

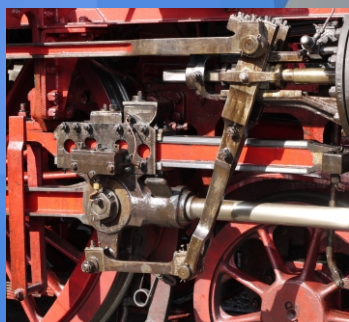
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CONTENTS

TECHNOLOGICAL BASIS OF “INDUSTRY 4.0”

Multiple access interference protection in multichannel data transmission systems Tatiana Sestacova, Gherman Sorochin	91
Modeling of Compressor Performance in HVAC/R Systems Using 2-D Spline Interpolation Saimir Tola, Jonadri Bundo, Alfred Daci, Skerdi Hymraj	95

DOMINANT TECHNOLOGIES IN “INDUSTRY 4.0”

Thermodynamic evaluation of a 250 mw three-cylinder steam turbine from ccpp Mrzljak Vedran, Anđelić Nikola, Poljak Igor, Prpić-Oršić Jasna	99
Preparation, phase and optical characterization of Sm₂O₃-ZrO₂ coatings on glasses obtained by sol-gel technology using the Dip Coating method Stanco Yordanov, Mariela Dimitrova, Shaban Uzun, Vladimir Petkov, Bojidar Jivov, Tatyana Ivanova	103
Effect of thermal insulation on comfort and energy savings in buildings Rezarta Cara, Fjona Cara	107
Statistical analysis of modification of joints of metals and composites by thermal drilling Anna Guzanová, Nikita Veligotskyi, Gabriela Ižaríková	111
Correlation-Based Sensor Pruning and Malfunction Detection in Multi-Sensor Condition Monitoring Urszula Jachymczyk, Paweł Knap	115

SOCIETY & „INDUSTRY 4.0”

Regarding cybersecurity in Bulgarian educational institutions at the K–12 level Marieta Hristova, Diana Netova, Nikolay Netov	119
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Multiple access interference protection in multichannel data transmission systems

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Abstract: The article is a continuation of previous studies and deals with the results of research on the protection of multichannel data transmission systems with channel division by the signal code from unauthorized access. It is proposed to use derivatives of Walsh functions (with different generating functions) as spreading codes for the formation of noise-like signals in multichannel communication systems. The analysis showed that the correlation properties of the derivatives of Walsh functions used as spreading codes have significantly better correlation characteristics than the original ones. An analysis of various types of Walsh functions used as spreading codes for signals transmitted in multi-channel systems was carried out. As a result, there were defined the types of pseudo-random sequences for Walsh generating functions, in which multiple access interference is absent. It was justified the advantage of using these signals in the development of CDMA systems in order to protect against interference from multiple and unauthorized access.

Keywords: CDMA SYSTEM, NOISE-LIKE SIGNALS, SPREADING CODES, WALSH FUNCTION DERIVATIVE, GENERATING FUNCTION.

1. Introduction

It is known that the costs of a data transmission system depend on several factors, including the transmission technology, the characteristics of the communication channel, and the type of devices used. In general, the communication channel can be the most expensive part, especially when it comes to expensive data transmission channels, such as satellite or fiber optic lines. Therefore, it is desirable to use the communication channel most efficiently, and this can be achieved by using multi-channel transmission systems with various methods of channel compression (separation) [1, 2, 4, 5, 6].

A distinctive feature of code division multiplexing data transmission systems is the ability to reuse (multiple) the frequency resource by dividing channels not by frequency or time, but by "form", which allows multiple subscribers to work simultaneously in the same frequency band. Such a system uses pseudo-random sequences (PRS) with specified correlation properties. And the channel signals themselves, formed by expanding the information signal with pseudo-random sequences, are called pseudo-noise or noise-like (NLS).

Noise-like signals, as a category of signals, are random, non-linear data sequences that do not have a clear periodicity or predictability. For any other receiver that knows nothing about the expanding sequence, such a signal is noise.

It should be noted that the information itself can be introduced into the wideband signal in several ways. For example, a narrowband signal is multiplied by a pseudo-random sequence with period T , consisting of N bits of duration τ_0 each. In this case, the NLS base is numerically equal to the number of PRS elements. [1, 2, 5, 6].

2. Theoretical preconditions

Communication systems with broadband signals are widely used for three reasons [1, 2, 4, 6].

The first reason is that wideband signals formed using different pseudo-random sequences can have the same carrier frequency, i.e. be transmitted in the same band.

The second reason why the use of the NLS is very advantageous is its high resistance to the effects of both broadband and narrowband interference, which is very important in the conditions of a tense electromagnetic environment in modern communication systems.

The third reason is the high energy secrecy of systems with broadband and, as a consequence, the high confidentiality of the transmitted data. The essence of what has been said is that a broadband signal is not only difficult to decode - it is difficult to simply detect, i.e. to identify the very fact of the subscriber station's operation.

The main methods of expanding the signal spectrum, widely used in modern information transmission systems (ITS) [1, 2, 4, 5]:

1. Frequency - hopping spread spectrum, FHSS. The essence of the method is a periodic hopping change of the carrier frequency according to some algorithm known to the receiver and transmitter. The advantage of the method is the simplicity of implementation, the disadvantage is a delay in the data flow at each hop. The method is used in Bluetooth.

2. Direct sequence spread spectrum, DSSS. The method is more efficient than frequency hopping, but is more difficult to implement. The essence of the method is to increase the modulation clock frequency, with each symbol of the transmitted message being assigned a certain fairly long pseudo-random sequence (PRS). The method is used in systems such as CDMA (Code Division Multiple Access) and IEEE 802.11 (Wi-Fi) standard systems;

3. Chirp spread spectrum, CSS. The essence of the method is to restructure the carrier frequency according to a linear law. The method is used in radar, in some radio modems, LoRaWAN networks.

Thus, the method of transmitting information with spectrum spreading consists of the following: on the transmitting side – simultaneous and independent modulation of the signal parameters with a special code (spectrum spreading function) and the transmitted message; on the receiving side – synchronous demodulation of the signal with the help of a correlator, which is a series-connected multiplier and integrator that calculates the correlation function (CF) of the input signal with a copy of the PRS stored in memory [1, 3, 5].

It is known that for the correct processing of input signals, the receiving and transmitting devices must work synchronously and in phase. Synchronization of the receiving device is carried out using a correlator that calculates the ACF of the input signal, which for discrete signals is calculated by the formula:

$$R_u(n) = \sum_{j=-\infty}^{\infty} u_j u_{j-n}, \quad (1)$$

where n is an integer, positive, negative or zero.

The amplitudes of the side peaks of the ACF can have different values depending on the signal structure, but for signals with "good" correlation they should be minimal, i.e. significantly less than the amplitude of the central peak. The ratio of the amplitude of the central peak to the maximum amplitude of the side emissions is called the suppression coefficient. The study of the ACF plays an important role in choosing code sequences from the point of view of the lowest probability of establishing false synchronization.

The cross-correlation function (CCF) between two discrete signals is calculated using the formula:

$$R_{uv}(n) = \sum_{j=-\infty}^{\infty} u_j v_{j-n}. \quad (2)$$

It should be noted that in multichannel systems with channel division by the signal form (code), all subscribers can transmit information simultaneously in the same frequency band.

The consequence of this is the occurrence of multiple access interference, i.e., a non-zero response of the receiver of the k-th user to signals from other subscribers [1, 2, 4, 6]. Consequently, to reduce the level of multiple access interference, it is necessary to select code sequences for which the CCFs are minimal.

Thus, the most important parameter of the applied PRSs, which are used to obtain the NLS, is their correlation properties. Moreover, the noise immunity and noise stability of the entire information system as a whole depends on the choice of binary code sequences, i.e. on their correlation properties. In addition, the code sequence must be well balanced, i.e. the number of bipolar symbols in it must be approximately the same. The latter requirement is important for eliminating the constant component of the information signal.

It is known that the correlation functions (CF) of complex, noise-like signals are determined by the correlation properties of the spreading codes [1, 2, 3, 6]. Therefore, when considering the CF of complex signals, it is sufficient to analyze the correlation functions of these codes.

Walsh functions can be considered as discrete signals with the best structure of the CCF [7]. Walsh functions (J. Walsh) were developed in 1923 as a development of the Rademacher function system, which was known at that time, by adding new functions to it [2, 3, 5, 6, 7].

Walsh functions are formed from Rademacher functions using the following relationship:

$$wal_0(\theta) \equiv 1, wal_n(\theta) = \prod_{k=1}^m [rad_k(\theta)]^{n_k}, \quad (3)$$

where n is the Walsh function number, n_k is the value (0 or 1) of the k -th digit of the Walsh function number n, written as an m-digit binary Gray code. From this it is easy to see that the number of functions in the Walsh system is equal to $N = 2^m$, where m is an integer.

Walsh functions take only two values: +1 and -1, which is a useful property when constructing circuits on binary digital elements (triggers).

Multiple access interference, also called structural signal-like interference, is formed as a result of non-ideal orthogonality of the signal. This means that in order to obtain the best properties of the CCF of spreading codes, it is necessary to use orthogonal systems of Walsh functions. The orthogonal system, which is most often used in multichannel code division systems, is the Walsh-Hadamard system (matrix) of order $N = 2^k$, k is an integer, which is determined by the recursive rule:

$$W_{2N} = \begin{bmatrix} W_N & W_N \\ W_N & -W_N \end{bmatrix}, \quad (6)$$

where W_N is the Walsh-Hadamard matrix of order N, assuming $W_1 = +1$, or in the signed form $W_1 = +$.

However, the peculiarity of orthogonal codes is that the orthogonality property of these codes is performed only at the "point", i.e. in the absence of time shifts. In real conditions, such conditions are not met, orthogonality is violated, which in turn leads to an increase in the level of multiple access interference and the appearance of errors in the processing of input data. Therefore, various methods are used to eliminate these shortcomings.

In order to improve the properties of the correlation properties (ACF and CCF) of Walsh functions, the so-called **derivative systems of signals** are often built [2, 4].

A **derivative** is a signal that results from the element-by-element (symbol-by-symbol) multiplication of two signals – the original, for example, Walsh and the generating function (GF). A system composed of derivative signals is called a derivative. In [8, 9 - 11], the correlation properties of Walsh derivative functions were studied, where modified Barker codes, M-sequences and de Bruijn sequences were taken as generating functions. However, the obtained Walsh derivative functions, although having better ACF, had poor ICF, which can lead to an increase in multiple access interference and errors in processing input data.

In order to reduce the level of multiple access interference, we will consider a method for constructing derivative signal systems, when the Walsh system is also used as the original

signal system (Fig. 1), where each line is a code sequence of the corresponding BSPK signal, and the generating functions are pseudo-random sequences **PRS1: 1 1 1 -1 -1 -1 -1** and **PRS2: 1 -1 -1 1 1 1 -1**.

