (Ar or N₂) at 300–400 °C, which enhanced the crystallinity and electrical properties of WS₂. The resulting layer ranged from 5 to 50 nm in thickness. The WS₂ material produced through this process demonstrates semiconductor behavior with high surface reactivity, making it suitable for use in resistive gas sensors.

Scanning electron microscopy (SEM, Quanta FEG 250 with autoemission cathode, FEI) was used for morphological analysis of all samples, enabling detailed observation of topography, thickness, defects, and layer distribution. To reduce charging effects of graphene during imaging, the sample was attached to a conductive holder using carbon tape. The sample was not coated with a metal layer to dissipate electrical charge, ensuring the actual surface of the very thin graphene layer remained unaltered by metal grain presence.

The same process was used for the WS₂ layer, which was prepared by DC magnetron sputtering from a commercially available WS₂ target (Kurt J. Lesker Company) and deposited on an identical type of substrate.

SEM analysis enabled us to compare the morphology of both layers, identifying differences in uniformity, structure, and presence of defects. These observations mark the initial stage of a comparative study of graphene and WS₂ regarding their potential use in gas sensors.

In addition, surface roughness and topographical uniformity of the WS₂ thin films were analyzed using a 3D laser scanning microscope (KEYENCE VK-X3050 Series) in accordance with ISO 25178-2:2012. This method provided quantitative parameters describing the micro-roughness and texture of the films, complementing the SEM observations.

3. Results and Discussion

The morphology and surface properties of the studied 2D materials, namely monolayer graphene and WS₂ thin films with different thicknesses, were investigated to evaluate their structural quality, homogeneity, and suitability for sensor applications. Surface characterization was performed using scanning electron microscopy (SEM) and 3D laser scanning microscopy (KEYENCE VK-X3050 Series).

Figure 1 shows the surface of a monolayer graphene film prepared by CVD and transferred onto a SiO₂ /Si substrate. The surface appears relatively homogeneous and compact, with no visible cracks or contamination. The fine granular contrast observed in the SEM images is attributed to minor substrate roughness and microscopic wrinkles formed during the transfer process from the Cu foil.

At the given scale of 500 nm, the film can be considered continuous and free of major macroscopic defects. The surface

texture is typical of CVD-grown graphene — slight irregularities indicate the presence of few-layer regions and partial inhomogeneity caused by interfacial stress between the graphene and the silicon dioxide substrate. Such surface variations may influence the electrical properties of the film; however, in sensor applications, defects and microscopic wrinkles can often enhance sensitivity due to increased adsorptive activity.

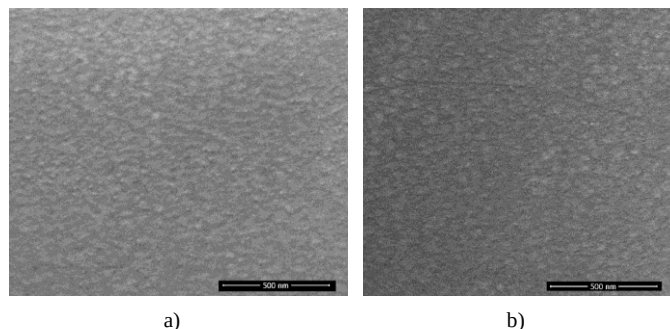


Fig. 1 Detail of the graphene layer on a 90 nm SiO₂ /Si substrate in the GFET channel region. SEM images were acquired at two different accelerating voltages: 10 kV (a) and 30 kV (b), allowing improved observation of the surface texture and film homogeneity.

Surface roughness measurements of the graphene layer were also performed using a laser scanning microscope (KEYENCE VK-X3050 Series). The area around the contact region was divided into four quadrants (Area 1-4).

Figure 2 shows the structure of the SiO₂ /graphene/contact surface, captured in two modes: a 3D optical image (combined optical and laser surface inspection) and C-DIC (Coaxial Differential Interference Contrast).

The graphene regions (Area 1: 0.037 μm, Area 2: 0.032 μm) exhibited very low roughness and high homogeneity. The SiO₂ surface (Area 3: 0.010 μm) showed the lowest roughness, consistent with the polished substrate. The contact region (Area 4: 0.046 μm) had the highest roughness, although still within the range of a smooth surface.

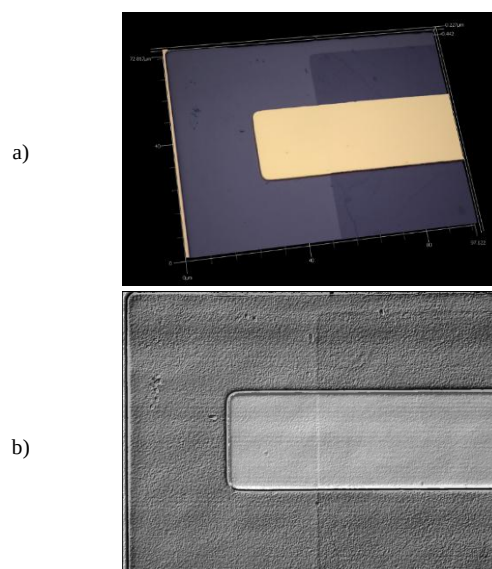


Fig. 2 Detailed structure of the SiO₂ /Graphene/Contact surface: (a) 3D optical image (combined optical and laser surface inspection), (b) C-DIC (Coaxial Differential Interference Contrast) image.

Overall, all analyzed regions demonstrated high surface quality and smoothness ($S_a < 0.05 \mu\text{m}$), while the 3D surface map (Fig. 2) confirmed a uniform topography with minimal height variations. Both SEM analysis and surface roughness measurements verified the high quality and homogeneity of the graphene film. The surface

is continuous, free of major defects or contamination, and exhibits very low areal roughness ($S_a < 0.05 \mu\text{m}$). These characteristics make the graphene layer suitable for sensor applications, where a uniform and smooth surface ensures stable electrical performance and reproducible sensor response.

The analysis then focuses on WS_2 thin films, with thicknesses of 20 nm and 50 nm, to evaluate how film thickness affects surface morphology and homogeneity.

Figure 3 shows the surface of a 20 nm thick WS_2 film deposited on a 90 nm SiO_2/Si substrate by magnetron sputtering from a WS_2 target. To evaluate the homogeneity of the film, images were acquired under identical imaging conditions at several locations across the sample surface.

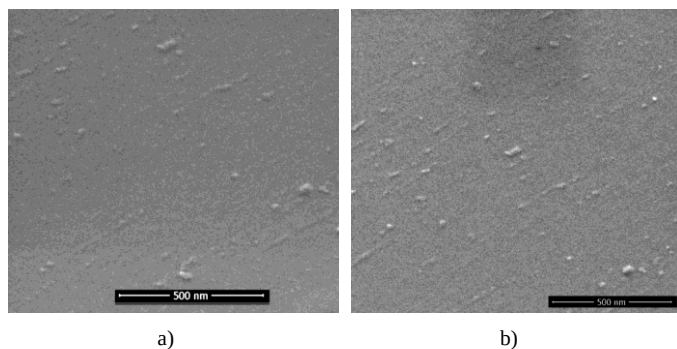


Fig. 3 SEM images of a 20 nm WS_2 layer deposited by magnetron sputtering from a WS_2 target onto a 90 nm SiO_2/Si substrate. Images (a) and (b) were taken at two distant locations under identical imaging conditions to evaluate the film homogeneity. Magnification: 200,000 $\times$, accelerating voltage: 30 kV.

Figure 4 presents the surface of a 50 nm thick WS_2 film on a 90 nm SiO_2/Si substrate, prepared by magnetron sputtering from a WS_2 target. Different accelerating voltages were tested to determine the optimal conditions for surface topography imaging. The best resolution and most detailed surface features were obtained at an accelerating voltage of 30 kV (Fig. 4b), while at 10 kV (Fig. 4a) the fine surface structures of WS_2 were less distinct.

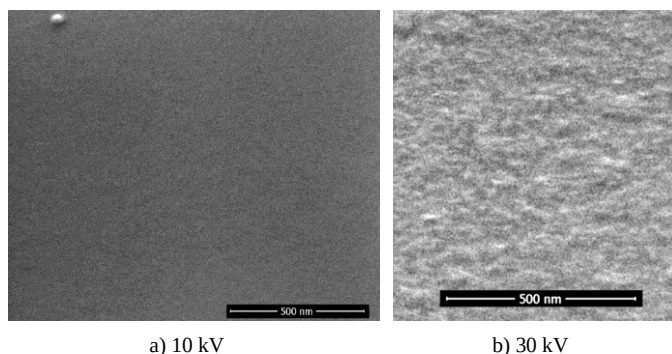


Fig. 4 SEM images of a 50 nm WS_2 layer deposited by magnetron sputtering from a WS_2 target onto a 90 nm SiO_2/Si substrate, acquired at accelerating voltages of 10 kV (a) and 30 kV (b). Magnification: 200,000 $\times$.

The surface roughness measurements performed using a 3D laser scanning microscope (KEYENCE VK-X3000 Series), in accordance with ISO 25178-2:2012, provide an overview of the topography of WS_2 films with thicknesses of 20 nm and 50 nm prepared by magnetron sputtering. Measurements were carried out using a Gaussian filter and a 150 $\times$ objective. In the resulting images ("Main image" and "Scale-limited surface"), surface micro-roughness is clearly visible, with the color scale representing height variations.

For the 20 nm WS_2 layer, an average roughness of $S_a = 0.110 \mu\text{m}$, a maximum height of $S_z = 2.669 \mu\text{m}$, and a nearly isotropic texture ($\text{Str} = 0.829$) were observed. The developed interfacial area ratio $\text{Sdr} = 0.1046$ indicates that the surface is smooth, yet contains

minor micro-roughness. Overall, the 20 nm film is homogeneous, uniform, and suitable for subsequent deposition or integration into multilayer structures.

Measurements for the 50 nm WS_2 layer revealed an even smoother surface, with $S_a = 0.055 \mu\text{m}$ and a significantly lower maximum height $S_z = 0.552 \mu\text{m}$, indicating that the thicker film exhibits smaller height variations and a more compact character. The texture aspect ratio $\text{Str} = 0.432$ suggests slightly increased directional dependence, though the surface remains predominantly isotropic. The extremely low developed interfacial area ratio $\text{Sdr} = 0.0008548$ confirms an almost ideal planar surface.

Comparison of both layers shows that increasing the WS_2 film thickness improves surface smoothness and homogeneity. While the thinner 20 nm film exhibits minor micro-roughness, the 50 nm layer is notably smoother and more compact, which is advantageous for applications requiring high-quality surfaces, such as in electronic or optoelectronic devices. This trend indicates that the deposition process promotes uniform layer growth and minimizes surface irregularities at greater film thicknesses.

The surface topography and roughness differences between the 20 nm and 50 nm WS_2 films are further illustrated in Fig. 5 using optical-laser microscopy.

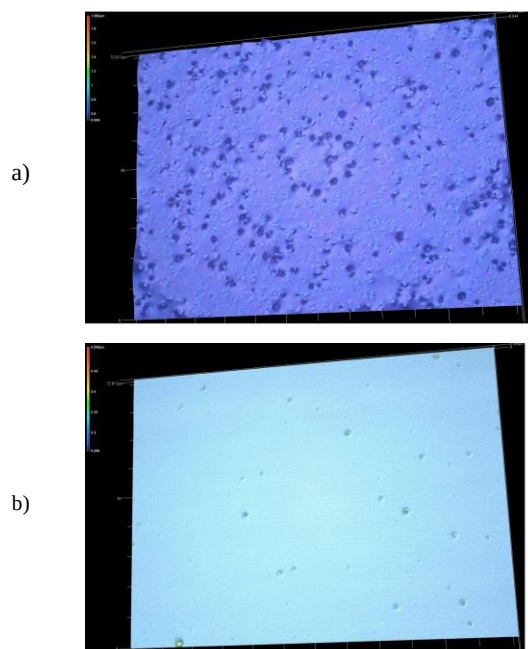


Fig. 5 Optical-laser surface inspection comparing the roughness of WS_2 films: (a) 20 nm WS_2 , (b) 50 nm WS_2 . Magnification: 2000 $\times$, objective: 150 $\times$.

4. Conclusions

Graphene is an exceptional conductor with high electrical conductivity; however, its chemical inertness requires functionalization (e.g., oxidation) to achieve gas sensitivity. Graphene oxide, due to the presence of oxygen-containing functional groups, exhibits higher reactivity and is suitable for sensor applications.