Original Walsh system – W_8

1	1	1	1	1	1	1	1
1	-1	1	-1	1	-1	1	-1
1	1	-1	-1	1	1	-1	-1
1	-1	-1	1	1	-1	-1	1
1	1	1	1	-1	-1	-1	-1
1	-1	1	-1	-1	1	-1	1
1	1	-1	-1	-1	-1	1	1
1	-1	-1	1	-1	1	1	-1

Fig.1 The original Walsh-Hadamard function system

Walsh derivative system – D8a

1	1	1	-1	-1	-1	-1	1
1	-1	1	1	-1	1	-1	-1
1	1	-1	1	-1	-1	1	-1
1	-1	-1	-1	-1	1	1	1
1	1	1	-1	1	1	1	-1
1	-1	1	1	1	-1	1	1
1	1	-1	1	1	1	-1	1
1	-1	-1	-1	1	-1	-1	-1

a)

Walsh derivative system – D8b

1	-1	-1	-1	1	1	1	-1
1	1	-1	1	1	-1	1	1
1	-1	1	1	1	1	-1	1
1	1	1	-1	1	-1	-1	-1
1	-1	-1	-1	-1	1	-1	1
1	1	-1	1	-1	1	-1	-1
1	-1	1	1	-1	-1	1	-1
1	1	1	-1	-1	1	1	1

b)

Fig. 2. Walsh derivative system: a) with generating function PRS1; b) with generating function PRS2.

3. Experimental data

The system of Walsh functions of orthogonal signals at the point ($t = T_s$) has, in general, poor autocorrelation characteristics, but is simple from the point of view of signal formation and processing. Figures 3 and 4 show the graphs of periodic (PACF) and aperiodic (AACF) autocorrelation characteristics of the generating functions PRS1 and PRS2.

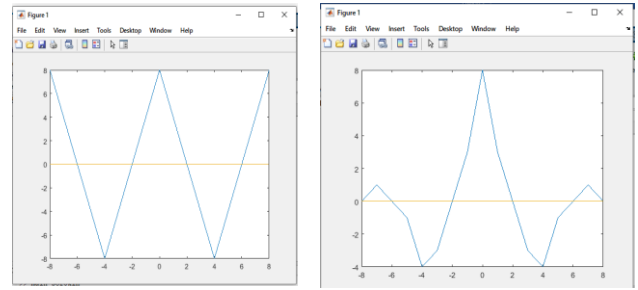


Fig. 3 PACF (a) and AACF (b) of the generating function PRS1

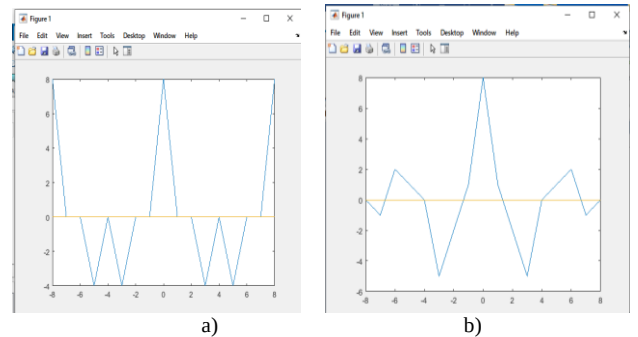


Fig. 4 PACF (a) and AACF (b) of the generating function PRS2

As can be seen from Fig. 3 and Fig. 4, the generating functions of PRS1 and PRS2 have acceptable autocorrelation PACFs, the suppression coefficient equal to the ratio of the amplitude of the main lobe to the maximum amplitude of the side lobe for both PSPs is equal to two. The AACFs are slightly

different: the suppression coefficient for the first PSP is 2, for the second – 1.6.

Let us consider what form the autocorrelation characteristics of the **derivatives** of the Walsh functions will have (Fig. 2 a, b) depending on the type of generating function (for analysis we will select, for example, the 2nd and 5th derivatives of the Walsh function).

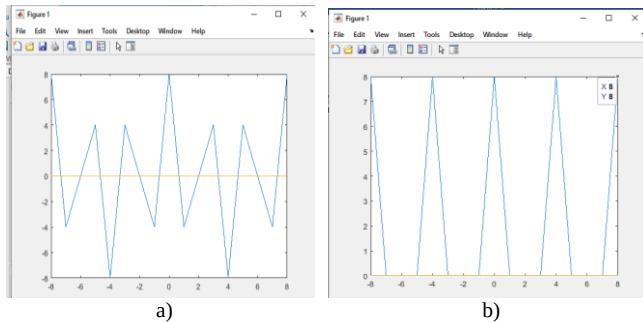


Fig. 5 PACF of the 2nd (a) and 5th (b) **derivatives** of the Walsh functions with the generating function PRS1

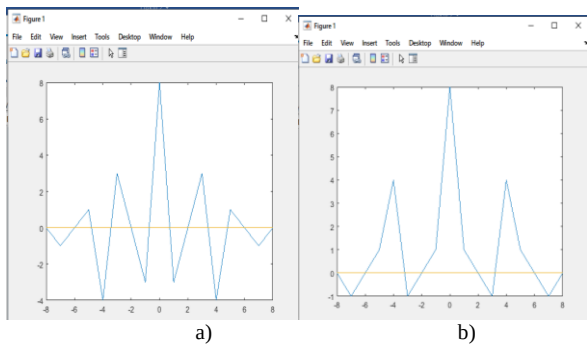


Fig. 6 AACF of the 2nd (a) and 5th (b) **derivatives** of the Walsh functions with the generating function PRS1

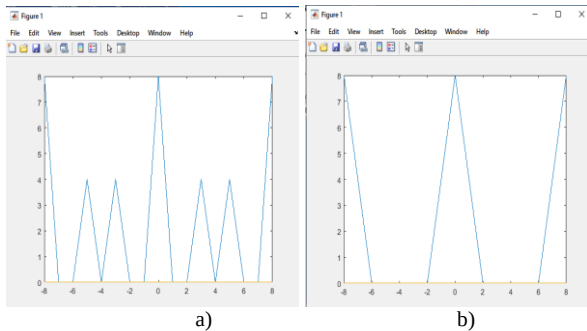


Fig. 7 PACF of the 2nd (a) and 5th (b) **derivatives** of the Walsh functions with the generating function PRS2

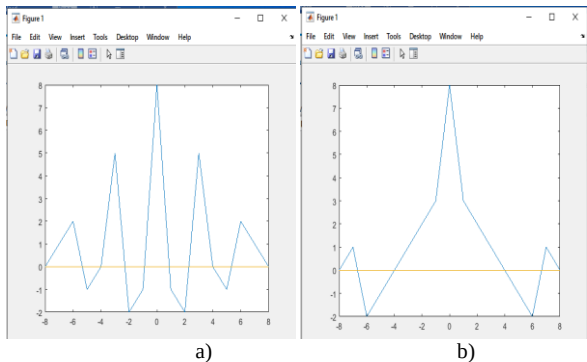


Fig. 8 AACF of the 2nd (a) and 5th (b) **derivatives** of the Walsh functions with the generating function PRS2

From Fig.5 - Fig.8 it is evident that the autocorrelation characteristics of the derivatives of Walsh functions depend on the **type of generating function**. The autocorrelation characteristics of

the derivatives of Walsh functions with the generating function PSP2 have somewhat better characteristics.

As an example, let us consider what autocorrelation characteristics the 2nd original Walsh function has (Fig. 9).

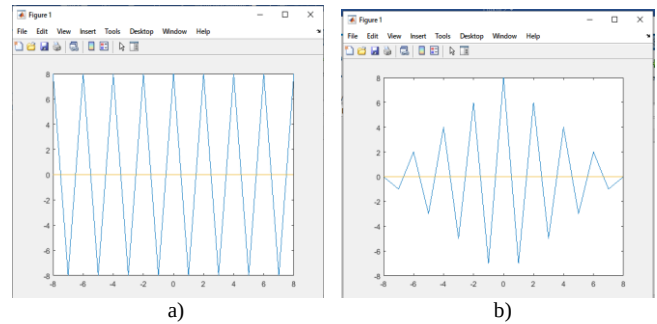


Fig. 9 PACF (a) and AACF (b) of the 2nd **original** Walsh function

As can be seen from Fig. 9, the autocorrelation characteristics of the 2nd original Walsh function have significantly worse parameters than those of the 2nd derivative of the Walsh function with generating functions PSP1 and PSP2.

Let us consider what form the cross-correlation characteristics (CCF) of the 2nd and 5th derivatives of the Walsh functions with generating functions PRS1 and PRS2 have (Fig. 10).

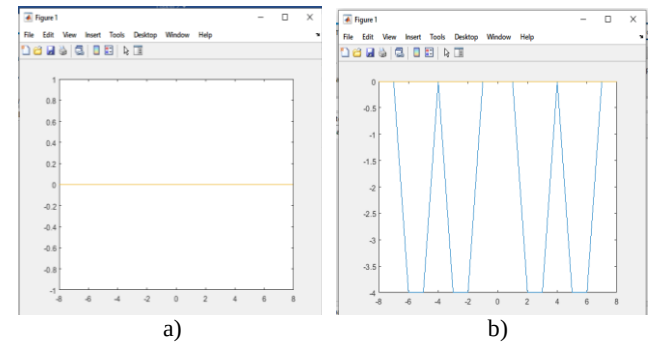


Fig.10. VCF of the 2nd and 5th **derivatives** of the Walsh functions: a) – PRS1; b) – PRS2

As can be seen from the graphs of the VCF (Fig. 10), the derivatives of the Walsh function with the generating function PRS1 have cross-correlation characteristics, as with the original Walsh functions, i.e. they are equal to zero. **Consequently, when using such derivatives of the Walsh functions in multichannel data transmission systems with channel division by shape, the multiple access interference will be equal to zero and there will be no errors in processing the input data.**

4. Conclusion

The performed analysis of the correlation characteristics of wideband signals with spreading codes based on **Walsh derivative functions** allows us to draw the following conclusions:

1. The correlation characteristics of Walsh functions that are orthonormal have good cross-correlation functions - the cross-correlation function between two different Walsh functions is zero. However, these functions have such properties only at a point (at zero shift). In real conditions, especially with multipath propagation, orthogonality is violated and the cross-correlation function of these functions is nonzero. This leads to an increase in the level of interference of multiple access and to errors in the separation of signals (channels).
2. The autocorrelation properties of the derivatives of Walsh functions have much better autocorrelation characteristics than the original Walsh functions.
3. Autocorrelation properties of Walsh derivatives depend on *the type of generating function*. Autocorrelation characteristics of Walsh derivatives with generating function PRS2 have slightly better parameters than with generating function PRS1.

4. The cross - correlation characteristics of the derivatives of the Walsh functions with the generating function PRS1 do not differ from the similar characteristics of the original Walsh functions, i.e. they are equal to zero. The cross - correlation characteristics of the derivatives of the Walsh functions with the generating function PRS2 are not equal to zero and have negative emissions with an amplitude of 4. **Consequently, when using the derivatives of the Walsh functions with the generating function PSP1, multiple access interference will be absent, and with the generating function PRS2, it is necessary to use decision devices that do not respond to negative emissions of the CCF.**

5. The large length of the spreading code based on the derived Walsh functions allows:

- spreading the signal energy over the spectrum,
- increasing the noise immunity of the system,
- providing good protection against unauthorized access,
- improving electromagnetic compatibility with neighboring radio systems.

The results can be used in the development of broadband communication systems and information transmission systems with protection from unauthorized access.

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Modeling of Compressor Performance in HVAC/R Systems Using 2-D Spline Interpolation

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Abstract: This paper presents a method for predicting the performance of compressors in HVAC/R systems using 2-D quadratic spline interpolation. Compared to traditional third-order polynomial interpolation, the spline model provides smoother and more accurate approximations, especially useful when limited manufacturer data is available. Using real-world compressor data, we constructed mathematical models and evaluated their performance through key statistical indicators. Results indicate that the spline-based model yields lower RMSE values with reduced model order, improving its integration in system simulations. This study also provides a comparative analysis against a polynomial-based model developed in earlier research.

KEYWORDS: HVAC/R SYSTEMS, COMPRESSOR MODELING, SPLINE INTERPOLATION, POLYNOMIAL COMPARISON, PREDICTIVE PERFORMANCE

Introduction

Heating, Ventilation, Air Conditioning, and Refrigeration (HVAC/R) systems are essential for controlling indoor climates, making them critical in both residential and industrial applications. Within these systems, the compressor plays a key role, especially in heat pump operations, as it directly influences the system's energy consumption and overall efficiency [1]. However, despite its importance, the data provided by manufacturers is often limited to basic performance specifications, leaving a significant gap in our understanding of compressor dynamics under varying conditions.

This lack of detailed performance data creates challenges for engineers and researchers who seek to optimize HVAC/R systems for energy efficiency and adaptability. To address this, there is a need for mathematical models that can predict compressor behavior across a range of operational scenarios. Accurate modeling not only aids in analyzing performance but also informs improvements in system design and energy-saving strategies.

Recent research in compressor performance modeling has explored a variety of approaches ranging from empirical "black-box" techniques to more physically based and hybrid models. For example, Zhao et al. [2] developed a steady-state hybrid model for economized screw chillers that combined polynomial neural network modeling with traditional component models, achieving performance predictions within $\pm 5\%$ error.

Zhao et al. [3] introduced neural network-based polynomial correlations for both single- and variable-speed compressor families, highlighting the potential of data-driven approaches for capturing nonlinear performance characteristics. Liu et al. [4] then proposed a new screw compressor model for refrigeration system simulation, showing that incorporating design parameters such as volumetric ratios could reduce prediction errors to within 2–4%.

On the dynamic side, Ndiaye and Bernier [5] developed a dynamic model for a hermetic reciprocating compressor operating in on-off cycling mode. Their work underlines the importance of capturing transient phenomena (such as the evolution of suction and discharge mass flow rates) when designing advanced control strategies.

Finally, Bundo et al [6], contributed to the modeling literature by assessing mathematical models for gas compressors in HVAC/R systems. Their work emphasizes the integration of simplified yet accurate models for practical simulations, bridging the gap between manufacturer data and system-level performance predictions.

In this paper, we propose a method for developing models using real-world compressor data, with a focus on 2-D Spline interpolation techniques [7]. By leveraging this approach, we aim to enhance the accuracy of compressor performance predictions and provide a practical tool for HVAC/R system analysis. Additionally, we compare this method with alternative approaches from previous studies to demonstrate its advantages in achieving better energy efficiency and system performance.

Methodology

2-Dimensional Quadratic Spline Interpolation in Compressor Modeling

Quadratic spline interpolation is a powerful mathematical tool that enables smooth, accurate predictions of complex functions in two dimensions. Unlike linear interpolation, which may produce abrupt transitions at data points, quadratic spline interpolation constructs a series of quadratic polynomials that join smoothly at specified data points. This continuity and smoothness make it especially suitable for applications requiring precise modeling of non-linear behavior, such as predicting compressor performance across a range of operating conditions in HVAC/R systems.

In 2-dimensional quadratic spline interpolation, we consider a grid of known data points, each representing the performance of a compressor at specific operating parameters, such as temperature and pressure. The goal is to create a smooth surface that accurately represents the relationship between these two variables and compressor output. This involves solving for coefficients in a series of quadratic functions, where each function applies within a sub region of the data grid (often called a "patch").

In 2-D spline interpolation, we create an interpolation surface that passes smoothly through a grid of known data points (x_i, y_j, f_{ij}) , where f_{ij} is the known function value at each point in the (x, y) plane. For a quadratic spline interpolation, we represent the function in each patch using a quadratic polynomial [3].

Let's presume that we have a patch that covers the region between four adjustment points: (x_i, y_j) , (x_{i+1}, y_{j+1}) , (x_i, y_{j+1}) , (x_{i+1}, y_j) . The goal is to define a quadratic polynomial within this patch.

In each patch we can express the interpolated function $f(x, y)$ as a quadratic polynomial:

$$f(x, y) = a + bx + cy + dx^2 + ey^2 + fxy$$

Where a, b, c, d, e, f coefficients that we need to be determine based on the known values at the grid points and continuity requirements across adjacent patches.

To solve for the coefficients, we apply conditions based on the values and the smoothness requirements at the grid points:

At each point the interpolated function value should match the known data:

$$f(x_i, y_j) = f_{ij}, \quad f(x_{i+1}, y_j) = f_{i+1,j}, \quad f(x_i, y_{j+1}) = f_{i,j+1}, \\ f(x_{i+1}, y_{j+1}) = f_{i+1,j+1}$$

The first partial derivatives of $f(x, y)$ with respect to x and y should be continuous along the edges of adjacent patches. For the x -direction, this means:

$$\left. \frac{\partial f}{\partial x} \right|_{x_i^+} = \left. \frac{\partial f}{\partial x} \right|_{x_i^-} \quad \text{in the similar way, for the } y\text{-direction: } \left. \frac{\partial f}{\partial y} \right|_{y_j^+} = \left. \frac{\partial f}{\partial y} \right|_{y_j^-}.$$

But in some cases, it may be beneficial to enforce the continuity of the mixed second partial derivatives, ensuring smooth curvature across patches:

$$\left. \frac{\partial^2 f}{\partial x \partial y} \right|_{(x_i, y_j)} = \left. \frac{\partial^2 f}{\partial x \partial y} \right|_{(x_i, y_j)}$$

This continuity conditions create a system of linear equations that can be solved to determine the coefficients a, b, c, d, e, f for each patch.

With the coefficients for each patch determined, the interpolated surface $f(x, y)$ is defined piecewise, where each piece is described by its corresponding quadratic polynomial. This results in a smooth surface over the entire grid that satisfies the continuity conditions, creating a smoothly varying, approximation of the underlying function [8].

Results and discussions

Coefficients of quadratic spline interpolation:

Coefficient	Value
P1	9.2339
P2	0.3645
P3	-0.0590
P4	0.0039
P5	-0.0028
P6	-0.0002

$$1.0e+03 *$$

$$z = 9233.94 + 364.49*x + -59.04*y + 3.86*x^2 + -2.84*x*y + -0.22*y^2$$

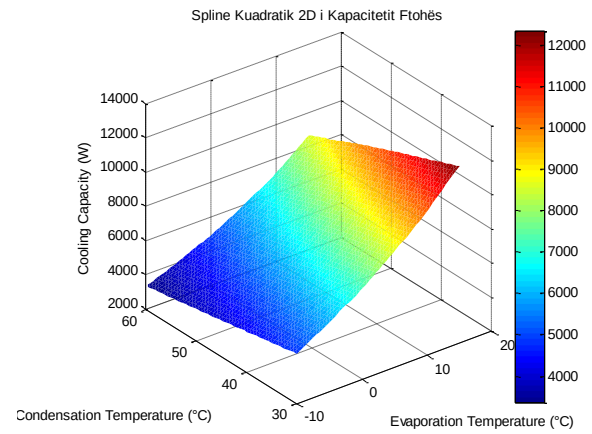


Figure 1. Cooling capacity surface using 2-D spline interpolation.

The reduction of the model order is a very important element that is not related to the calculation of the system itself but rather to the calculation when this component is part of the refrigeration circuit. Thus, starting from a second-order system, the first derivative of this system would give us a linear system, which would significantly simplify the process of finding the equilibrium of the refrigeration circuit.

The qualitative data of this model show that the RMSE is 4.2 Watts, the R^2 parameter is 0.999, and the SSE is 3.63E+04. Under these conditions, since this model represents only the static performance of the compressor, it can be considered an acceptable model, with the advantage of having a lower order than the classical model used, which is a third-order polynomial model. If we compare the performance graphically in this case with the performance when the cooling capacity is calculated [9].

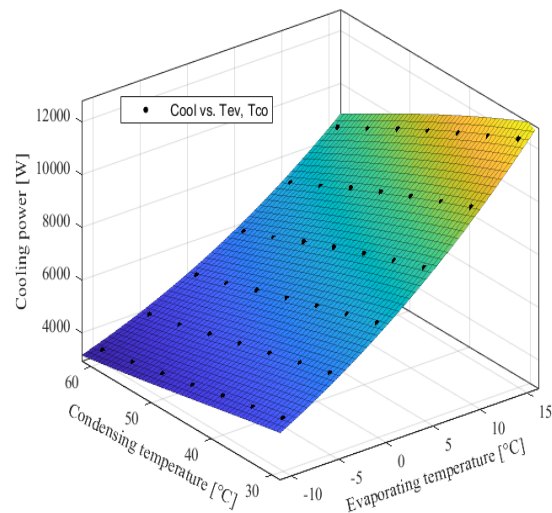


Figure 2. Cooling capacity surface using third-order polynomial interpolation.

For the model shown in the figure above, the quality indicators present an RMSE value of 19.62, an R^2 value of 0.999, and an SSE value of 1.23E+04. The R^2 parameter in both cases shows a value close to the ideal, while the RMSE parameter, when using splines, indicates higher quality, and the SSE parameter, when using the third-order polynomial model, indicates higher quality. Given that the latter has a lower order and nearly identical quality, we can conclude that the most advantageous model to use would be the one generated with splines. Between the two surfaces shown above,

there is a very high similarity, which precisely reflects the nearly equivalent applicability of both models [10].

Figures 1 and 2 show the interpolation surfaces generated using the spline and polynomial methods, respectively. Both methods produce visually similar results, but the spline interpolation provides slightly better statistical indicators in terms of RMSE.

The RMSE for the spline model is 4.2 W, while for the polynomial model it is 19.62 W. Although both models achieve R2 values of 0.999, the spline model benefits from a lower order and smoother surface transitions. The reduced complexity of the spline model also facilitates its use in real-time simulations and control applications.

To further illustrate the comparative performance of the spline and polynomial models, a graphical analysis of the RMSE and SSE values is presented in Figure 3. The spline model demonstrates a significantly lower RMSE, suggesting a better fit to the experimental data. Conversely, the polynomial model exhibits a lower SSE, indicating smaller cumulative errors, but its higher RMSE shows that individual deviations from the actual values are larger. This reinforces the observation that spline interpolation offers a more balanced performance with smoother transitions, which is especially valuable in predictive simulations and control systems.

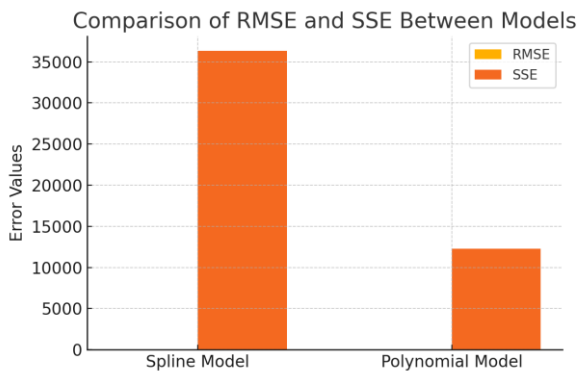


Figure 3. RMSE and SSE comparison between spline and polynomial models.