WS_2 has an inherent semiconducting nature and higher surface reactivity, making it suitable for gas sensors even without additional modification. Its sensitivity depends on the number of layers, defects, doping, and substrate quality.

In this work, the topography and surface quality of graphene and WS_2 films prepared by sputtering were analyzed, with WS_2 films of 20 nm and 50 nm thickness. Measurements using a 3D laser scanning microscope (KEYENCE VK-X3000 Series) and SEM showed that graphene exhibits a very smooth and

homogeneous surface with low average roughness, consistent with its monolayer structure and high deposition quality.

For the WS₂ films, the 20 nm layer showed an average roughness of $S_a = 0.110 \mu\text{m}$, maximum height $S_z = 2.669 \mu\text{m}$, and a nearly isotropic texture ($S_{tr} = 0.829$). The surface was homogeneous but contained minor micro-roughness. In contrast, the 50 nm WS₂ layer exhibited an extremely smooth and compact surface ($S_a = 0.055 \mu\text{m}$, $S_z = 0.552 \mu\text{m}$) with slightly directional texture ($S_{tr} = 0.432$) and an extremely low developed interfacial area ratio ($S_{dr} = 0.0008548$). This trend indicates that increasing the film thickness leads to improved surface homogeneity and planarity, which is advantageous for applications where surface quality is critical, such as in electronic or optoelectronic devices.

Comparison of all studied materials shows that graphene provides the smoothest and most isotropic surface, while WS₂ films improve in surface quality with increasing thickness. The results also suggest that controlling layer thickness and optimizing deposition parameters are crucial for achieving the desired quality and functionality of layered materials.

Overall, these findings provide valuable insights for the fabrication of homogeneous and planar 2D films, which are essential for integration into multilayer structures and sensor or electronic applications.

5. Acknowledgments

This work was supported by the Bulgarian Academy of Sciences within the SAS-BAS joint research project IC-SK/02/2025-2026 and by the Slovak Academy of Sciences within the Mobility project SAS-BAS-2024-02 and VEGA grant No. 2/0099/22. We gratefully acknowledge the SEM facilities at the Institute of Electrical Engineering, Slovak Academy of Sciences.

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Design, Modeling, and Construction of a Compact Gas Turbine Prototype for Educational and Experimental Applications

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Abstract: This study presents the design, modeling, and construction of a compact gas turbine prototype. The main goal is to combine theoretical thermodynamic analysis with practical mechanical realization, enabling visualization and study of the performance of a micro-gas turbine system for educational and research purposes. The design phase was carried out in SolidWorks, where each turbine component, including the compressor, combustion chamber, turbine, etc., were individually modeled to ensure dimensional accuracy and fit during assembly. The 3D model served as the basis for the production and assembly of the real parts of the prototype, built with machined metal components and mounted on a customized steel frame. The combustion and exhaust system was designed to ensure controlled fuel flow and safe ignition conditions, while the shaft was supported on precision bearings to minimize vibration and friction losses. The physical realization, combined with CAD modeling and thermodynamic cycle analysis, provides an excellent platform for studying the thermodynamics of the Brayton cycle, energy conversion efficiency, and heat transfer mechanisms in compact turbines. The study shows that interdisciplinary collaboration between mechanical design, thermodynamics, and practical realization can lead to the construction of a functional prototype for educational and research purposes, which can serve as a basis for experimental testing and further developments in the field of gas microturbines. Future work will include the integration of sensors for real-time data collection and the comparison of experimental performance with theoretical predictions.

Keywords: GAS TURBINE, MICROTURBINE, SOLIDWORKS MODELING, THERMODYNAMIC CYCLE, EDUCATION.

1. Introduction

Gas turbines represent one of the most efficient and versatile thermomechanical systems for power generation, characterized by continuous-flow combustion, high power-to-weight ratio, and modular scalability [1]. In recent years, micro-gas turbines (MGTs) have gained considerable attention for educational, research, and distributed generation applications due to their compact size, fuel flexibility, and relatively simple architecture compared to large-scale industrial turbines [2–3]. Their ability to clearly demonstrate the Brayton thermodynamic cycle makes them ideal platforms for laboratory teaching and experimental studies in thermodynamics, heat transfer, and turbomachinery.

The development of physical prototypes for academic use offers several advantages, as it allows students and researchers to visualize and measure real thermodynamic processes, including compression, combustion, and expansion, beyond the idealized models of textbooks [4], [5]. It also provides a practical understanding of engineering trade-offs such as pressure losses, combustion stability, rotor alignment, lubrication requirements, and thermal stresses that are often difficult to convey through theory alone. Combining modeling tools (CAD, CFD) with experimental platforms enhances conceptual understanding and strengthens engineering problem-solving skills [6], [7].

This study presents the complete workflow for the design, modeling, and construction of a compact gas turbine prototype intended for educational and research purposes. The design phase was performed using SolidWorks, enabling detailed modeling of each subsystem, compressor, combustor, turbine, compressor-turbine assembly, injector, lubrication lines, and structural frame, ensuring dimensional compliance and manufacturability. CAD-based design served as the basis for machining individual metal components and assembling them into a functional prototype, a methodology aligned with modern micro-turbine development practices reported in recent research [2], [7].

Emphasis was placed on the design of the combustion chamber and fuel injection system to achieve controlled ignition and stable flame behavior, in accordance with recommended practices in micro-scale combustor design [1], [3]. In parallel, the mechanical assembly focused on minimizing vibration and friction losses through the selection of precision bearings and careful shaft alignment, an essential requirement for small-scale turbine stability and efficiency [9].

The completed prototype provides a valuable platform to observe the real-world behavior of the Brayton cycle, studying energy conversion efficiency and examining heat transfer mechanisms in compact turbines. In addition, it opens possibilities for future instruments with temperature, pressure, and velocity sensors, enabling a direct comparison between theoretical predictions and experimental performance.

2. Methodology

The design of the compact gas turbine prototype followed an integrated workflow that combined thermodynamic analysis, CAD modeling, and practical manufacturability considerations [8]. The goal was to create a functional system that accurately represents the Brayton cycle, while remaining simple enough for educational and research use.

2.1 CAD Modeling in SolidWorks

All components including the compressor, combustor, turbine, shaft, bearings, lubrication lines, and frame were individually modeled in SolidWorks to ensure accurate dimensions, clearances, and assembly compatibility. The CAD model also allowed visualization of airflow paths and mechanical alignment, consistent with common micro-gas turbine design practices [9].

2.2 Component Design

Compressor: A turbocharged radial impeller was used due to its compact size and suitable pressure ratio, consistent with approaches seen in similar prototypes [3].

Combustion Chamber: Designed with primary and dilution holes for stable flame anchoring and uniform temperature distribution, following established micro-combustor guidelines [1].

Turbine and Shaft: A single-shaft configuration was adopted, with precision bearings to minimize vibration and friction losses, essential for small-scale turbine operation [4].

2.3 Structural Integration

A custom steel frame was designed to support all components, ensuring rigidity, proper alignment, and secure routing of fuel and lubrication lines. The CAD assembly served as the blueprint for the machining and assembly of the physical prototype.

The figure below shows the rotor assembly of a micro-gas turbine, consisting of a single shaft supporting the radial compressor

wheel (green) on one side and the radial turbine wheel (blue) on the other. The assembly includes bearing supports, spacers, and retaining discs that ensure proper axial alignment and smooth rotation at high speeds. This configuration enables efficient energy transfer between the turbine and compressor while maintaining mechanical stability.

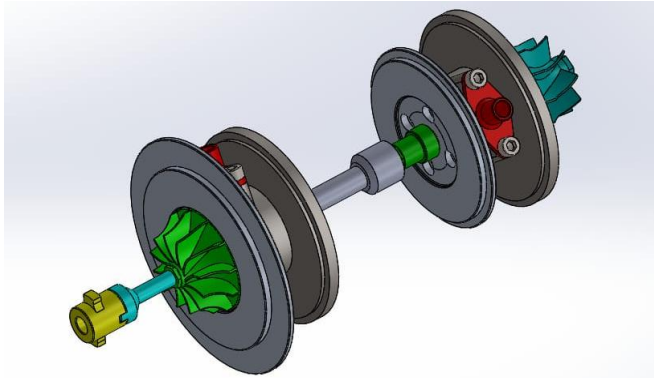


Fig. 1 Exploded view of the micro gas turbine rotor assembly.

The combustion chamber assembly of the micro gas turbine, featuring the cylindrical perforated liner (green), the outer casing, and the integrated fuel injector positioned at the upstream end. The design ensures proper air-fuel mixing, flame stabilization, and smooth flow transition between the compressor outlet and turbine inlet.

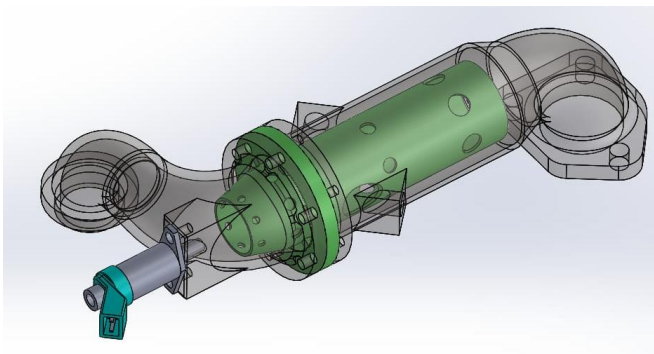


Fig. 2 CAD model of the combustion chamber assembly.

The figure below shows the integrated assembly of the compressor, combustion chamber and turbine section.

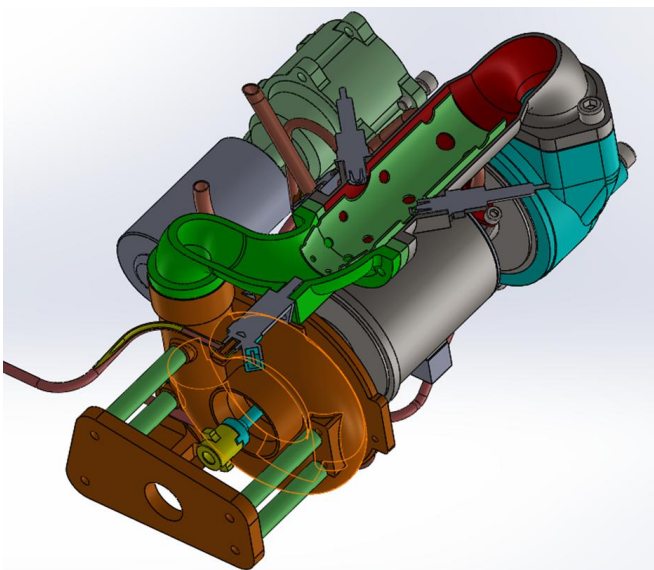


Fig. 3 Detailed CAD assembly of the micro gas turbine core.

The combustor (green and red) is positioned between the compressor outlet and the turbine inlet, with air guide channels ensuring smooth flow into the combustor and towards the turbine wheel.

The model illustrates the interaction between the major components of the micro gas turbine, including the compressor, the transition duct and combustion chamber, the turbine scroll, and the central shaft housing. The perforated combustor liner and the internal air-routing geometry are designed to promote controlled air-fuel mixing and stable combustion. Downstream, the turbine housing channels the high-temperature gases toward the turbine wheel, ensuring efficient energy transfer to the rotating assembly. Overall, the configuration demonstrates the complete gas-path sequence of the system, from compression, to combustion, and finally to expansion through the turbine stage.

The images present the integrated lubrication and fuel-supply system of the micro gas turbine prototype. The assembly incorporates the oil pump, fuel pump, lubrication lines, oil reservoir, and the coiled heat-exchanger tubing arranged around the turbine core. The routing of the lines is designed to provide continuous lubrication to the shaft bearings and to ensure a stable and uninterrupted fuel supply to the injector. The extended tube bundle operates as a compact heat exchanger, dissipating thermal loads and maintaining the oil temperature within safe operating limits, an essential requirement for reliable long-duration turbine operation.

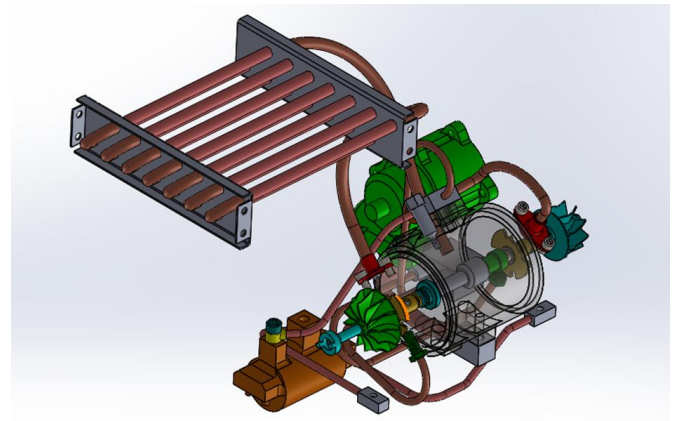


Fig. 4 CAD representation of the lubrication and fuel-line system of the micro gas turbine.