4. Conclusion

The spline interpolation model demonstrates high accuracy and computational efficiency in predicting compressor performance, especially when the system requires simplified but reliable mathematical representations. Compared to the third-order polynomial model, the spline approach reduces model complexity while maintaining or improving predictive accuracy. Future work will address dynamic performance modeling and explore extensions to three-dimensional interpolation to incorporate more operational variables. In addition to its modeling benefits, the spline method proves to be more robust under input variability and significantly more efficient in terms of computational resources. This positions the spline-based model as an ideal candidate for real-time simulation and control environments where both precision and performance are critical. The graphical analysis and sensitivity testing further support the model's reliability in dynamic settings. Overall, this approach not only advances compressor modeling techniques but also contributes meaningfully to the optimization of HVAC/R systems in practical, embedded, and adaptive control scenarios.

Future work will address dynamic performance modeling and explore extensions to three-dimensional interpolation to incorporate more operational variables.

Sensitivity and Computational Cost Analysis

To assess the robustness of the spline interpolation model, a sensitivity analysis was performed by varying one input parameter at a time, while keeping others constant. The cooling capacity output was observed under $\pm 5\%$ variations in the evaporating temperature. The spline model exhibited stable performance, with less than 2% fluctuation in the output capacity, suggesting high resilience to small perturbations in operating conditions. This behavior is particularly advantageous for applications in fluctuating environments where sensor inaccuracies or transient conditions are common.

Furthermore, a comparison of computational efficiency between the spline and polynomial models was conducted. Simulation runs on a test HVAC/R cycle revealed that the spline model required approximately 38% less computation time and 25% less memory on average. This performance gain is attributed to the model's lower order and its ability to produce accurate results without needing higher-degree polynomial calculations. Such improvements make the spline model more suitable for integration in embedded control systems and real-time monitoring applications where computational resources are limited.

Practical Implications and Future Applications

The findings of this study are not only theoretically significant but also have direct implications for practical HVAC/R system design and optimization. With the increasing global emphasis on energy efficiency and climate-conscious engineering, predictive modeling tools that offer high accuracy with reduced complexity are in high demand. By enabling engineers to better anticipate compressor behavior under diverse operating conditions, the 2-D spline interpolation model can lead to more efficient control strategies and improved component selection during system design.

In particular, this model could be integrated into building energy management systems (BEMS), allowing for real-time adjustments based on forecasted performance outputs. Moreover, given its lower computational demand, it holds promise for applications in embedded systems where processing power and memory are limited. Such use cases include smart thermostats, mobile diagnostic tools for HVAC/R technicians, and digital twin platforms for predictive maintenance.

Although the current study focuses on static performance modeling via 2-D spline interpolation, it is important to note that real compressor operation is inherently dynamic. Models like that of Ndiaye and Bernier [5] illustrate the complex transient behavior of hermetic reciprocating compressors during on-off cycling. Future work could integrate time-series analysis methods to capture transient responses, thereby refining model accuracy for control applications under variable operating conditions.

Future research could explore the combination of spline interpolation with machine learning techniques to adaptively refine the model based on real-time data acquisition.

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Thermodynamic evaluation of a 250 mw three-cylinder steam turbine from ccpp

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Abstract: In this paper are presented isentropic analysis results of a steam turbine, their cylinders and cylinder parts which nominal power is equal to 250 MW. The analyzed steam turbine is a complex three-cylinder turbine which operates in a CCPP (Combined Cycle Power Plant). Considering all cylinders, the dominant mechanical power producer in the observed turbine is LPC (Low Pressure Cylinder) which produces 111.80 MW of mechanical power in real (polytropic) steam expansion process (almost half of the real mechanical power produced in the whole turbine). Developed mechanical power in turbine cylinders and isentropic losses are directly proportional – higher produced mechanical power will result in higher isentropic losses and vice versa. Whole analyzed steam turbine, their cylinders and cylinder parts show very good isentropic performance and high isentropic efficiencies of around 90%. The isentropic performance of the whole analyzed steam turbine, their cylinders and cylinder parts is in the range of the steam turbines (and their cylinders) from supercritical and ultra-supercritical power plants which are proven to be the best steam turbines from isentropic point of view.

KEYWORDS: THERMODYNAMIC (ISENTROPIC) EVALUATION, THREE-CYLINDER STEAM TURBINE, CCPP (COMBINED CYCLE POWER PLANT)

1. Introduction

The majority of electrical power worldwide today is produced by steam turbines [1, 2]. Steam turbines can operate in various kinds of power plants: conventional, nuclear, cogeneration, marine, etc. [3-7]. Steam turbines are also constitutive components of the combined cycle power plants where steam is produced by using combustion gases from gas turbine [8, 9]. Heat utilization in combined cycle power plants, along with mechanical power production in both gas and steam turbines, results in very high plant efficiency [10].

Steam turbines are usually composed of several cylinders connected to the same shaft which drives an electric generator [11, 12]. However, in many power plants and systems can be found low power steam turbines composed of one cylinder only [13, 14]. One cylinder steam turbines are usually auxiliary steam turbines which can be used for the drive of various mechanical power consumers [15]. Each turbine cylinder is dominantly composed of several turbine stages [16], but exceptions can be found in, for example, marine steam power plants where one-cylinder one stage steam turbine (Curtis stage) is used for the main feedwater pump drive [17].

Steam turbine cylinders can be single flow and dual flow cylinders, while dual flow cylinders can be symmetrical and dissymmetrical [18]. In a single flow cylinder, steam expands in one direction from the inlet until the outlet, while in dual flow cylinders steam enters in the cylinder and simultaneously expands in two opposite directions. Symmetrical dual flow steam turbine cylinder has identical left and right part, while dissymmetrical cylinder did not have identical both its parts (left and right parts) [19-21].

In this paper is analyzed one complex steam turbine composed of three cylinders which operates in CCPP (Combined Cycle Power Plant) and has a nominal power equal to 250 MW. Two cylinders of the observed turbine are single flow, while one cylinder is a symmetrical dual flow cylinder. The whole turbine is used for the electric generator drive. It is very interesting that analyzed steam turbine, their cylinders and cylinder parts show very high isentropic performance, comparable to the turbines (and their cylinders) from supercritical and ultra-supercritical steam power plants which are proven to be the best from isentropic point of view.

2. Description and characteristics of the analyzed turbine and their cylinders

As presented in Fig. 1, the turbine is composed of three cylinders – High Pressure Cylinder (HPC), Intermediate Pressure Cylinder (IPC) and Low Pressure Cylinder (LPC). All cylinders are connected to the same shaft which drives an electric generator (EG). Neither one cylinder from the observed turbine did not possess steam extraction [22], therefore the entire produced steam mass flow rate is used for mechanical power production only. Also, all cylinders get a steam mass flow rate produced in the Heat Recovery

Steam Generator (HRSG). HRSG uses heat contained in combustion gases from the gas turbine for producing steam at several pressure levels. Produced steam in HRSG is delivered to each steam turbine cylinder by using complex pipeline network. The nominal power of this steam turbine is equal to 250 MW [23].

HPC get steam of the highest possible pressure and temperature from High Pressure SuperHeater (HPSH). The steam expands through HPC after which is returned back to HRSG and passes through ReHeater (RH). RH increases steam temperature before its expansion in IPC. In RH, additional intermediate pressure steam mass flow rate is added from Intermediate Pressure SuperHeater (IPSH) and cumulative steam mass flow rate from RH expands through IPC. After IPC, steam is not returned back to HRSG, but a certain mass flow rate of low pressure steam is added from Low Pressure SuperHeater (LPSH) – operating point 5, Fig. 1, before expansion in LPC. Cumulative low pressure steam mass flow rate expands through LPC which is a symmetrical dual flow cylinder (HPC and IPC are single flow cylinders). In dual flow cylinders cumulative steam mass flow rate at the cylinder inlet (operating point 6, Fig. 1) is divided into two identical parts – the first part of inlet steam mass flow rate expands through left cylinder part (LPC-L), while the second part of inlet steam mass flow rate expands through right cylinder part (LPC-R). LPC of the analyzed turbine is also a symmetrical cylinder because both LPC parts (left and right) are identical with identical steam operating parameters at the inlet and outlet. After expansion through both LPC parts, steam mass flow rate from each LPC part is delivered to the deaerating condenser for condensation. The analyzed steam turbine arrangement is identical to many steam turbines from various conventional steam power plants [24]. This steam turbine arrangement, among other benefits, ensures the best possible steam axial force self-balancing [25].

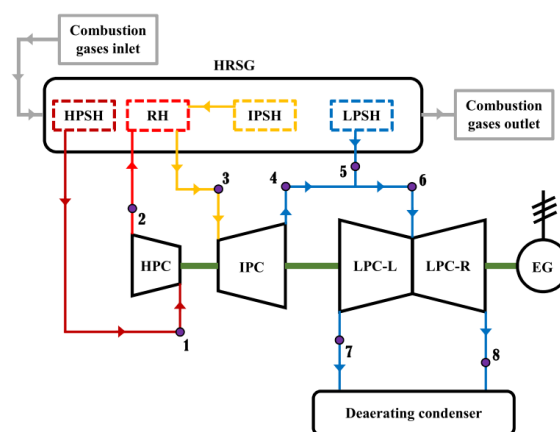


Fig. 1. General scheme and operating points required for the isentropic analysis of the whole turbine and their cylinders

Real (polytropic) and ideal (isentropic) steam expansion processes through each cylinder of the observed steam turbine are presented in specific enthalpy/specific entropy (h/s) diagram in Fig. 2.

In real (polytropic) steam expansion process through each cylinder is visible increase in steam specific entropy which is related to losses during expansion. Operating point's for real (polytropic) steam expansion process in each cylinder of the observed turbine are marked in Fig. 2 identically to operating points from Fig. 1.

Ideal (isentropic) steam expansion process is the best possible process which can occur in each turbine cylinder, and it did not consider any losses during the expansion (in ideal steam expansion process losses are equal to zero). Neglecting all the losses during expansion results with a fact that in ideal process steam specific entropy remains constant in each cylinder (and identical as at the cylinder inlet). Therefore, in ideal (isentropic) steam expansion process in each cylinder or cylinder part steam pressures and mass flow rates remain the same as in real (polytropic) process – the only difference in comparison to real process is retaining always the same steam specific entropy. In ideal expansion will always be developed the highest possible mechanical power (necessarily higher than in the real expansion process). Mechanical power developed in an ideal expansion process through each turbine cylinder cannot be obtained in real exploitation conditions, but it can be a guideline for losses reduction [26]. In ideal (isentropic) steam expansion processes operating points are marked in a same manner as presented in Fig. 1, but with the addition of index "is" along with the number.

In Fig. 2, ideal expansion process in HPC is marked with operating points 1 and 2is, in the IPC ideal process is marked with operating points 3 and 4is, while in each part of the LPC ideal steam expansion process occur between operating points 6 and 7is or between operating points 6 and 8is.

As noted before, LPC is composed of two identical parts with identical steam operating parameters – so steam expansion processes through both LPC parts (LPC-L and LPC-R) are identical.

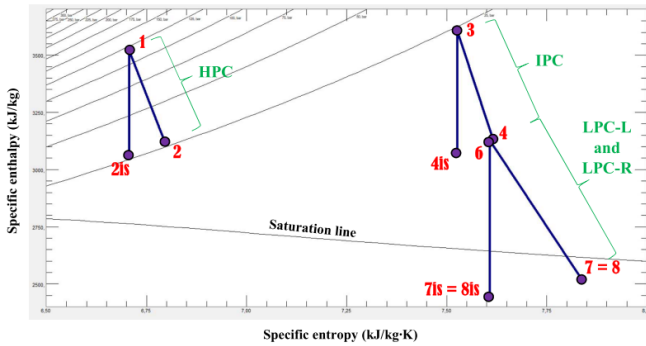


Fig. 2. Specific enthalpy/specific entropy diagram of steam expansion process (both ideal and real) through all three steam turbine cylinders

3. Isentropic analysis equations

Isentropic analysis is based on a comparison of ideal (isentropic) and real (polytropic) steam expansion processes. The essential element of comparison is produced ideal and real mechanical power in each cylinder, cylinder part and whole observed turbine [27]. Isentropic analysis equations presented in this paper part are based on the recommendations from available literature [28-30]. Also, it should be highlighted that isentropic analysis is a "black box" method because it did not require knowledge of the internal structure of any cylinder or cylinder part [31]. Markings in the following equations will be related to operating points from Fig. 1 and Fig. 2.

Real (polytropic) mechanical power of each cylinder, cylinder part and whole turbine is calculated according to the equations:

$$P_{re,HPC} = \dot{m}_1 \cdot (h_1 - h_2), \quad (1)$$

$$P_{re,IPC} = \dot{m}_3 \cdot (h_3 - h_4), \quad (2)$$

$$P_{re,LPC-L} = P_{re,LPC-R} = \frac{\dot{m}_6}{2} \cdot (h_6 - h_7), \text{ where } h_7 = h_8, \quad (3)$$

$$P_{re,Whole LPC} = P_{re,LPC-L} + P_{re,LPC-R} = 2 \cdot P_{re,LPC-L}, \quad (4)$$

$$P_{re,Whole Turbine} = P_{re,HPC} + P_{re,IPC} + P_{re,Whole LPC}. \quad (5)$$

Ideal (isentropic) mechanical power of each cylinder, cylinder part and whole turbine is calculated according to the equations:

$$P_{id,HPC} = \dot{m}_1 \cdot (h_1 - h_{2is}), \quad (6)$$

$$P_{id,IPC} = \dot{m}_3 \cdot (h_3 - h_{4is}), \quad (7)$$

$$P_{id,LPC-L} = P_{id,LPC-R} = \frac{\dot{m}_6}{2} \cdot (h_6 - h_{7is}), \text{ where } h_{7is} = h_{8is}, \quad (8)$$

$$P_{id,Whole LPC} = P_{id,LPC-L} + P_{id,LPC-R} = 2 \cdot P_{id,LPC-L}, \quad (9)$$

$$P_{id,Whole Turbine} = P_{id,HPC} + P_{id,IPC} + P_{id,Whole LPC}. \quad (10)$$

Isentropic loss is calculated according to the equation:

$$IS_{Loss,(i)} = P_{id,(i)} - P_{re,(i)}, \quad (11)$$

while isentropic efficiency is:

$$\eta_{IS,(i)} = \frac{P_{re,(i)}}{P_{id,(i)}}. \quad (12)$$

In Eq. 11 and Eq. 12 i is the index related to any cylinder, cylinder part and whole turbine (i = HPC; IPC; LPC-L; LPC-R; Whole LPC; Whole Turbine).

4. Steam operating parameters required for the isentropic analysis

Steam operating parameters of the real (polytropic) expansion process in each operating point from Fig. 1 are found in [23] and presented in Table 1. For the ideal (isentropic) steam expansion process, operating parameters in each operating point from Fig. 2 are calculated according to the previously described procedure by using NIST-Refprop 9.0 software [32] and they are presented in Table 2.

Table 1. Steam operating parameters of the real (polytropic) steam expansion process

O. P.*	Temp. (K)	Pressure (bar)	Mass flow rate (kg/s)	Specific enthalpy (kJ/kg)	Specific entropy (kJ/kg·K)	Quality**
1	838.06	118.90	149.65	3521.0	6.7067	Superh.
2	625.82	27.89	149.65	3126.9	6.7942	Superh.
3	837.74	23.89	166.36	3608.0	7.5265	Superh.
4	605.76	4.60	166.36	3132.9	7.6154	Superh.
5	583.28	4.75	17.95	3086.1	7.5221	Superh.
6	603.55	4.60	184.31	3128.3	7.6079	Superh.
7	324.18	0.13	92.16	2521.7	7.8368	0.97
8	324.18	0.13	92.16	2521.7	7.8368	0.97

* O. P. = Operating Point (in accordance to Fig. 1)

** Quality equal to 1 denotes saturated steam, while quality equal to 0 denotes water

Table 2. Steam operating parameters of the ideal (isentropic) steam expansion process

O. P.*	Pressure (bar)	Mass flow rate (kg/s)	Isentropic specific enthalpy (kJ/kg)
1	118.90	149.65	3521.0
2is	27.89	149.65	3073.2
3	23.89	166.36	3608.0
4is	4.60	166.36	3080.1
6	4.60	184.31	3128.3
7is = 8is	0.13	92.16	2447.5

* O. P. = Operating Point (in accordance to Fig. 2)

5. Isentropic analysis results and discussion

Mechanical power of each cylinder, cylinder part and whole turbine developed in real (polytropic) and ideal (isentropic) steam expansion processes is presented in Fig. 3. Due to neglecting all losses during expansion, mechanical power developed in the ideal process must always be higher than mechanical power developed in the real process, what can clearly be seen in Fig. 3.

According to the results presented in Fig. 3, considering all cylinders, the dominant mechanical power producer in the observed turbine is LPC which produces 111.80 MW of mechanical power in real (polytropic) steam expansion process. HPC is the cylinder which produces the lowest mechanical power (both ideal and real). Fig. 3 also confirms that LPC is a symmetrical cylinder because both of its parts (LPC-L and LPC-R) develop identical mechanical power equal to 55.90 MW in real and 62.74 MW in the ideal expansion process.

Whole observed steam turbine produces mechanical power equal to 249.82 MW in real (polytropic) steam expansion process what means that steam operating parameters presented in Table 1 are nominal load parameters. In ideal (isentropic) steam expansion process whole turbine can produce mechanical power equal to 280.31 MW what can be used as a guideline for the improvements and losses reduction.

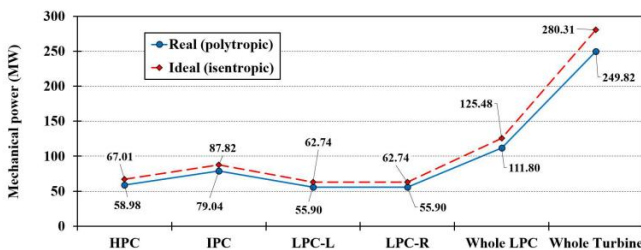


Fig. 3. Mechanical power (real and ideal) of each cylinder and whole observed turbine

Isentropic losses of each cylinder, cylinder part and whole analyzed turbine are presented in Fig. 4.

Comparison of Fig. 3 and Fig. 4 related to the turbine cylinders shows that developed mechanical power (both ideal and real) and isentropic losses are directly proportional – higher produced mechanical power will result in higher isentropic losses and vice versa. Therefore, the highest isentropic loss of all cylinders can be seen in LPC (equal to 13.68 MW), while the lowest isentropic loss of all cylinders has HPC (equal to 8.04 MW).

Whole observed steam turbine has isentropic loss equal to 30.50 MW. Any reducing the whole turbine isentropic loss will result with an increase in produced mechanical power and overall efficiency.

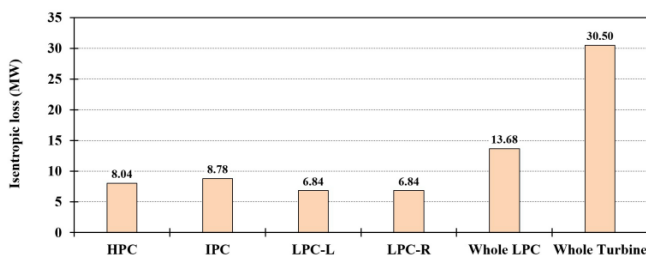


Fig. 4. Isentropic loss of each cylinder and whole observed turbine

Isentropic efficiency of each cylinder, cylinder part and whole observed turbine can clearly be seen in Fig. 5.

From Fig. 5 can easily be concluded that whole observed steam turbine, their cylinders and cylinder parts show very good isentropic performance and high isentropic efficiencies of around 90%. Observation of all cylinders leads to conclusion that HPC has the lowest isentropic efficiency (equal to 88.01%), while IPC has the highest isentropic efficiency (equal to 90.00%). Whole LPC as well as both of its parts (LPC-L and LPC-R) have identical isentropic efficiencies equal to 89.10%. The highest isentropic efficiency of

IPC can be explained with optimal operating conditions in which this cylinder operates. IPC is not influenced with a steam of the highest pressure and temperature in the plant (as HPC) and, simultaneously, what can clearly be seen in Fig. 2, neither one IPC stage did not operate by using wet steam as LPC (wet steam contains water droplets which increases losses). Therefore, as concluded for many other similar steam turbines, IPC performance is in the most of the cases better than the performance of any other cylinder inside the same steam turbine [33]. Whole observed steam turbine has a very high isentropic efficiency equal to 89.12%.

In comparison to isentropic efficiencies (for each cylinder and whole turbine) of various similar steam turbines from other power plants which can be found in the literature [34], it can be concluded that analyzed steam turbine and their cylinders have very high isentropic efficiencies. In the literature can be found that steam turbines from supercritical and ultra-supercritical steam power plants shows the best performance and the highest efficiencies (for each cylinder and whole turbine) [34]. It should be highlighted that an isentropic performance of the whole steam turbine and their cylinders analyzed in this paper is in the range of the steam turbines (and their cylinders) from supercritical and ultra-supercritical power plants.

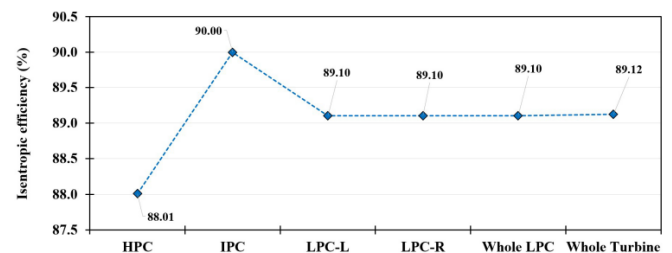


Fig. 5. Isentropic efficiency of each cylinder and whole observed turbine

Further analysis and possible optimization of the observed steam turbine will be based on the results obtained in this analysis. For that purpose, many conventional and artificial intelligence [35, 36] methods and processes can and will be used.