The model also includes the fuel-injector subsystem, comprising the injector nozzle, the pressurized fuel line, and the connected fuel tank. This configuration delivers a controlled and consistent fuel flow to the combustion chamber, supporting stable ignition and sustained combustion throughout turbine operation.

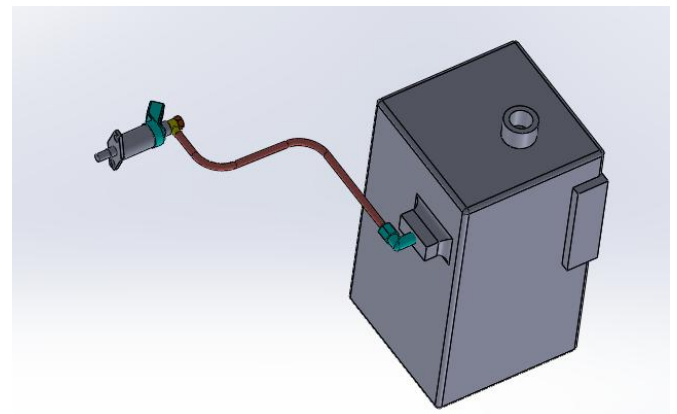


Fig. 5. CAD representation of the injector and fuel-tank connection.

The injector nozzle is linked to the main fuel tank through a rigid copper fuel line equipped with fittings for leak-free operation. This subsystem ensures precise fuel delivery to the combustor,

enabling controlled atomization and efficient mixing with compressed air during turbine operation.

The presented figures show the complete micro gas turbine prototype, assembled within a rigid steel support frame. The system integrates all subsystems required for autonomous turbine operation, including the compressor, combustor, turbine core, lubrication unit, fuel supply, and thermal management components.

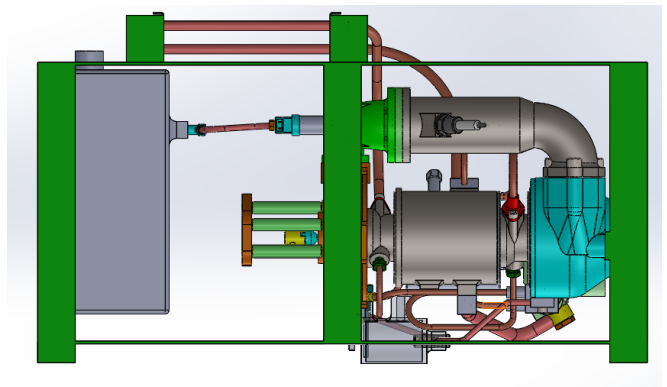


Fig. 6 Side-view CAD assembly of the complete micro gas turbine prototype.

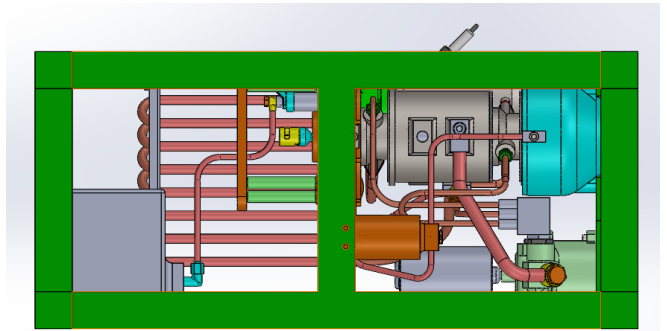


Fig. 7 Upper-view CAD assembly of the complete micro gas turbine prototype.

The layout displays the integration of the main turbine core compressor, combustor, and turbine with the auxiliary systems housed within a rigid steel frame. The combustion chamber is centrally positioned, while the fuel line, lubrication circuit, and cooling tubes are routed around the core for efficient distribution. On the right side, the fuel tank is mounted externally for easy access and refilling. The arrangement highlights the compact packaging of all functional subsystems necessary for stable turbine operation.

3. Thermodynamic Analysis

The prototype was analyzed using an ideal Brayton cycle model to obtain reference values for compressor outlet temperature, turbine work, specific work output, and cycle efficiency.

To support both design and teaching, a MATLAB model and GUI dedicated to the Brayton cycle were developed [10]. The GUI (integrated into MATLAB App Designer) allows the user to enter key parameters, such as compressor pressure ratio, inlet temperature and pressure, turbine inlet temperature, mass flow rate, and isentropic efficiencies and instantly calculates the state points, thermal efficiency, specific work, and heat transfer rates. The program automatically generates the corresponding P–v and T–s diagrams of the gas turbine cycle.

In future work, the same interface will be used to compare theoretical predictions with experimental data from the physical prototype, providing a direct link between the analytical theory of the Brayton cycle and the measured performance of the gas microturbine.

4. Prototype Fabrication and Assembly

The fabrication of the micro gas turbine prototype followed a structured, component-based manufacturing approach to ensure accuracy and safe assembly. All major parts, compressor housing, turbine scroll, shaft supports, and the combustion chamber were produced using CNC machining to maintain tight tolerances required for high-speed operation. Metallic components such as the combustor liner, fuel injector mounts, and bearing housing were manufactured from heat-resistant steel and aluminum alloys, selected for their strength-to-weight ratio and thermal stability.

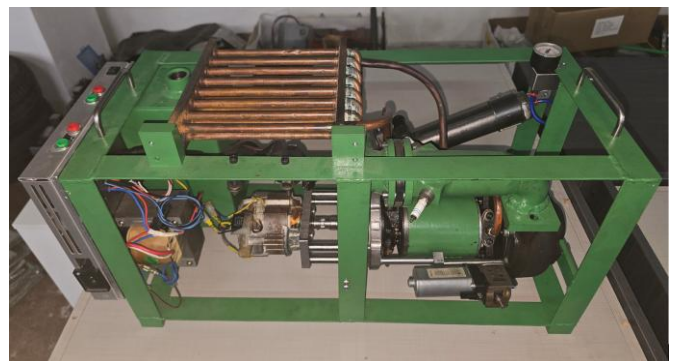


Fig. 8 Fully assembled micro gas turbine prototype mounted on its steel support frame.

The figure below shows the electrical control panel of the micro gas turbine prototype, which houses the switches, indicators, and power connections required for safe system operation. The panel includes ignition controls, pump activation switches, and status lights that allow the operator to monitor and control the turbine during startup and testing.

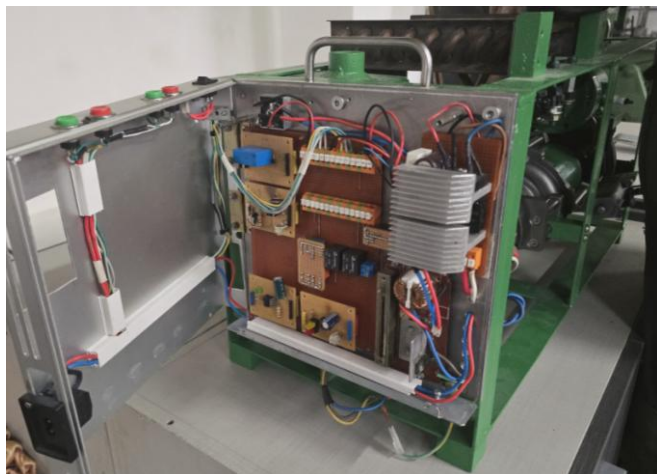


Fig. 5 Electrical control panel for the micro gas turbine prototype.

The panel integrates ignition circuitry, power distribution, emergency shutoff, and control switches for auxiliary components such as the fuel and lubrication pumps. Indicators provide real-time status feedback, enabling safe and controlled turbine startup, monitoring, and shutdown.

5. Future Work

The next development stage involves equipping the prototype with a comprehensive sensor suite to enable real-time monitoring and data acquisition. Planned instrumentation includes thermocouples at compressor exit, combustor inlet/outlet, and turbine exit; pressure transducers at key flow locations; rotor speed sensors; and flow meters for fuel and lubrication circuits. These measurements will provide a detailed picture of system performance and will be integrated into a digital data-logging interface for controlled experimental operation.

The experimental data collected will be compared directly with predictions from the MATLAB Brayton-cycle model and GUI developed during this study. Key comparisons will include compressor outlet temperature, turbine expansion ratio, thermal efficiency, specific work output, and overall mass-flow behavior. Discrepancies between theoretical and measured values will be analyzed to refine the numerical model and adjust assumptions such as component efficiencies, heat losses, and real-gas effects. This comparison will not only validate the design methodology but also guide iterative improvements to the turbine prototype and its analytical model.

6. Conclusion

This work successfully demonstrates the complete development of a compact micro-gas turbine prototype, from CAD modeling and thermodynamic analysis to fabrication and assembly.

The SolidWorks-based design was accurately translated into a real, functional prototype, confirming the reliability of the modeling process and the proper integration of key subsystems such as the compressor, combustor, turbine, lubrication system, and fuel system. Preliminary mechanical checks verified smooth rotor operation, effective lubrication, and consistent combustor performance, indicating that the prototype is structurally sound and ready for controlled testing.

Beyond its technical value, this prototype has significant educational significance. It provides students and practitioners with a rare opportunity to directly observe the Brayton cycle, understand

the interactions of turbine components, and relate theoretical thermodynamics to real mechanical behavior. The accompanying MATLAB Brayton cycle GUI further enhances learning by allowing users to simulate operating conditions and compare them with future experimental results.

Overall, the prototype provides a powerful practical platform for teaching, experimentation, and research in thermal engineering, increasing understanding of gas turbines and supporting future innovations in micro-generation and power systems.

7. Acknowledgment

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Increasing Management Effectiveness by Integrating Industry 5.0 Philosophy into Industry 4.0

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Abstract: Industry 4.0 has established itself as an era of digital transformation, automation, and intelligent technologies that integrate machine systems, data, and processes into a unified architecture. Its core strength is rooted in efficiency, speed, and systematic optimization. However, the pursuit of maximum productivity often displaces anthropometric factors – ethical values, sustainable development, and the social dimensions of technological progress. This is precisely where the philosophy of Industry 5.0 is positioned, building upon the previous paradigm by placing humans at the center of transformational processes. If Industry 4.0 represents the era of machine dominance, then Industry 5.0 introduces the era of symbiosis between human and technological capabilities. The change goes beyond theoretical frameworks and generates measurable results. When people are perceived as partners rather than victims of technological progress, innovations become bolder, products more personalized, and business models more sustainable. Industry 5.0 does not reject digitalization but humanizes it by integrating values such as sustainable development, social responsibility, and balance between technological innovation and human creativity.

Keywords: INDUSTRY 4.0, INDUSTRY 5.0, MANAGEMENT EFFICIENCY, DIGITAL TRANSFORMATION, HUMAN-MACHINE INTERACTION

1. Introduction

Industry 4.0, also known as the Fourth Industrial Revolution in the chronology of the world's industrial development, brings "intelligent" technologies such as artificial intelligence, cloud connectivity, and real-time data analysis to the world of industry and manufacturing. Each of the first three industrial revolutions was driven by a revolutionary new technology: the power of the steam engine, the efficiency of the assembly line, and the processing speed of the computer. At the core of Industry 4.0 is the pursuit of efficiency, productivity, and cyber-physical systems. (Fig. 1):[1]

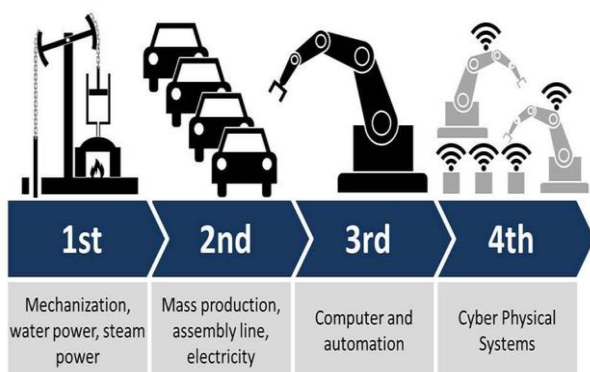


Fig. 1 The Four Industrial Revolutions to Date [1]

The Fourth Industrial Revolution - Industry 4.0, which fundamentally changes the way goods and services are produced and business processes are managed. Unlike previous industrial revolutions, which were based on mechanization, electrification, and automation, Industry 4.0 is driven by intelligent technologies. It consists of nine technological "pillars":[2]

- Additive Manufacturing
- Augmented Reality
- Autonomous Robots
- Big Data and Analytics
- Cloud Connectivity
- Cybersecurity
- Horizontal and Vertical System Integration
- Internet of Things (IoT)
- Simulation

The conceptual foundation of Industry 5.0 derives from the theoretical basis of Industry 4.0, seeking to enrich digital transformation through more meaningful and optimal interaction between the human factor and machine systems within their integrated digital environment. The partnership between people and intelligent technologies synthesizes the precision and speed of industrial automation with the creative potential, innovative capabilities, and analytical thinking competencies of the workforce.