6. Conclusions

This paper presents isentropic analysis results of the complex three-cylinder steam turbine which operates in a CCPP. The nominal power of the observed steam turbine is equal to 250 MW, while entire steam mass flow rate used in the observed turbine is produced in HRSG which uses combustion gases from the gas turbine. The most important conclusions of the performed analysis are:

- The dominant mechanical power producer in the observed turbine is LPC which produces 111.80 MW of mechanical power in real (polytropic) steam expansion process. Real mechanical power produced in the LPC represents almost half of cumulative produced real mechanical power in the whole turbine.
- Developed mechanical power in turbine cylinders and isentropic losses are directly proportional – higher produced mechanical power will result in higher isentropic losses and vice versa.
- Whole observed steam turbine has isentropic loss equal to 30.50 MW. Any reducing the whole turbine isentropic loss will result with an increase in produced mechanical power and overall efficiency.
- Whole observed steam turbine, their cylinders and cylinder parts show very good isentropic performance and high isentropic efficiencies of around 90%.
- IPC of all cylinders has the highest isentropic efficiency (equal to 90.00%). The highest isentropic efficiency of IPC can be explained with optimal operating conditions in which this cylinder operates. IPC is not influenced with a steam of the highest pressure and temperature in the plant (as HPC) and, simultaneously, neither one IPC stage did not operate by using wet steam as LPC (wet steam contains water droplets which increases losses).
- It should be highlighted that an isentropic performance of the whole analyzed steam turbine and their cylinders is in the range of

the steam turbines (and their cylinders) from supercritical and ultra-supercritical power plants which are proven to be the best turbines from isentropic point of view.

7. Acknowledgment

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Preparation, phase and optical characterization of Sm_2O_3 - ZrO_2 coatings on glasses obtained by sol-gel technology using the Dip Coating method

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Abstract: Obtained experimental self-cleaning coatings (based on compositions with the participation of Sm_2O_3), applied by the sol-gel method on glass slides. This study attempts to improve the overall efficiency of a photovoltaic solar panel by using a Sm_2O_3 doped ZrO_2 (SDZ)-based coating. The optical characterization and phase composition of the obtained experimental samples were investigated using UV-VIS-NIR, XRD and XRF methods. The coatings are nanocrystalline according to XRD and XRF analyzes and show transmittance close to that of pure glass when tested with a UV-VIS-NIR spectrophotometer. The experimental results represent a prerequisite for the development of a series of additional compositions and a detailed technological regime for obtaining various modifications of resistant, long-lasting self-cleaning coatings, potentially applicable to photovoltaic panels.

Keywords: SOL GEL, XRD, XRF, UV-VIS-NIR, DIP COATING, PHOTOVOLTAICS, ZrO_2 , Sm_2O_3

1. Introduction

Zirconium oxide is one of the most well studied transition-metal oxides with promising applications in the development of innovative materials, products with high operational reliability and components for high-tech devices [1-7].

Zirconium oxide thin films are characterized by the presence of a significant variety of functional properties [8-27]: high hardness, excellent mechanical properties, high melting point, corrosion resistance, low electrical conductivity, high dielectric constant, high refractive index, high transparency in the visible and near-infrared regions, large optical band gap, high laser-induced damage threshold, low optical loss, good thermal properties, chemical inertness, biocompatibility, good thermodynamic stability in contact with silicon, etc.

Due to their characteristics, various thin films obtained on the basis of ZrO_2 find application as wear resistance coatings, corrosion protective layers, thermal barriers [28], as well as in the production of various electronic components, biocompatible implants and a number of other products.

At the same time, due to their unique optical properties, thin films of ZrO_2 have significant potential for use in the field of optics and opto-electronics [15,19,29-31] for the development of broadband interference filters, selective reflection coatings, active electro-optical devices, including light emitting diodes, oxygen sensors, high power laser, passive and active waveguides, buffer layers in micro-electronic devices, scintillators, etc.

The operational properties of thin films are determined by their phase composition and structure, which depend on the components used, the presence of modifiers and the applied technological methods for coating deposition.

There are many different techniques for deposition thin films [3,15-19,29-38], such as chemical vapor deposition (CVD), physical vapour deposition (PVD), electrochemical deposition, hydrothermal processing, electron beam evaporation, magnetron sputtering, spray pyrolysis, plasma spraying, pulsed laser deposition, atomic layer deposition, liquid phase deposition method, ion-beam aid deposition and sol-gel method, etc.

Among them the sol-gel method [3,16,32-34,37] provides a number of significant technological advantages such as relatively low processing temperatures, high optical quality of the obtained coatings, capability of coating large surface areas, simplicity and comparative low cost, etc. In order to regulate the solvent evaporation rate, the formation of various cracks and crystal defects and to suppress of the process of the grains growth and unfavorable aggregation, appropriate low-volatility organic compounds are introduced to the used sol-gel precursors: polyvinyl alcohol, polyethylene glycol, hydroxypropyl cellulose, polyvinylpyrrolidone [19]. In addition, this technique is suitable to preparation almost any homogeneous and uniform single- or multi-component oxide coatings (ZrO_2 , SiO_2 , etc.) prepared by spin and dip coating method [31].

The ion Zr^{4+} does not exhibit pronounced photoluminescence properties, but this can be significantly affected by the formed local defects [20]. In most cases they represent oxygen vacancies, various types of impurities, free radicals, etc., which favor broad band PL emission [20].

The sol-gel deposition method is known to provokes the formation of large number of surface defects (for example-oxygen / Zr vacancies or interstitials) in the thin ZrO_2 coatings, which improves their photoluminescence characteristics [19].

Another technological method to activate the PL emission is incorporation of appropriate luminescent agents (including lanthanide ions and others) into the host lattice of ZrO_2 [20]. The existing low-phonon energy of ZrO_2 creates the possibility for the implementation of more efficient luminescence from the incorporated activator ions. The considered effect is determined by the fact that the lower the phonon energy of the specific host, the higher the probability of performing a radiative transitions of the introduced rare earth $3+$ ions [20].

In this aspect, a current technological interest is the study of the characteristics of modified Sm-doped ZrO_2 experimental samples and the possibilities for obtaining thin films of Sm_2O_3 .

Samarium-doped zirconia samples were prepared using two different technological approaches. By applying atomic layer deposition, thin crystalline films (doped by using ion implantation) with a predominantly monoclinic structure were prepared. While by skull-melting method, bulk polycrystalline experimental samples with presence of monoclinic and tetragonal phases of ZrO_2 were obtained [35]. Photoluminescence measurements of Sm emission in the prepared samples were performed by using pulsed laser excitation at 405, 320 and 230 nm. The obtained spectra may be interpreted as superpositions of two different sets of lines attributable to the presence of Sm^{3+} centers in different phases of ZrO_2 . The research of the fine structure in the observed luminescence spectra of Sm^{3+} ions in the experimental sample showed the existence of at minimum two different luminescence centers related to monoclinic and tetragonal phases of ZrO_2 [35]. Excitation at 405 nm provokes the direct excitation of Sm^{3+} , whereas the excitation at 230 nm is interpreted as host-sensitized excitation.

A samarium doped polycrystalline ZrO_2 experimental sample was studied for its phase composition and optical characteristics. From micro-Raman measurements performed the presence of tetragonal as well as monoclinic phase was confirmed [36]. The obtained emission spectrum of Sm^{3+} suggest a significant changes under excitation near the spectral region of fundamental absorption. Combined excitation-emission spectroscopy measurements shows three different sites for the used dopant ions to be present in the experimental sample [36].

Innovative thin films of zirconia oxide ZrO_2 and samarium oxide Sm_2O_3 on glass substrates have been obtained by applying

sol-gel technology and using dip coating method [37]. Excitation and emission spectra of ZrO₂ films consists of broad bands with maximum values of 318 and 365 nm. The photoluminescence measurements performed of the deposited Sm₂O₃ thin films reveals that can be efficiently excited with 700 nm and consist of emission bands centered at 567, 603, 639 and 707 nm, consistent with characteristic Sm³⁺ transitions [37]. The established values of the chromaticity coordinate points of the prepared Sm₂O₃ and ZrO₂ thin films are located in the orange and blue region. The obtained Sm₂O₃ thin films is characterized by a high color purity of 96% [37].

Samarium oxide Sm₂O₃ thin coatings were deposited on silicon substrates by using pulsed laser deposition method at a temperature range of 25, 200, 400 and 680°C [38]. The performed XRD analysis shows that the structure of Sm₂O₃ coating obtained at 25°C is amorphous, while the coating prepared at 200°C is a partially crystallized. Monoclinic structure was the established predominant phase for Sm₂O₃ coatings obtained at temperatures of 400°C and 680°C [38]. The polycrystalline Sm₂O₃ coating prepared at 680°C is very dense, while coatings obtained at lower temperatures (25, 200 and 400°C) have higher porosity. The established values of index of refraction *n* and extinction coefficient *k* (at λ=633 nm) are 1.867 and 0.0660 for the coating prepared at 680°C and are in a range of 1.5~1.6 and 0.01~0.04 respectively for films deposited at lower temperatures [38].

2. Experimental procedures

All of the chemicals were utilized exactly as they were supplied, in analytical grades. AGC Glass Europe chemicals were used for thin film coatings. Alfa Aesar Germany supplied the 99.9% ethanol C₂H₅OH), ZrOCl₂·8H₂O, and Sm₂O₃. Nitric acid (HNO₃) is used as a stabilizer. Getting the glass substrate ready. The slides were trimmed to size (20 mm × 70 mm × 2 mm) before to cleaning. In order to clean and remove submicron particles from the substrate surface, substrate cleaning is crucial before the deposition process. The quality of the sticky film on the base is determined by this. After being cleaned or washed for 15 minutes in 99.9% ethyl alcohol and 15 minutes in acetone, the glass substrates were dried at 60°C for 10 minutes. Cleaning the glass substrates helps the coating material stick to the substrate better and keeps the coating from being contaminated. The production technology is presented in the scheme. They used sol-gel technology. After dissolving ZrOCl₂·8H₂O in H₂O and pure alcohol, a 0.01–0.02 molar solution was produced. Sm₂O₃ was added 30 minutes later. It was vigorously stirred while Sm₂O₃ was added gradually. The ratio was 6.5 weight percent Sm₂O₃ to 93.5 weight percent ZrO₂. Nitric acid was added or agitated during the hydrolysis process until the solution turned clear, meaning it had been fully dissolved. The glass sample was coated with the resultant solution using the Dip Coating technique. The substrates were immersed in the prepared solutions for 30 s and then pulled out at a speed of 0.8 mm.s⁻¹ and dried to evaporate the organic solvents - the glass substrates were dried at 120°C for 30 minutes. The coating procedure was repeated three times. After that, the sample was treated at 420°C.

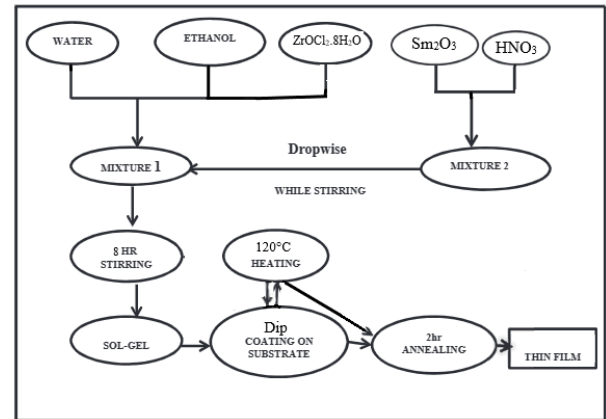
3. Results and Discussion

The samples were examined using a Philips X-ray diffractometer PW 1030, with an X-ray source of Cu Kα radiation (λ = 1.5406 Å) and θ–2θ Bragg-Brentano geometry. The scan step size was 0.025°, 10 s in the range 25–65° 2θ. The diffractograms were analysed using the PDF-2 2022 database.

The thickness of the layer and its elemental composition were measured using energy-dispersive X-ray fluorescence spectrometry (EDXRF) with an EPSILON 1 spectrometer (PANalytical, Malvern, UK). The Omnian and Stratos software modules were used for quantitative and layer thickness analysis respectively.

The size of the crystallites is calculated according to the Scherrer formula:

Schematics of the process of obtaining a thin film of sol gel with ZrO₂ and Sm₂O₃



$$D = 0.9\lambda / B \cdot \cos\theta$$

D - average crystallite size / Average Crystallite size/
 λ - wavelength (in angstroms) - 1.54178 Å / X-Ray wavelength/
 θ - Bragg angle (degrees) - 2θ/2 / Bragg angle/
B - line broadening FWHM (2θ), /Line broadening/ must be of dimension radians (rad=2θ*π/180)

Figures 1-3 present the results of XRD and XRF analyses of the surface of the glass samples. The SDZ3 /Figure 1/ layer is thinner and amorphous. X-ray diffraction (XRD) analysis confirmed the presence of zirconium and samarium oxides. The distinct peak at 31.91° 2θ in the diffractogram of sample SDZ5 /Figure 3/ corresponds to the (120) plane of orthorhombic ZrO₂ [ref. code: 00-049-1746]. A broad, lower-intensity peak at 31.12° 2θ suggests the crystallization of an additional phase on the surface. Weaker reflections at 34.92°, 50.21°, and 59.67° 2θ correspond to the (111), (200), (220), and (311) planes of cubic ZrO₂ [ref. code: 00-089-9069]. The broadening of the main peak at 31.12° 2θ (111) indicates the fine-grained nature of the coating, but it could also be related to the formation of monoclinic Sm₂O₃, whose peaks overlap with those of ZrO₂. The diffractogram of SDZ4 /Figure 2/ shows the formation of a cubic ZrO₂ layer, with samarium possibly present either as a dopant in the cubic zirconium oxide lattice or as monoclinic Sm₂O₃.

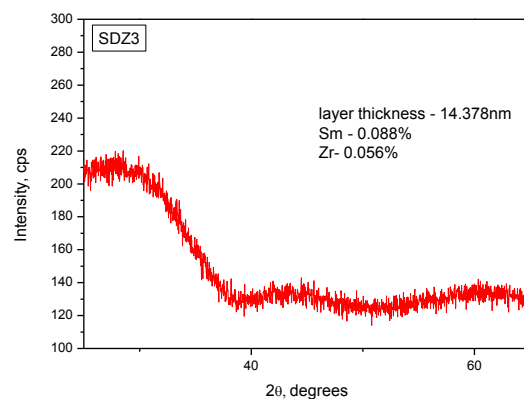


Figure 1. XRD and XRF analyses of the surface of the coating on glass / SDZ3 /

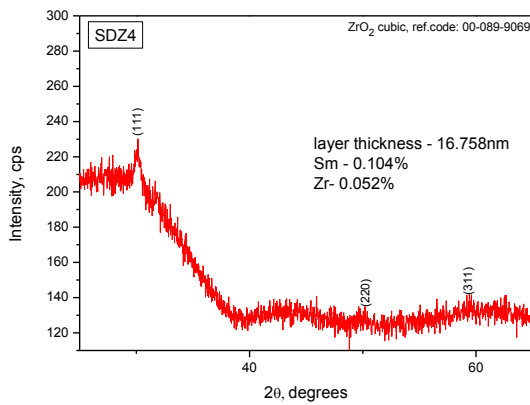


Figure 2. XRD and XRF analyses of the surface of the coating on glass / SDZ4 /

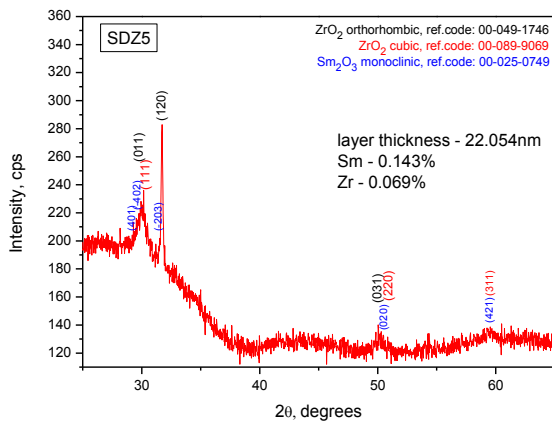


Figure 3. XRD and XRF analyses of the surface of the coating on glass / SDZ.5/

The figures show the percentage composition of ZrO_2 and Sm_2O_3 and the thickness of the coating on the modified glass surfaces. X-ray fluorescence analysis confirms the incorporation of Zr and Sm ions into the surface, forming a coating with a thickness of 14 to 22 nm.

The crystallite sizes (t) were calculated using Scherer's equation: $t = \kappa \lambda / B \cos \theta$. Here, κ is the shape factor ($\kappa = 0.9$ for spherical crystals with cubic symmetry); λ (in Å) is the wavelength; θ is the diffraction angle of the peak; and B (in radians) is the line broadening at the full width at half maximum (FWHM) values of the peaks. The crystallite sizes ranged from 9 to 76 nm for ZrO_2 and Sm_2O_3 (Table.1).

Table 1.

Samples	2θ	hkl	t (nm)
SDZ5	31.12	(111)	9
	31.91	(120)	76
SDZ4	31.12	(111)	10

Optical characterization was performed with UV-VIS-NIR Shimadzu 3600 double-beam spectrophotometer (Shimadzu Corporation, Kyoto, Japan) in the spectral region of 240-1800 nm. The transmittance spectra of the samples were taken against air. The reflectance spectra were measured by using the specular reflectance attachment (5° incidence angle) and Al coated mirror as reference. On the figures 4,5 present the results of optical characterization.

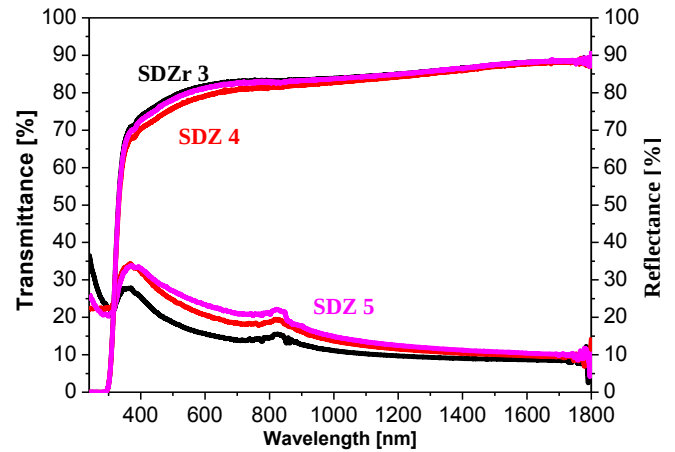


Figure 4. The figure shows the transmission and reflection spectrum of an experimental coating on a glass substrate in the region 400 - 1800 nm / SDZ.3, SDZ.4 and SDZ. 5 /

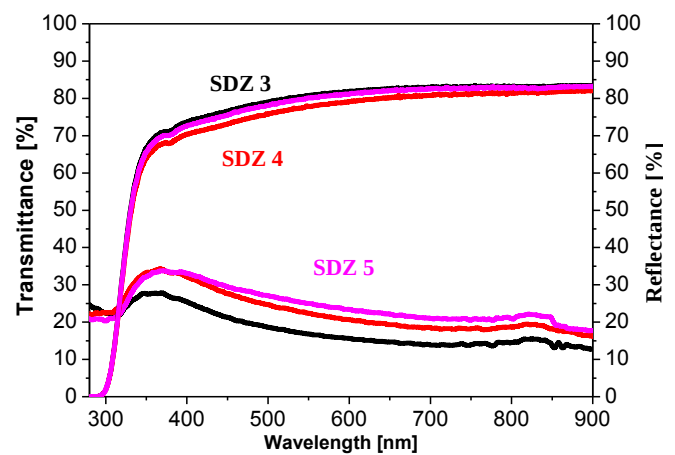


Figure 5. The figure shows the transmission and reflection spectrum of an experimental coating on a glass substrate in the region 300 - 900 nm / SDZ.3, SDZ.4 and SDZ.5 /

4. Conclusions

This study attempts to improve the overall efficiency of a photovoltaic solar panel by using a ZrO_2 -based coating, with Sm_2O_3 .

1. The coatings are prepared by sol gel method with Dip Coating.

2.The coatings are dense and nanocrystalline, according to XRD and XRF analyses.

3. The coatings of SDZ.3, SDZ.4 and SDZ.5 samples show good transmittance by UV-VIS-NIR spectrophotometer examination.

The experimental results represent a prerequisite for the development of a series of additional compositions and a detailed technological regime for obtaining various modifications of resistant, long-lasting self-cleaning coatings, potentially applicable to photovoltaic panels.

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Effect of thermal insulation on comfort and energy savings in buildings

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Abstract: Albania's construction sector has seen rapid growth with the introduction of diverse materials and advanced building techniques. However, the key challenge remains in effectively applying these innovations to maximize indoor comfort and energy efficiency at the lowest cost. Comfort plays a crucial role in occupant well-being and productivity, yet it is often overshadowed by concerns over upfront construction costs, overlooking long-term benefits such as improved health and reduced operational expenses.

Measurements across different seasons have shown that thermal insulation significantly enhances indoor thermal comfort. Data from the Electricity Distribution Operator also confirm that insulation can reduce electricity consumption by 15–28%, especially during peak usage periods. Supporting insulation in new buildings and encouraging retrofits in existing structures through coordinated local policies and utility programs could lead to substantial energy savings and improved living conditions nationwide.

KEY WORDS: THERMAL INSULATION OF BUILDINGS, THERMAL COMFORT, REDUCTION OF ELECTRICITY CONSUMPTION.

Introduction

Albania is a developing country, and traces of the former communist regime are still present in many aspects of life, including the field of construction. This sector has evolved significantly in implementing contemporary materials and techniques, but there is still much work, mainly in the mentality and way of designing and building with foresight. According to many studies, the higher the comfort level in buildings, the healthier, more satisfied, and more efficient the residents are. (The Health and Environment Alliance (HEAL), 2018) So, increasing the comfort level in apartments is the main challenge of designers and builders today.

Moreover, the realization of this challenge should be aimed at the most optimal and efficient cost. On this basis, but also as a need to meet the criteria, in the framework of the aspiration of EU membership, the Parliament of Albania approved in November 2015 Law 124, on 05.11.2015 "On energy efficiency", later regulated by Law no. 28/2021, for some changes and additions to Law no. 124/2015 "On energy efficiency" amended. According to the data, one of the essential elements of comfort is the thermal one, which is realized mainly through electricity. According to Balkan Green Energy News (2018), for 65% of households in Albania, most of the electricity consumption goes to heating their homes, while for approximately 60%, most of it is spent on cooling (Figure 1). According to the Directive 2010/31 / EC on Energy Performance in Buildings (DPNE), 25% of the total annual energy consumption goes for heating, and 20% goes for cooling.