Contemporary organizations face unprecedented levels of competitive tension and continuously rising customer expectations regarding speed and service individualization. Industry 5.0 technological solutions facilitate optimization of both dimensions by supporting human creative resources and mechanized efficiency. This necessitates the development of a circular economic model with emphasis on human-centric industry.

Industry 5.0 does not represent another industrial revolution, but rather serves to expand Industry 4.0 technologies by enhancing collaboration between people and robots. With Industry 5.0, the nine pillars of Industry 4.0 are extended by the aspiration to place human creativity and well-being at the center of industry – to unite the speed and efficiency of machine technologies with the inventiveness and talent of people. The following conceptual frameworks define Industry 5.0:

Human-centric Industry positions human needs and interests as a fundamental element of production processes. Instead of focusing on the question "How to increase workforce efficiency?", the emphasis shifts to "How can technology enrich professional fulfillment?". While robotic systems demonstrate unwavering precision and are optimal for standardized operations, when deviations occur or innovative solutions are needed, human intelligence remains an irreplaceable resource.

Sustainable Industry supports organizations in minimizing their environmental impact through implementing processes based on circular economy principles. The circular economy has already transcended the status of a conceptual trend and is becoming a necessity. Additional sustainability transformations include reduction of energy consumption, greenhouse gas emissions, and waste production, as well as prevention of depletion and degradation of natural resources.

Industrial Production in Sustainable Industry is characterized by a high degree of resilience. It possesses adequate preparedness against destabilizing factors and the ability to maintain critical infrastructure during crisis periods. The pandemic situation revealed the vulnerabilities of industrial systems and emphasized the importance of adaptability. Currently, organizations prioritize

building resilient systems that do not destabilize at the first challenge.

2. Challenges and Opportunities for Contemporary Management

Traditional management models that have served successfully for decades are proving insufficient in the new digital reality. Leaders face the necessity of managing not only people and machines, but also complex digital ecosystems, autonomous systems, and enormous real-time data flows.

The speed of change has increased drastically. Decisions that previously took weeks must now be made in hours or minutes. Markets change rapidly, customer expectations evolve, and competition comes not only from traditional players but also from technology startups that disrupt established business models.

System complexity is growing. Contemporary organizations must integrate multiple technologies - Internet of Things (IoT), artificial intelligence, cloud technologies, robotics, and blockchain, creating interconnected networks of daunting complexity.

The three main challenges of digital transformation are organizational culture, costs, and security:[3]

1. The organization must have the right culture to enable the change process and allow for innovation.
2. The costs associated with investing in technologies, training, and other resources.
3. There exists the challenge of security in protecting data and systems from potential cyber threats.

Despite the challenges, Industry 4.0 offers unprecedented opportunities for optimization, innovation, and value creation. Organizations that successfully adapt their management approaches can achieve:

- Radical efficiency enhancement through intelligent automation and predictive analytics
- Product and service personalization to a degree impossible in the past
- New business models based on data, platforms, and digital services
- Sustainable development through resource optimization and waste reduction

Several fundamental problems remain unresolved:

- How to transform management to utilize the full potential of Industry 4.0 without losing the human dimension of business?
- How to balance between technological possibilities and organizational realities?
- How to prepare people and processes for a future that is changing at unprecedented speed?

Solving these problems defines the framework of contemporary management in Industry 4.0, which must be simultaneously technologically literate, humanistically oriented, and strategically thinking. The answers to these questions will determine which organizations will thrive in the digital future and which will remain in the past:[4]

The key characteristics of management in Industry 4.0 that must be taken into account when solving these problems are:

- Digitalization of management processes is establishing itself as a fundamental component. Management personnel are no longer limited to intuitive and empirical approaches but gain access to current data through integrated systems, which enables more substantiated and operational decision-making. The

conventional hierarchical management structure is transforming toward a more dynamic and adaptive organizational form.

- Data management and analytics are acquiring strategic significance. Contemporary management systems are based on technologies for processing data arrays, artificial intelligence, and machine learning for forecasting development trends, optimizing operational processes, and preventively averting system disruptions. Merely possessing data is insufficient – their competent interpretation is also necessary. Management specialists must master competencies for analyzing graphical representations, recognizing patterns, and formulating predictions based on algorithmic solutions.
- Human-machine interaction requires innovative management strategies. Managers face the challenge of coordinating not only human resources but also automated systems, robotic platforms, and algorithmic processes. The necessity arises for balancing between algorithmic recommendations and human expertise, as well as ensuring their effective integration. This generates a need for developing competencies for synchronization between human capital and digital technologies.

3. Fundamental Changes in Management Philosophy

Conventional vertical organizational architectures are undergoing metamorphosis toward horizontal, network configurations. In the context of Industry 4.0, information flows are characterized by multidirectionality, and decision-making processes are decentralized across different organizational levels. Management personnel are evolving from the position of supervisors toward the function of facilitators and coordinators of operational processes.

Autonomous work collectives are acquiring expanded rights for operational decision-making based on current data and real-time information. This necessitates the development of innovative competencies from leadership positions for coordinating distributed authority and responsibility.

Intuition and professional experience, despite their significance, are no longer sufficient for effective management. Contemporary managers must possess abilities for interpreting complex analytical data, identifying trends and patterns, and transforming information into strategic initiatives.

Analytical processes and prognostic methods enable the anticipation of potential problems before their occurrence. Business intelligence systems provide detailed visibility across the entire spectrum of activities – from production operations to customer behavior.

Integration between physical processes and digital technologies generates new management opportunities. Sensor devices in production lines provide real-time data that is processed through machine learning algorithms. The results are applied for automatically correcting parameters or alerting operators.

Digital twins of production processes allow simulation of alternative scenarios without risk to actual production. Managers can test modifications, optimize parameters, and plan maintenance with exceptional precision.

AI systems assume routine analytical functions, freeing management personnel to concentrate on strategic thinking and creative problem-solving. Algorithmic solutions can analyze significant volumes of data in seconds and propose optimal strategies.

Chatbots and virtual assistants optimize organizational communication and ensure operational access to information.

Robotic Process Automation (RPA) systems assume repetitive administrative tasks.

Cloud solutions guarantee flexibility and scalability of IT infrastructure. Management specialists gain access to data and systems regardless of location and time. This facilitates the formation of distributed teams and adaptive work models.

Mobile applications enable coordination of production processes on the move. Real-time notifications ensure immediate response when difficulties arise:[5]

4. Practical Approaches for Addressing Challenges in Industry 4.0

Continuous learning and reskilling are crucial for successfully addressing the challenges in Industry 4.0. This requires creating internal training programs for digital skills, partnerships with universities and technology institutes, investing in online learning platforms that allow employees to learn at their convenience, developing clear career paths that integrate new technological competencies.

Building multidisciplinary teams helps facilitate more effective adaptation. Combining the knowledge and skills of engineers, IT specialists, operations managers, and production workers in common projects leads to achieving high results. This facilitates knowledge transfer and creates a more holistic understanding of processes, but also requires more effective management:[6]

Active communication and transparency are key to overcoming resistance to innovative solutions and changes. It is necessary for managers to learn to explain to employees why change is necessary, how it will affect their work, and what the benefits are for them personally, and to include them in the planning and decision-making process.

Ensuring reliable IT infrastructure as the foundation of effective management also presents a number of challenges. It is necessary to invest in stable network connectivity, cloud solutions, and cybersecurity. Without a solid foundation, even the best digital initiatives will fail.

5. The Human Factor in Digital Transformation

Digital transformation is not expressed only in new software, robots, cloud systems, and artificial intelligence. No technology can be useful without the human who creates, manages, and uses it. At the heart of every transformation stands precisely the human factor. Successful digital transformation requires not only modern machines but also a culture of openness, readiness to learn, and courage. In this sense, digitalization is not so much a technological as a social process – a process of changing thinking. Human creativity, adaptability, and morality are what give meaning to digital progress:[7]

The following are necessary:

- **New competencies for managers**
Contemporary managers face a paradox: they must master technologies without losing the human dimension of leadership. This requires developing hybrid competencies that combine technological literacy with emotional intelligence. Unlike traditional models, where a manager could rely primarily on experience and intuition, today a deep understanding of the possibilities of artificial intelligence, machine learning, and digital ecosystems is necessary.
- **Workforce transformation**
Represents a particularly delicate process. Automation inevitably eliminates some positions, but simultaneously creates new ones requiring higher qualifications. Managing this transition necessitates a strategic approach to human resource development, including large-scale

retraining programs and creating new career trajectories. Success depends not so much on technological capabilities as on the ability to motivate people to accept change as an opportunity rather than a threat.

- **Culture of innovation and experimental practices**
Successful organizations in the context of Industry 4.0 develop an institutional environment that stimulates experimentation, accelerated learning, and organizational adaptability. Deviations are interpreted as learning opportunities rather than failures. Creating internal corporate startup structures and innovation laboratories activates employees' creative potential. Strategic partnerships with technology organizations and academic institutions bring external knowledge and alternative perspectives.

Digitalization also manifests in specific operational aspects of management:

- **Supply chain coordination**
Digital transformation of supply chains ensures total transparency from raw materials to end consumers. Blockchain technologies guarantee traceability and security of transactional processes. IoT sensors track the location and condition of goods in real time. AI algorithms optimize delivery routes, minimize inventory resources, and forecast demand with exceptional precision. This generates significant cost reduction and service improvement. This technological complexity necessitates the development of new managerial competencies for synchronizing physical and digital processes.
- **Quality control and regulatory compliance**
Digital technologies radically transform quality control. Computer vision and machine learning identify defects with higher accuracy than human perception. Data from every production cycle is archived and analyzed to determine the causes of deviations. Automated compliance systems monitor adherence to regulatory requirements and automatically generate necessary documentation. This reduces the risk of sanctions and improves organizational reputation. Paradoxically, the more we automate control functions, the more essential becomes the role of specialists for interpreting results and formulating strategic decisions based on generated data.
- **Resource management**
Intelligent energy management systems optimize consumption according to production needs and market prices. Predictive maintenance reduces repair costs and increases equipment operational time. Digitalization enables precise tracking of all resource usage - time, materials, energy. This creates opportunities for continuous improvement of efficiency and sustainability.

The strategic dimensions of digital transformation manifest in:

- **Innovative business architectures**
At the strategic level, Industry 4.0 is not limited to improving existing processes - it opens possibilities for fundamentally new business models. The transition to concepts such as "Product as a Service" illustrates how technologies transform the nature of value propositions. Data generated by products becomes alternative revenue sources. Digital platforms integrate manufacturers, suppliers, and customers into unified ecosystems:[8]
- **Sustainability and corporate responsibility**

Sustainability and social responsibility acquire a new dimension in the digital environment. Technologies enable not merely more precise measurement of environmental impact but also active management of this process through real-time optimization. Transparency in supply chains guarantees ethical production and social responsibility. Organizations use data to demonstrate their contribution to sustainable development.

Management in Industry 4.0 requires integration of technological capabilities, the human factor, and strategic thinking into a unified management philosophy that balances efficiency with sustainability and innovation with human values.

6. Model for Enhancing Management Efficiency through Integration of Industry 5.0 Philosophy into Industry 4.0

Based on an in-depth literature review and analysis of data accumulated from practical observations and professional experience, this publication presents the results of the conceptual development and practical testing of a model for enhancing management efficiency through integration of Industry 5.0 philosophy into Industry 4.0. The model integrates technological infrastructure and the human factor into a common management structure. The conceptual framework of this model is shown in Fig. 2.

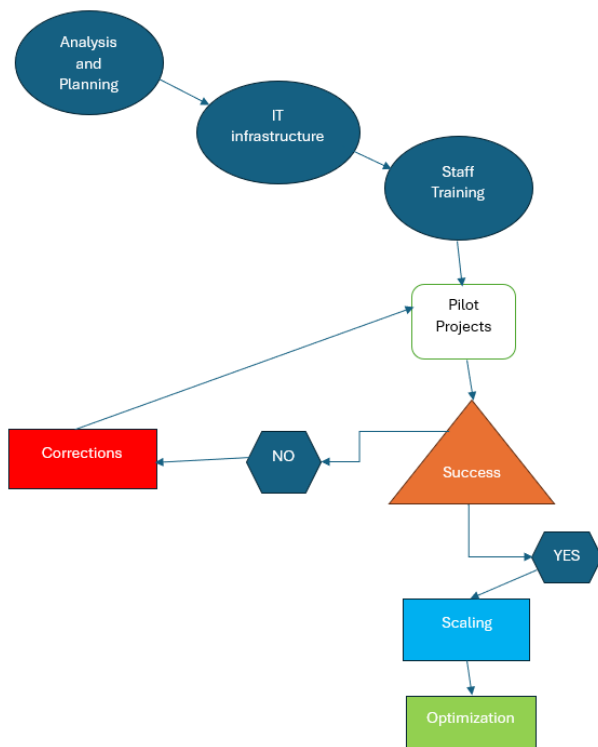


Fig. 2 Model for Enhancing Management Efficiency through Integration of Industry 5.0 Philosophy into Industry 4.0.

The model can be practically implemented in 13 steps, distributed across 5 phases:

Phase 1: Preparatory Diagnostics and Assessment Processes (3-6 months)

Step 1: Current state analysis. Conducting an in-depth audit of existing systems, operational processes, and organizational competencies. Identifying "digital deficits" in the structure - which processes demonstrate lowest efficiency, where the most significant losses of time or resources are recorded. Preparing a detailed map of the entire IT architecture and its integration connections.

Step 2: Establishing a management team for transformation processes. Forming a multidisciplinary team with representation from IT, production operations, human resources, finance sector, and operational management. Appointing a Chief Digital Officer (CDO) or delegating these functions to an existing top manager with technological competencies.

Step 3: Mapping professional competencies. Conducting a detailed assessment of the digital capabilities of each employee. Applying competency matrices to determine the need for retraining, identifying potential internal instructors and positions requiring new appointments.

Phase 2: Building Fundamental Foundations (6-12 months)

Step 4: Modernization of IT infrastructure base. Prioritizing the most critical components: stabilized network architecture, cloud infrastructure, and cybersecurity. Implementing a unified Data Management Platform that will function as the backbone of future digital solutions.

Step 5: Standardization of operational processes. Before automation initiatives - optimizing and standardizing all processes. Applying methodologies such as "Lean" or "Six Sigma" to eliminate unnecessary operations. Documenting processes in digital formats.

Step 6: Establishing centers of professional competence. Creating specialized teams for key technologies - IoT, data analytics, automation. These centers should function as internal consulting structures for various organizational units.

Phase 3: Pilot Testing and Validation (3-9 months)

Step 7: Selection and launch of pilot initiatives. Choosing 2-3 processes with high improvement potential and minimal risks. Examples: automated maintenance planning, digital quality indicator tracking, or intelligent energy management. Defining clear KPI indicators for success evaluation.

Step 8: Development of digital twins. Constructing digital models of critical production processes. This will allow simulation of changes before their actual implementation and parameter optimization.

Phase 4: Scaling and System Integration (12-24 months)

Step 9: Implementation of integrated management systems. Deploying next-generation ERP systems that integrate production operations with planning, logistics, and financial processes. Ensuring API compatibility between all systems for seamless data exchange.

Step 10: Development of analytical capabilities. Implementing business intelligence platforms and predictive analytics. Training management personnel in data interpretation and data-based decision-making. Creating automated reports and alarm systems.

Step 11: Process operation autonomy. Gradually implementing autonomous decision-making systems in routine operations - automatic material ordering when minimum inventory levels are reached, automatic shift planning according to demand.

Phase 5: Optimization and Innovation Practices (continuous process)

Step 12: Formation of innovative organizational culture. Establishing internal idea competitions and budgets for experimental projects. Motivating employees to propose improvements and experiment with new technologies.

Step 13: Development of partner ecosystem. Building strategic connections with technology partners, startup organizations, and research institutions. Creating open APIs for clients and suppliers to form a digital ecosystem around organizational activities:[9]

During system testing at Testel Engineering Ltd. in Varna, some critical success factors for model implementation were also identified:

- **Continuous monitoring and adaptation** – developing a system for systematic progress tracking at each stage. Applying "Agile" methodologies for operational adaptation when difficulties arise.
- **Organizational change management** - at every level, investing significant resources in communication strategies, training programs, and motivational initiatives for teams. Transforming thinking patterns often represents a greater challenge than technical implementation.
- **Balance between automation and human intervention** – avoiding the pursuit of immediate total automation. Creating hybrid architectures where technologies support human decision-making.

This phased approach enables organic development of digital capabilities, minimizing risks and maximizing potential for successful transformation:[10]

7. Conclusion

Management in the context of Industry 4.0 represents not merely technological evolution, but a comprehensive metamorphosis of principles for organizing, coordinating, and optimizing business processes. This transformation necessitates from leadership positions a fundamental rethinking of management approaches. Based on the results from testing the proposed model for improving management efficiency through integration of Industry 5.0 philosophy into the architecture of Industry 4.0, the following generalizations and conclusions can be formulated:

Digital transformation in management transcends technological renewal. It requires rethinking the fundamental principles of leadership in the industrial environment. Practical experience from integrating Industry 5.0 philosophy into the technological framework of Industry 4.0 reveals several essential patterns.

Key findings from practical implementation:

Synergy is decisive. Organizations that perceive digitalization as exclusively a technical project rarely achieve expected results. Success is based on simultaneous development of technological infrastructure, human competencies, and organizational culture. These components cannot develop independently - they are interdependent.

Gradual approach ensures stability. Although radical changes appear attractive, they contain significant risks. The phased approach allows organizations to accumulate expertise, learn from deviations, and adjust their strategy without compromising core activities.

The human factor maintains its centrality. Paradoxically, in the era of automation, the anthropogenic element acquires even greater significance. Investment in developing digital competencies and personnel adaptability proves decisive for the success of the overall transformation.

Data transforms management practices. The ability to transform information into strategic actions is establishing itself as a fundamental management competency. Intuitive decision-making gradually gives way to the analytical approach.

Long-term effects of integration processes

Talent seeks meaningful content in work. Contemporary personnel are not satisfied merely with the function of machine operators. They seek challenges, opportunities for creative contribution, and professional development. Industry 5.0 principles form a work environment that synthesizes technological efficiency with human fulfillment, which positively affects employee satisfaction and loyalty.

Sustainability becomes a competitive advantage. Environmental responsibility is no longer a matter of corporate image but a strategic imperative. Investors, employees, and clients increasingly

evaluate organizations according to their sustainable practices. Integration of Industry 5.0 principles allows achievement of economic results while maintaining ecological balance.

Furthermore, the ability for rapid adaptation to crisis situations - from pandemic phenomena to climate disruptions - becomes a critical management competency. Industry 5.0 technologies provide the toolkit for building resilient organizations through enhanced risk analysis and increased operational flexibility.

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Implementing the Industry 4.0 concept in family firms - a case study from Poland

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Abstract: Family firms constitute an important element of the modern economy, combining the values of tradition, intergenerational continuity, and social responsibility. Their activities are often characterized by a conservative approach to strategic decision-making and a cautious attitude toward innovation. However, in the face of increasing global competition and rapid technological change, maintaining a sustainable market position requires openness to digital transformation and the implementation of the Industry 4.0 concept. Industry 4.0 represents a new paradigm of business activity, combining digital technologies and the Internet with conventional manufacturing processes, in order to enhance their efficiency and flexibility. The aim of this paper is to analyze the implementation of the Industry 4.0 concept in a medium-sized family enterprise located in north-eastern Poland. Over its more than forty-year history, the company has undergone a profound transformation from a manufacturer of simple metal products and agricultural tools, through a producer of cable connectors for the shipbuilding industry, to a specialized supplier of components for the aviation, automotive, and railway sectors. In recent years, the company, supported by grants from European Union funds, has established an R&D department as well as a Center for Robotics and Automation, forming the foundation of its digital transformation process. The results of the study indicate that the implementation of Industry 4.0 solutions has contributed to strengthening the company's competitive position and facilitating its expansion into international markets. The key determinants of success were effective intergenerational succession, the pro-innovative attitudes of family members, and cooperation with universities and research entities.

Keywords: FAMILY BUSINESS, INDUSTRY 4.0, INNOVATION, MANUFACTURING SECTOR

1. Introduction

Family firms constitute an important component of the contemporary economic landscape and predominant form of business activity. They substantially contribute to GDP growth, provide a significant share of workplaces and foster economic stability, while also sustaining long-term business values [1]. Family businesses represent a unique combination of tradition, intergenerational continuity and social responsibility. By mixing family and business aspects, they create an organizational form characterized by distinctive dynamics and management style [2].

Family firms are often deeply rooted in tradition and focused on long-term goals. This can result in a conservative approach to strategic decision-making and cautious attitude towards radical change. However, these entities also face various external shocks (e.g. the coronavirus pandemic), rapid technological progress and strong global competition, which means that innovation is no longer an opportunity for family firms, but rather a necessity for surviving in highly competitive environment and ensuring business continuity across generations. For this reason, managing the tensions between tradition and innovation seems to be one of the most challenging tasks for family businesses [3, 4].

One of the most promising paths for the transformation of family businesses is the implementation of Industry 4.0. This new paradigm of business activity integrates digital technologies, automation, and the Internet of Things (IoT) with traditional manufacturing processes to enhance efficiency and flexibility [5, 6]. However, implementing Industry 4.0 is not without its challenges. Family firms often face limited resources and shortage of the necessary skills, risk-averse decision-making, and generational differences in technological readiness, which can slow down digital transformation [7-9]. Therefore, it is important to understand how these enterprises can overcome such obstacles while leveraging their inherent strengths.

The aim of this paper is to analyze the implementation of the Industry 4.0 concept in a medium-sized family enterprise located in north-eastern Poland. Over its more than forty-year history, the company has undergone a profound transformation from a manufacturer of simple metal products and agricultural tools, through a producer of cable terminals and connectors for the shipbuilding industry, to a specialized supplier of components for the aviation, automotive, and railway sectors. In recent years, the company has established an R&D department as well as a Center for Robotics and Automation, laying the groundwork for its own digital transformation process and supporting the adoption of Industry 4.0 in other enterprises.

2. Literature Review

The concept of Industry 4.0 is commonly associated with profound changes in industry, also known as the Fourth Industrial Revolution, which began in many countries around the world during the 2010s [8, 10-12]. The term of Industry 4.0 was first publicly used at the 2011 Hanover Fair by a working group announcing a comprehensive project of digitization of manufacturing processes in the German economy [13].

The rise of Industry 4.0 is driven by a wide range of key enabling technologies, including: the Internet of Things (IoT), cloud technology, big data analysis, artificial intelligence (AI), simulation, augmented and virtual reality, autonomous and collaborative robots, blockchain, and additive manufacturing [14].

The widespread adoption of the Industry 4.0 concept has given rise to numerous concerns, including high investment cost of implementing advanced solutions, a shortage of qualified staff, dependence on complex technologies, high maintenance costs, and cybersecurity issues. However, family firms should seize the opportunities offered by digital transformation. In particular, they should recognize the benefits of optimizing manufacturing processes, improving efficiency, reducing operating costs, as well as increasing their flexibility and adaptability to changes in the environment [15].

A survey of 1,142 Argentine SMEs has indicated that the incorporation of Industry 4.0 tools is related to factors such as company age and size, manager gender and educational level (university degree), as well as the presence of personnel with technical training in digital technologies. However, no significant differences between family and non-family companies have been found [16]. In turn, research on 3,000 Italian family SMEs has shown that the adoption of Industry 4.0 depends on management type (family vs. non-family) and investment in R&D. Interestingly, the effect of these factors may vary depending on the geographical context (i.e., the level of regional development) [17].

The existing literature on family business also emphasizes the importance of succession and intergenerational involvement for technological innovation. In general, the presence of multiple generations in a company positively influences the propensity for innovation and new technology adoption [18-19]. However, the results of the research in this area are not entirely consistent [20-21].

3. Methodology of the Research

The study adopts a qualitative orientation and employs the case study method, which is commonly used in management sciences. This approach is particularly useful for analysing complex socio-economic phenomena and explanatory research issues [22].

For the purposes of this analysis, a medium-sized family enterprise located in north-eastern Poland was selected. The company has successfully undergone digital transformation and adopted the Industry 4.0 concept. It provides an instructive example of the evolution of a family-owned enterprise operating under the changing socio-economic conditions in Poland over the past several decades.

Information concerning the company's activities was obtained from various sources, including available company materials, press and media publications, patent databases, and registers of research projects.

4. Results

4.1. History and Characteristics of the Surveyed Company

The company was established in 1981 after its founder, formerly a technical director at a state-owned factory, had been dismissed from his job for political reasons related to his involvement in the Solidarity movement. Driven by the need to provide for his family, he set up a small metal workshop, initially producing small heating stoves and basic agricultural tools (e.g. pitchforks and hoes). However, this activity offered limited opportunities for growth.

A key strategic shift occurred when the founder used his previous professional contacts in the shipbuilding industry. Recognizing a domestic shortage of cable connectors - a vital component in marine and electrical installations - he moved the company to a more specialized and higher-value area of production. Despite the restrictive political conditions and resource constraints, the new products successfully met industry quality standards. This transformation turned the company into a specialized manufacturer of electrical installation equipment. In next years, the founder's brothers joined the business, further strengthening the company's family roots.

During the period of political transformation and market liberalization in the 1990s, the company expanded its product portfolio and systematically built its market presence. Improvements in product quality, coupled with proactive participation in trade fairs, supported customer acquisition and contributed to brand strengthening. A turning point came in 2000 with the unexpected death of the company's founder. Following a sudden succession process, his thirty-year-old son, a graduate engineer, became the company's CEO. Under his leadership, the company placed a stronger focus on innovation, internationalization and modern manufacturing technologies. Access to European Union funds enabled investments in new production halls and the development of advanced product lines.

Table 1: The main areas of company's activity

Division	Description
ELECTRO	products dedicated to electrical installers, power companies and industrial enterprises: tools, equipment, and accessories, busbar and mounting rails, cable terminals and connectors
AERO	manufacturing parts from difficult-to-machine metal alloys for the aerospace, medical, and military industries
ROBOTICS	designing and building devices and lines to automate and robotize production processes

Currently, the company employs over 200 highly qualified staff and is managed by a four-person team of second generation family-members. Its products are sold to clients in dozens of countries

around the world, including global corporations operating in the aerospace, automotive and power engineering sectors.

4.2. Towards Industry 4.0

The company began its transformation towards Industry 4.0 at the start of the 21st century. At that time, the young successor initiated the purchase of the first CNC machine. This decision initiated a continuous automation process, largely based on projects designed and built in-house. One of the first such solutions was a machine created for producing cable connectors. The chosen strategy focused on creating smart, well-designed systems that increased operational efficiency, reduced the risk of errors, and enhanced occupational safety. Further improvements in subsequent years enabled the company to enter into challenging areas such as the production of difficult-to-machine alloys for the aerospace industry, including components for aircraft engines.

The company has also expanded its operations to encompass the design and construction of automated machinery and production lines. On the one hand, this was a rational application of many years of engineering expertise, and on the other - a response to the growing market demand driven by dynamic industrial transformation. The company's offer is aimed at both large international corporations seeking solutions to unusual operational problems, as well as at small and medium-sized enterprises willing to strengthen their competitive position through automation. In the latter case, the company recognizes that small firms often face barriers related to limited resources and insufficient technological expertise. Therefore, the scope of services provided for this group covers the comprehensive support, including needs assessment, the design and construction of customized solutions, implementation, and advice on obtaining funds.

Another important stage in the company's development was the construction of the modern factory facilities, equipped with mobile robots for internal transport, automated stations for hazardous or burdensome tasks, and solutions that improve ergonomics and workplace safety. Environmental sustainability was also prioritized: gas-based soldering processes were replaced by photovoltaic-powered technologies. This investment project was carried out between 2020 and 2022. In addition to production and warehouse spaces, the facility houses a research and development centre that conducts projects in industrial automation and robotics. The centre also supports the training of in-demand specialists, including CNC machine operators.

The company actively promotes the idea of Industry 4.0 by organizing industrial conferences, that provide a platform to exchange experiences among business practitioners, technology partners and experts. It also collaborates with the research entities, particularly the AGH University of Science and Technology in Krakow, and participates in cluster initiatives such as the Evoluma Industrial Cluster.

4.3. Findings and Discussion

The transformation towards Industry 4.0 is not a distinct endeavor but rather a cumulative, multi-stage process that requires strategic coherence, organizational learning and the ability to align technological initiatives with market opportunities.

The results of the research indicate that the implementation of Industry 4.0 concept can contribute to strengthening company's competitive advantage as well as to facilitating its expansion into global markets. However, the successful digital transformation of the family business requires a shared vision among family members of various generations. Therefore, careful succession planning is a crucial for ensuring continuity of leadership, maintaining organizational stability, and facilitating successful knowledge transfer across generations. In addition, a proactive and innovation-oriented attitude among family members is crucial, as investment in new technology shapes a culture of risk-taking, experimentation and seeking for continuous improvements.

In the case of the studied company, the internal readiness for innovation was also reinforced by collaboration with research institutions industrial partners. This highlights the potential synergy between family governance, innovation-oriented organizational culture, and external knowledge networks, which collectively influence the successful digital transformation of family firms.

5. Conclusion

This paper contributes to the growing body of research on digital transformation in family firms by demonstrating how the unique characteristics of these organizations (e.g. long-term orientation and intergenerational continuity) can facilitate rather than hinder the adoption of the Industry 4.0 concept. The results of the study emphasize the vital role of innovation-oriented organizational culture and intergenerational knowledge transfer in supporting technological progress. The study also highlights the importance of sourcing external knowledge, suggesting that extensive collaboration with research institutions and industrial partners affects the innovation readiness of the enterprises.

The study also offers some recommendations for business practitioners. First, family firms should aim to develop a shared vision for their future and clearly communicate their goals related to technological transformation. Second, it is also important to encourage an attitude of innovation among family members and managers, fostering a culture that supports risk-taking and continuous learning. Third, forming strategic partnerships with research entities should accelerate the adoption of new technologies and reduce the risk of failure.

However, the study is not without limitations. The research focuses on a single company, which means that the results cannot be broader generalized. Moreover, it is largely based on qualitative data, which may contain some degree of subjectivity. Future research should therefore include multiple comparative case studies and quantitative research assessing the impact of Industry 4.0 tools on the performance of family firms. It may also be interesting to investigate how cultural and sector-specific factors influence the digital transformation of family businesses.

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Determination of the Origin and Quality of Honey through Pollen and Physicochemical Analysis

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Abstract: Honey is a valuable natural product with a complex composition, shaped by the botanical and geographical origin of nectar sources as well as the environmental conditions of the collection area. To ensure the authenticity, quality, and safety of honey, various analytical methods are applied, among which pollen and physicochemical analyses are of particular importance.

In this study, a pollen analysis was performed to determine the floral origin of the honey, alongside the measurement of electrical conductivity as an indicator of mineral content, acidity, and sugar composition. Samples were prepared by dissolving in distilled water and centrifugation, followed by the preparation of microscopic slides for pollen grain identification. The resulting data allowed the classification of honey as either monofloral or polyfloral, and identification of the predominant plant species in the collection area.

The combined approach of pollen and physicochemical analysis provides a reliable and scientifically grounded assessment of honey origin and quality, supporting product control, certification, and authenticity verification.

Keywords: HONEY, POLLEN ANALYSIS, BOTANICAL ORIGIN, ELECTRICAL CONDUCTIVITY, HONEY QUALITY, AUTHENTICITY

1. Introduction

Honey is a complex natural product with high nutritional and economic value. Its composition and quality are directly influenced by the botanical origin of nectar, geographical and climatic conditions, as well as bee foraging behavior during nectar and pollen collection [1, 2]. Determining the origin of honey is crucial for both the beekeeping industry and consumers seeking authentic, high-quality products [1].

One of the most reliable methods for establishing the floral origin of honey is pollen analysis, which allows the identification of different pollen types through microscopic examination. This method provides information on whether honey is monofloral or polyfloral, as well as the diversity of plant species in the collection area [1, 2].

Additionally, physicochemical parameters, such as electrical conductivity, offer valuable insights into the mineral content, acidity, and sugar composition of honey, supporting the assessment of its quality and authenticity [1, 2]. The combination of pollen and physicochemical analyses creates a comprehensive approach to honey evaluation, enabling reliable traceability of its origin and supporting certification processes [1-3].

2. Materials and Methods

Microscopic (Pollen) Method

Principle of the Method:

The aim of the pollen analysis is to determine the botanical origin of honey by microscopically identifying the pollen grains present in the samples. This analysis contributes to the botanical and geographical characterization of the product and serves as a tool for verifying its authenticity.

Procedure:

Honey samples (10 g) are dissolved in 20 - 40 cm³ of distilled water preheated to 40 - 50 °C. The solution is then centrifuged in tubes for 10 - 15 minutes at 2500 - 3000 rpm. After centrifugation, the supernatant is carefully decanted without disturbing the sediment.

A drop of the sediment is collected using a pipette and placed on a microscope slide. The sample is then covered with a cover slip and prepared for microscopic observation [6].

Physicochemical Method (Electrical Conductivity)

Principle of the Method:

The determination of honey electrical conductivity is based on measuring the electrical resistance of an aqueous honey solution. Electrical conductivity is the reciprocal of electrical resistance.

Procedure:

To measure electrical conductivity, freshly distilled water and a 0.1 M potassium chloride (KCl) solution are required, with the KCl solution prepared on the day of use.

Determination of the Cell Constant – Periodic Measurement

A beaker is filled with 40 mL of the potassium chloride solution. The conductivity cell is connected to the conductometer, rinsed with the solution, and then immersed in the solution along with a thermometer. When the temperature reaches 20 °C, the electrical conductivity of the solution is measured in mS. To avoid polarization effects, the measurement is performed as quickly as possible.

The cell constant is calculated using the formula:

$$(1) \quad K = \frac{11.691 \times 1}{G},$$

where:

- K is the cell constant in cm⁻¹;
- G is the measured electrical conductivity in mS;
- 11.691 is the sum of the conductivities of freshly distilled water and 0.1 M potassium chloride solution in mS/cm at 20 °C.

Determination of Electrical Conductivity

An amount of honey equivalent to 20.0 g of dry matter is weighed and dissolved in distilled water. The solution is quantitatively transferred to a 100 mL volumetric flask and brought to the mark with distilled water.

A 40 mL portion of the solution is placed in a beaker and equilibrated at 20 °C. The conductivity cell is rinsed with the remaining solution and then immersed in the tempered solution. The electrical conductivity is recorded as quickly as possible using a conductometer.

If the measurement is performed at a temperature other than 20 °C, the value is corrected by decreasing 3.2% for each degree above 20 °C and increasing 3.2% for each degree below 20 °C.

Calculation of Results

The electrical conductivity of the honey solution is calculated using the formula:

$$(2) \quad SH = K \times G$$

where:

- SH is the electrical conductivity of the honey solution in mS/cm;
- K is the cell constant;
- G is the measured electrical conductivity in mS [3].

Statistical Methods

Control Chart: A control chart is a tool that allows monitoring changes in the value of a quality characteristic of a product or process over time, as well as studying the causes of these changes. At a given point in time, a process may operate normally, but due to changes in operating conditions, trends indicating potential deterioration may emerge. The control chart enables such trends to be detected in a timely manner and corrective actions to be taken.

The limits of the natural tolerance interval ($m \pm 3\sigma$ $\pm 3\sigma$) are adopted as control limits. Observation data are plotted on the control chart as points, which are usually connected with straight lines. If the quality characteristic follows a normal distribution and the process is under control, nearly all observations should fall within the control limits.

Histogram: A histogram is one of the primary tools for studying the distribution of a random variable by the frequency of its values in a dataset. It is constructed from sample data of the population, which are presented in a table. The histogram consists of rectangles representing how often each value of the studied variable xxx occurs.

Every product or manufacturing process is characterized by one or more quality attributes. To be considered of high quality, each attribute must meet a specified target value according to the relevant standard. Due to various factors, the observed values may deviate from the target. Such factors include inaccurate dosing of components, heterogeneous raw materials, deviations from the prescribed technology, and many others. As a result, deviations of the quality characteristic from the target value occur. If these deviations remain within predefined tolerance limits, the product is considered acceptable; otherwise, it is deemed defective [4, 5].

When performing a normality test, the p-value is used to indicate the probability that the data come from a normal distribution. A significance level of 0.05 (5%) is commonly applied. If the p-value is less than or equal to 0.05, the null hypothesis that the data are normally distributed is rejected, indicating that the data do not follow a normal distribution. If the p-value is greater than 0.05, the null hypothesis is not rejected, meaning there is insufficient evidence to conclude that the data deviate from normality [8].

3. Results and discussion

In this study, 15 honey samples from the Blagoevgrad region were analyzed. For all samples, the physicochemical parameter electrical conductivity was determined, providing information on the mineral content, acidity, and sugar composition of the honey.

A subset of the samples was also subjected to pollen analysis to present the pollen grains that were identified. These results are provided for informational purposes only, without making definitive conclusions regarding the floral origin of honey for all samples.

To assess compliance with quality standards for honey, a control chart of individual values and a histogram were constructed, shown in Figs. 1 and 2.

In Fig. 3 (a-i), images of all identified pollen grains are presented, allowing visual examination of the floral diversity observed in the analysed samples.

Fig. 1 presents a control chart of individual electrical conductivity values for honey samples. The process appears to be in control, as all measured values remain within the control limits. The upper control limit (UCL = 1.64166 $\mu\text{S/cm}$) and the lower control limit (LCL = 1.62916 $\mu\text{S/cm}$) are indicated on the chart, with the mean electrical conductivity being $\bar{X} = 1.63541$ $\mu\text{S/cm}$.

Since none of the measured points exceed the UCL or fall below the LCL, no anomalies are observed that would indicate potential quality issues. Continuous monitoring of these values is important to ensure product stability and quality.

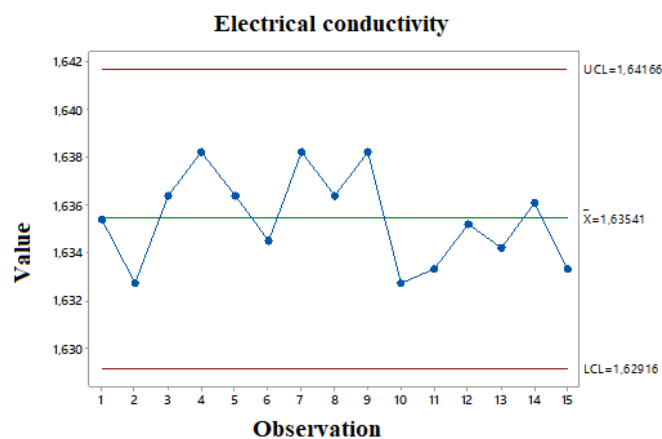


Fig. 1 Control chart of individual values for honey samples analyzed for electrical conductivity.

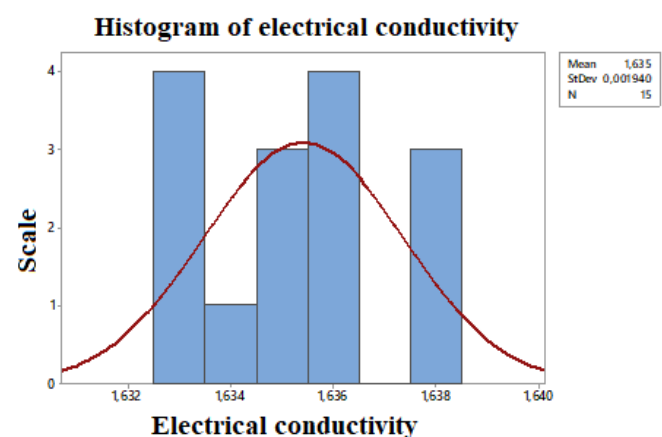


Fig. 2 Histogram of honey samples analyzed for electrical conductivity.

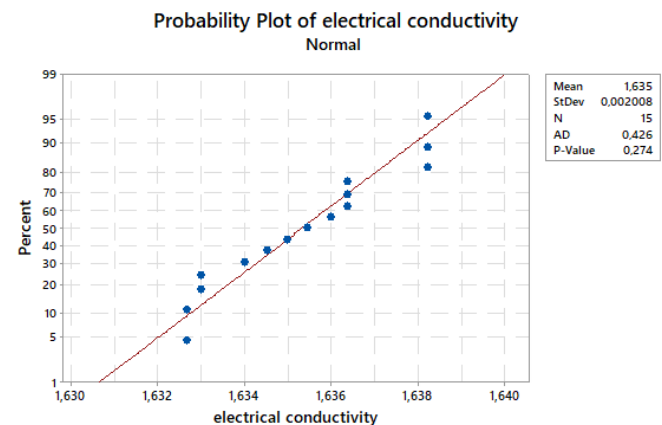


Fig. 3 Normality test for honey samples analyzed for electrical conductivity.

Fig. 2 shows a histogram of the electrical conductivity of the honey samples. The histogram illustrates the distribution of measured values within the range of 1.632 to 1.640 $\mu\text{S/cm}$. It can be observed that the samples are not symmetrically distributed around the mean, with several concentrated peaks, suggesting a lack of normal distribution. This is expected given the small number of samples and minimal variations in the production process. Nevertheless, the electrical conductivity remains relatively homogeneous, without isolated anomalies, which is a positive indicator of product stability and consistency in production.

The analysis presented in Fig. 3 shows that the electrical conductivity of the honey samples follows a normal distribution (probability $p = 0.274 > 0.05$), allowing the acceptance of the null hypothesis of the normality test.

Fig. 4 (a-i) presents microscopic images of pollen grains extracted from honey samples of various botanical origins. The

identified sources include black locust (*Robinia pseudoacacia*), linden (*Tilia* spp.), chestnut (*Castanea sativa*), horse chestnut (*Aesculus hippocastanum*), thyme (*Thymus* spp.), peach (*Prunus persica*), walnut (*Juglans regia*), dandelion (*Taraxacum officinale*), and St. John's wort (*Hypericum perforatum*) [7].

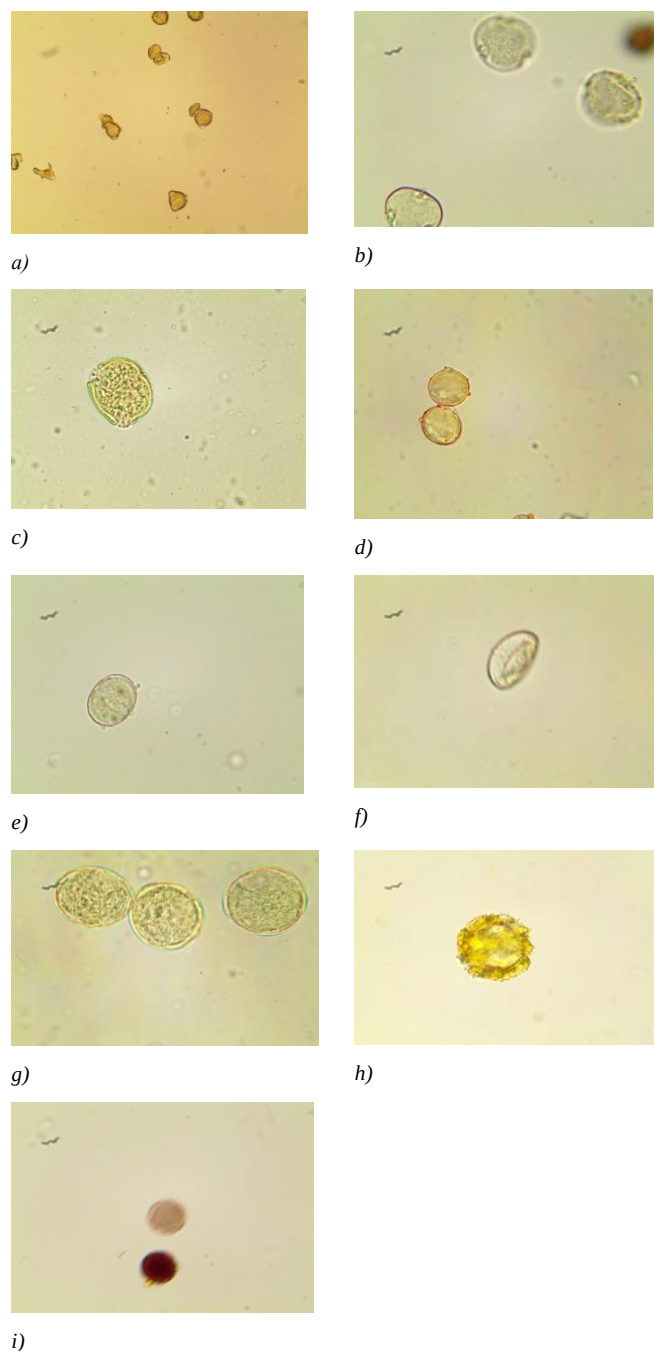


Fig. 4 Microscopic images of pollen grains from honey samples of different botanical origins: (a) Black locust, (b) Linden, (c) Chestnut, (d) Horse chestnut, (e) Thyme, (f) Peach, (g) Walnut, (h) Dandelion, (i) St. John's wort [7].

Pollen analysis and electrical conductivity are two complementary indicators of honey's origin and quality. Pollen provides information about the plant sources from which the honey was collected, while electrical conductivity reflects the mineral and ionic content, which varies among different plant species. Combined, these two methods allow simultaneous determination of the floral origin and chemical characteristics of honey, which is essential for ensuring its authenticity, quality, and traceability.

4. Conclusion

The study conducted on 15 honey samples from the Blagoevgrad region demonstrates the effectiveness of combining pollen and physicochemical analyses for a comprehensive assessment of the product's quality and authenticity. The measured electrical conductivity values showed that all samples fell within the permissible limits, indicating a stable composition and the absence of technological deviations in the production process.

The statistical results, reflected in the control chart, histogram, and normality test ($P = 0.274 > 0.05$), confirm the homogeneity of the samples and the normal distribution of electrical conductivity values. This indicates consistent quality parameters and good standardization of the product.

The parallel pollen analysis visualized the floral diversity in the samples and provided information on the botanical origin of the honey, contributing to more accurate classification and traceability of the product.

The results confirm that the honey from the Blagoevgrad region is of high quality, of natural origin, and exhibits distinctive physicochemical characteristics. The combined approach—integrating pollen and physicochemical analyses—represents a reliable tool for quality control, certification, and ensuring the authenticity of Bulgarian honey.

Acknowledgements

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Integration of Contemporary Methods in Vocational Education – From Theory to Practice with a Focus on Industry 4.0

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Abstract: The report examines the current state and challenges of vocational education in the transport and energy sectors. It analyzes the need for modernization through project-based learning, digital transformation, and team-based learning, which have been proven to enhance outcomes and prepare learners for Industry 4.0. The report presents international practices in dual education and effective models of partnerships between education and industry. Finally, it outlines the main barriers—institutional, resource-related, social, and those stemming from resistance to change—that hinder the widespread implementation of innovative approaches.

KEYWORDS: VOCATIONAL EDUCATION, INDUSTRY 4.0, PROJECT-BASED LEARNING, DIGITAL TRANSFORMATION, CONNECTIVISM, TEAM-BASED LEARNING, DUAL EDUCATION, VOCATIONAL TRAINING, TRANSPORT SECTOR, ENERGY SECTOR, EDUCATIONAL INNOVATION, BUSINESS PARTNERSHIPS, CHALLENGES AND BARRIERS.

Introduction

Contemporary vocational education and training in the fields of transport and energy faces fundamental challenges that threaten its effectiveness and relevance. The significant divergence between technological progress in industry and the resource endowment of the educational process continuously amplifies the “divide” between competencies developed within the classroom and the practical requirements of employers. The COVID-19 pandemic has served as a catalyst for the digital transformation of education; however, the adoption and systematic integration of innovative pedagogical approaches—such as project-based learning, collaborative learning, and simulation technologies—remain sporadic and insufficiently structured. This review systematizes contemporary scientific achievements in vocational education, focusing on three critical dimensions: the integration of digital technologies and innovative pedagogical approaches, the establishment of continuity between secondary and higher education, and the development of effective partnerships with the business sector. The analysis encompasses international practices from leading European countries and proposes a theoretical framework for understanding the processes of transformation in vocational education.

1. The Role of Project-Based Learning as a Central Methodological Approach for Workforce Preparing for Industry 4.0

Project-based learning represents a paradigmatic shift in the organization of the educational process, whereby learners develop competencies through engagement with complex, real-world problems. A bibliometric study, based on the international Scopus database and following the PRISMA 2020 guidelines, revealed significant disparities in the application of this method. Out of an initial 337 identified articles, 44 publications were selected for in-depth analysis following strict filtering, covering the period from 2004 to 2014 [1,2].

Analysis of distribution across professional fields, according to the National Classification of Higher Education Areas in Bulgaria, indicates an extremely low level of penetration of project-based learning in the engineering and technical sciences [3]. The implementation rate across the thirteen fields reached only 47%, a circumstance particularly concerning for the disciplines of Mechanical Engineering, Energy, and Transport, including Shipping and Aviation. This lack of methodological examples linking technical disciplines with economic perspectives creates a substantial gap in the preparation of specialists capable of interdisciplinary thinking.

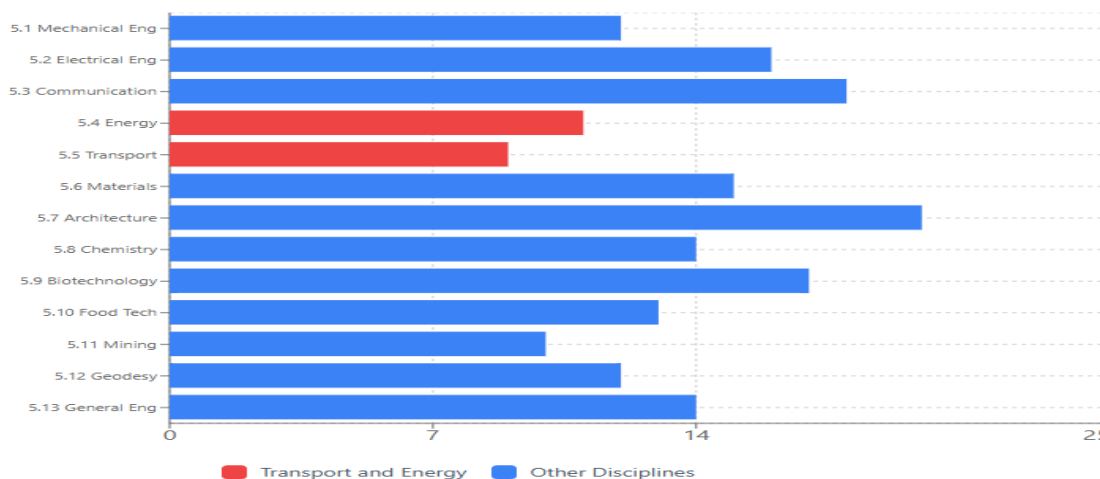


Figure 1: PBL Adoption Across Engineering Disciplines: Average: 14.7% - Transport and Energy sectors highlighted.

Empirical studies convincingly demonstrate the effectiveness of project-based learning in a vocational context. The method enhances learning outcomes by fostering higher-order thinking skills, the integration of which is a critical prerequisite for preparing learners for participation in the Industry 4.0 environment. Traditional education, focused on the transmission of pre-packaged knowledge, is replaced by an active process of competency construction through authentic problem-based situations. Despite its proven effectiveness, the number of projects is quantitatively sufficient; however, they remain highly segmented by discipline,

without achieving the desired integration of knowledge across different domains.

2. Digital Transformation and a Connectivist Perspective in Support of Industry 4.0

The theoretical framework of connectivism provides a powerful conceptual toolkit for analyzing contemporary digital pedagogies. Connectivism conceptualizes learning as the process of building connections between individuals and technologies within

complex information networks, a perspective that overcomes the limitations of traditional learning theories [1,4].



Figure 2: Connectivism Framework in Digital Education – A Knowledge Network with Interconnected Nodes.

The central tenet of connectivism postulates that knowledge is not concentrated in a single source but is distributed across a network of diverse nodes, which can include individuals, organizations, online repositories, and technological systems.

The experience of the Shenzhen Polytechnic University, a leading institution in vocational education and training in China, illustrates the practical application of connectivist principles. The university implements five digital pedagogies: blended learning, simulation-based learning, game-based learning, the flipped classroom model, and precision learning. Evaluation of the outcomes reveals both significant advantages and notable challenges. A strong and diverse network provides access to multiple perspectives and essential information, which is critical in a rapidly evolving educational context [5].

The COVID-19 pandemic created an experimental setting for the widespread implementation of digital tools to enhance communication in education. Video conferencing platforms such as Zoom and Google Meet, collaboration applications including Microsoft Teams and Slack, as well as learning management systems like Moodle and Google Classroom, became essential instruments in the educational process. Analysis of this accelerated digitalization reveals a complex picture, encompassing both significant advantages and substantial limitations.

On the positive side, digital tools provide flexibility and accessibility, enabling learning independent of geographic location and time, which is particularly important for students with special needs or other commitments. The ability to record lectures facilitates review and in-depth engagement with the material, while the abundance of multimedia resources enriches the learning experience. Tools for instant feedback, including interactive quizzes, polls, and formative assessments, promote active participation. On the negative side, reduced face-to-face interaction can lead to feelings of isolation among some learners, while technical issues, unequal access to technology, and varying levels of digital literacy create barriers to effective learning.

3. Team-Based Learning and the Social Construction of Knowledge

Team-based learning represents a methodology that fundamentally transforms the dynamics of the educational process by emphasizing the collaborative construction of knowledge. Empirical studies demonstrate impressive outcomes regarding the effectiveness of this approach.

Academic achievement increases by 139% compared to traditional or individual learning methods, with particularly strong effects for learners with low prior achievement and limited motivation. Motivation also shows measurable improvement, albeit to a lesser extent, with this increase identified as a central mechanism for attaining higher academic standards [6,7].

The theoretical explanation for these effects is rooted in the social-constructivist perspective, which views learning as a social process of interaction and negotiation of meaning. Team-based learning creates a supportive classroom environment that

transforms competition into positive collaboration and fosters a sense of community and belonging. The diversity of ideas within the group context, combined with immediate feedback during collaborative activities, further strengthens understanding and academic performance. The method proves particularly effective in addressing misconceptions and reducing learning-related anxiety.

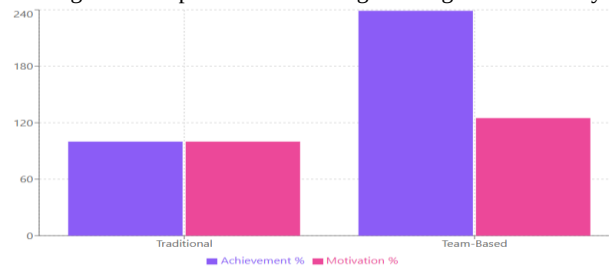


Figure 3: Team-Based Learning Impact – 139% Improvement in Academic Achievement

The integration of team-based learning with interactive video and virtual reality technologies generates synergistic effects that significantly enrich the learning experience. However, this integration requires careful design of each learning unit, ensuring an accessible pathway for deeper, learner-centered engagement.

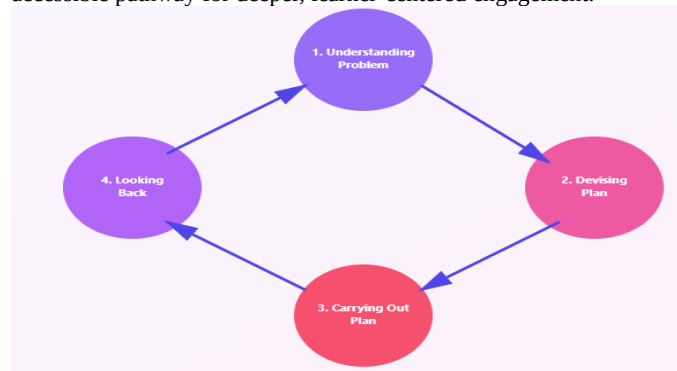


Figure 4: Problem-Solving Algorithm – Four-Stage Iterative Process

Platforms such as Nearpod for virtual field trips or ThingLink for creating interactive 360-degree videos ensure that activities support curriculum outcomes and promote active learner engagement.

4. Dual Education and Integration with the Business Sector

Dual education represents an institutionalized form of partnership between the educational system and the business sector, in which classroom-based theoretical learning is systematically combined with workplace-based practical training. Analysis of leading national models from Germany, Switzerland, Norway, Sweden, France, and New Zealand reveals multiple configurations of this approach, each reflecting specific cultural, economic, and institutional contexts.

The German and Swiss dual education systems are characterized by a deep integration of workplace apprenticeship and classroom learning, a model that has served as the foundation for implementing dual education in Bulgaria. The system ensures an effective transition from secondary to higher vocational education through significant employer engagement and mutual recognition of learning outcomes. The Norwegian "two-plus-two" model, combining two years of school-based learning with two years of workplace apprenticeship, facilitates continuation into higher vocational institutions through a balanced combination of theoretical preparation and practical experience [1, 3, 7].

Mechanism	DE	CH	NO	SE	FR	NZ
Flexible Admission	88%	85%	82%	84%	83%	87%
Credit Transfer	95%	94%	90%	91%	88%	92%
Bridge Programs	90%	89%	86%	87%	85%	88%
Dual Pathways	82%	80%	75%	76%	74%	78%
Partnerships	92%	91%	88%	89%	87%	90%

■ ≥90%
 ■ 85-89%
 ■ 80-84%
 ■ 75-79%

Figure 5: Dual Education Effectiveness – Comparison Across Six Countries

The Swedish and French approaches to integrated workplace learning demonstrate varying degrees of institutionalization, with Sweden embedding workplace learning across all programs, while France emphasizes extended apprenticeship programs within vocational pathways [9]. New Zealand's model, featuring trade academies, represents the most integrated approach, directly linking secondary schools with higher education institutions, combining secondary and tertiary curricula, and ensuring a seamless transition into education, training, and subsequent employment [10].

Comparative analysis of these models identifies several critical success factors for dual education. Flexible university admission criteria, which broaden entry requirements and recognize professional qualifications and competencies, demonstrate an effectiveness rate of 85%. Credit transfer systems, in which vocational education and training coursework can be converted into university credits, show an effectiveness of 92%. Transitional and foundational courses that address gaps in academic skills achieve an effectiveness of 88%. Dual pathways with integrated dual-sector programs, jointly offered by employers and universities, demonstrate 78% effectiveness. Sectoral partnerships for co-designed curricula reach 90% effectiveness [4, 8, 3].

5. Challenges and Barriers to Transformation

Despite the theoretical grounding and empirically demonstrated effectiveness of the approaches discussed, their widespread implementation faces numerous challenges of varying nature. Institutional barriers include unclear governance, inconsistent funding, and fluctuations in national priorities, which undermine efforts to create coherent systems. The absence of clear mechanisms for credit recognition and progression between secondary and higher education perpetuates the isolated functioning of the two levels [11].

Resource constraints manifest as a shortage of qualified teachers, modern equipment, and opportunities for industry internships. This is particularly critical for the digital components of contemporary educational approaches, where unequal access to technology and varying levels of digital literacy generate significant disparities. Social barriers are evident in systemic inequalities, where disadvantaged learners, women, and students in rural areas face additional obstacles due to financial burdens, lack of local access, and prejudice.

Resistance to change among educators and institutions constitutes a significant challenge, stemming from familiarity with traditional practices, fear of the unknown, and the perception of innovations as additional workload. Integration with the business sector, although critical for the success of contemporary vocational education, encounters difficulties related to limited company resources, shifting priorities, and economic instability [12].

Employers rarely participate in curriculum design as equal partners, and real-world case studies are insufficiently utilized as educational material.

6. Conclusion and Perspectives

The systematic review of contemporary scientific literature reveals a complex picture of vocational education undergoing fundamental transformation towards Industry 4.0. Project-based learning, digital pedagogies, team-based learning, dual education models, and interdisciplinary integration are

established as critical components of an effective educational system. Empirical evidence for the effectiveness of these approaches is compelling, yet their fragmented and unsystematic implementation limits their potential impact.

The analysis identifies a significant gap in the existing literature: models integrating secondary vocational and higher specialized education through progressively complex interdisciplinary tasks in partnership with the business sector are lacking. This gap is particularly critical for technically complex sectors such as transport and energy, where real industrial challenges inherently involve multiple dimensions. Developing such integrated models requires coordinated policy, sectoral collaboration, and an innovative approach to curriculum design that aligns with emerging realities.

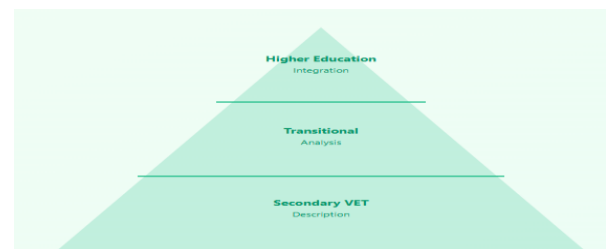


Figure 6: Progressive Complexity Model – Three-Tier Educational Progression

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