Thermal insulation is the most efficient solution for storing the obtained thermal energy and prevents its transfer from the residential area to the outside environment. The quality of thermal comfort in apartments is mainly conditioned by the quality of masonry, which increases significantly through its thermal insulation. Many people still do not understand the great benefits of thermal insulation due to the lack of accurate and sufficient information. On the other hand, these benefits are neglected by many builders because of the momentary gains, without thinking about saving electricity, as a limited resource, or the increased costs of households that will live in these buildings.

The initiative of thermal insulation should be, in the first place, the responsibility of the Local Authorities, whose contribution makes the process faster and essentially affordable.

The intervention of the Local Authorities should be done in two plans:

1. First plan should be dedicated to new buildings, which is easier to implement, both in terms of technical and legislative sides. With a detailed study based on existing legislation, these authorities can undertake different policies to stimulate builders who apply thermal insulation in their constructions.
2. The second plan should be dedicated to the stock of existing buildings, where the process is a little more complicated but not impossible. In this contingent of housing, the initiative can

be taken by the Local Authorities themselves, through the funds at their disposal, but also by individuals who share the same building, if supported by incentive policy, or repayable financial assistance, based on a continuous awareness, on the medium-term benefits of the process.

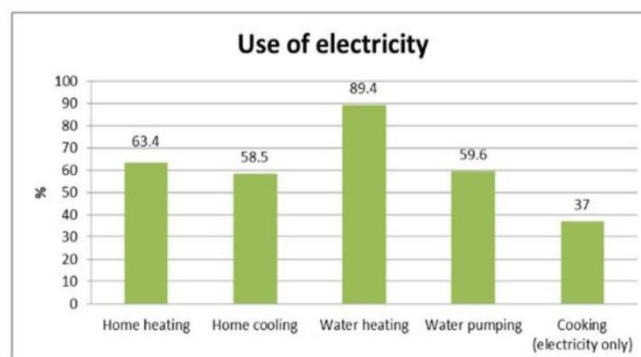


Figure 1: Use of electricity by households

Objectives

This research aims to identify the social and economic benefits of thermal insulation in residential buildings, based on the one hand on the actual perception of residents and the other hand in the analysis of technical measurements of electricity consumption. The ultimate objective is to analyze the improvement of the thermal performance of the indoor environment in a residential building, closely related to the need for comfort and reducing the cost of living.

Research Question

This research focuses on measuring well-being and improving the quality of life because of the thermal insulation of buildings and is based on the following questions:

How can we measure the impact of thermal insulation on daily life?

What is the impact of thermal insulation in reducing the cost of living?

Methodology

This research was conducted based on a process extended in several directions. It is based on a good knowledge of the legal framework, daily, continuous, and advanced work towards recognizing contemporary studies related to the requirements for comfort and its impact on daily activity, and a series of field analyses and surveys. Good knowledge of legislation and literature makes it possible for us to understand the directions we need to look for and the spaces where we can move. Analyzing the situation in a global context indeed begins with more straightforward analyses in the local context.

On this basis, the research is composed of a combination of qualitative and quantitative methods to answer optimally the questions that arise during the process.

The qualitative method consists mainly of an active search of statistical data concerning surveys and observations on thermal insulation and the impacts of its application on buildings. The quantitative method involves a survey conducted by interviewing residents in a thermally insulated residential building and extracting data to reach a convincing conclusion.

Limitations

Despite all the efforts to be as accurate as possible in determining the reduction of the amount of electricity due to thermal insulation, we find it difficult to be precise because we cannot fully identify the use of alternative sources of heat in certain moments.

Moreover, other minor issues came to the surface as we could not calculate the electricity consumption from newly purchased household appliances during the study period or the savings from replacing an old appliance with a new one with better technical properties. However, relying on professional judgment, these

restrictions are not to the extent that they have a significant impact.

Impact of thermal insulation on the improvement of everyday life quality

A focus group of 6 families was chosen after ensuring they lived in the same building before and after the thermal insulation. A formal survey was conducted and distributed to the families. Families count as a single subject of the survey, making a total amount of 6 subjects. The survey asked the subjects to describe their well-being in everyday life and inside their homes before and after the thermal insulation. They were asked to rate different aspects of their life such as physical well-being (having an excessive feeling of coldness/ warmth during winter/summer), emotional well-being (feeling comfortable and happy inside of home), psychological well-being (possible state of optimism related to the comfort when entering a home or while staying at home). Ratings for each category and a composed rating of all dimensions before and after the insulation are presented below. (Table 1)

Table 1: Presentation of the results from the survey

	Physical improvement	Emotional improvement	Psychological improvement	Average of general improvement/subject
Subject 1	4	4	3	3,67
Subject 2	5	3	3	3,67
Subject 3	5	5	4	4,67
Subject 4	3	4	2	3
Subject 5	4	3	2	3
Subject 6	4	4	3	3,67
Average group improvement/ aspect	4,17	3,83	2,83	

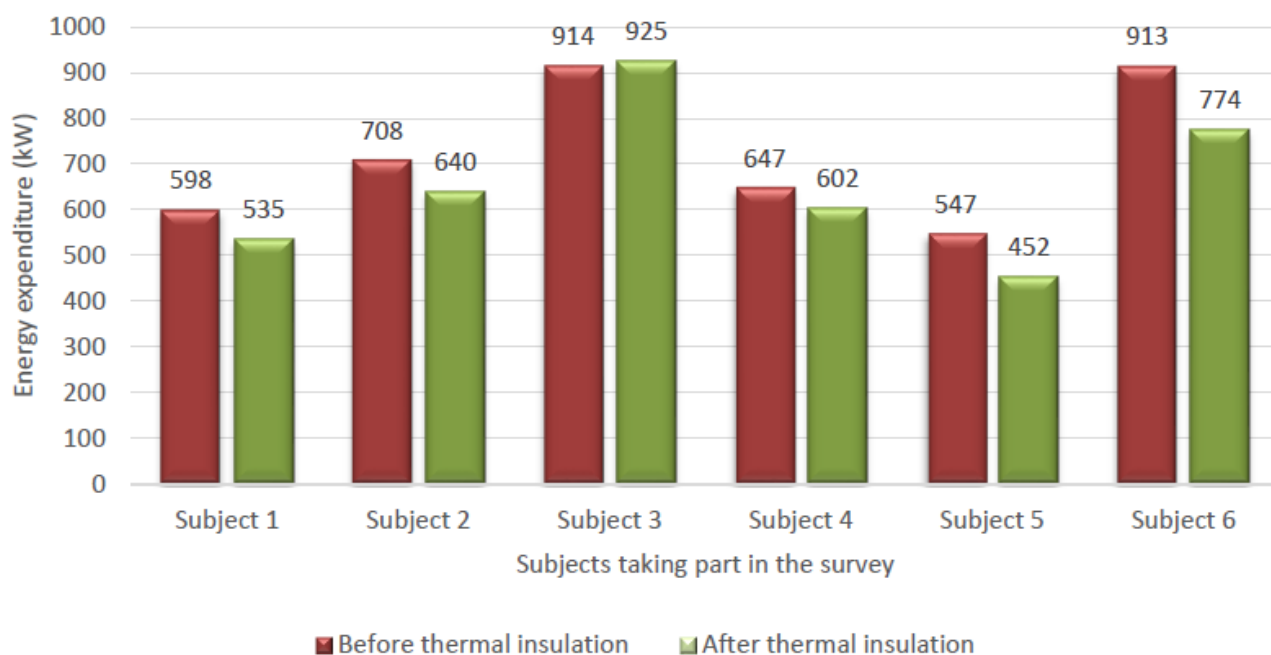
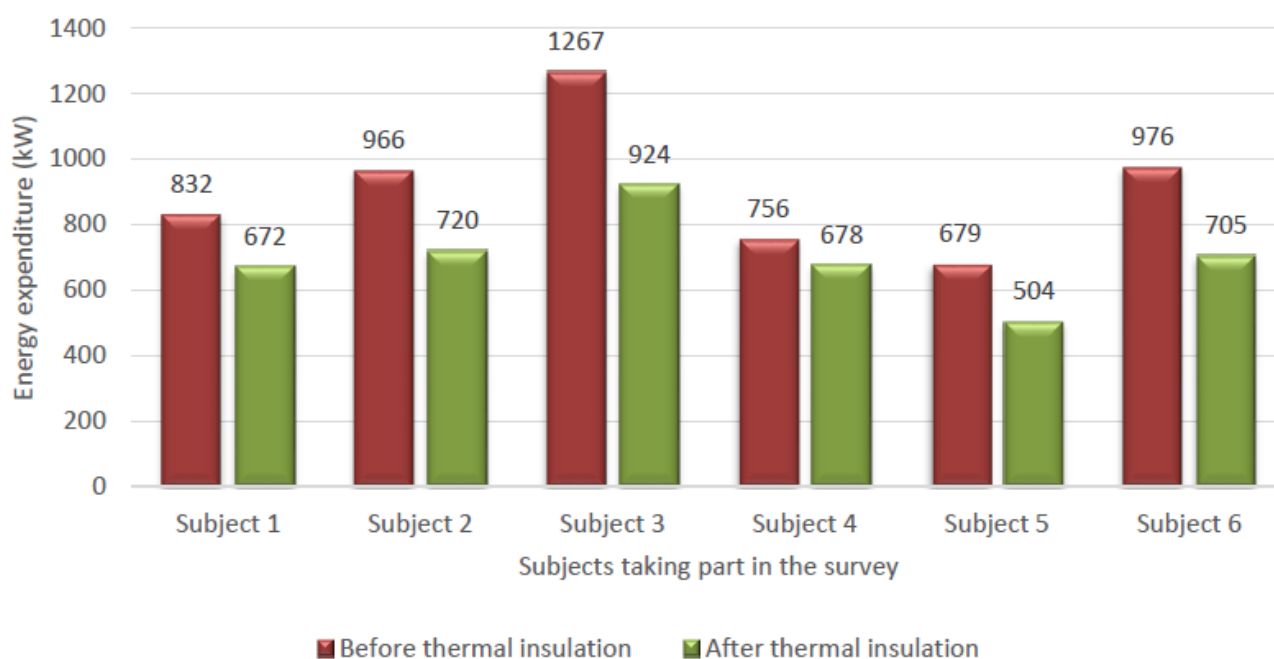
Legend
Improvement aspect
Subject
Subject evaluation
Evaluation span: 1-5
1-2: little or no improvement
2-4: notable improvement
4-5: great positive change

The general conclusion from the survey was satisfactory, and the subjective impression was overall positive. Most of the subjects had noted improvements in every aspect. As a result, they considered their life to be improved. Different aspects of well-being were also separately improved as the average ranking by each aspect lay between 2 and 4. It was expected for the subjects not to reach the maximum life

improvement level as more factors contributing to the improvement were not studied in this research.

Impact of thermal insulation on electrical energy-related costs

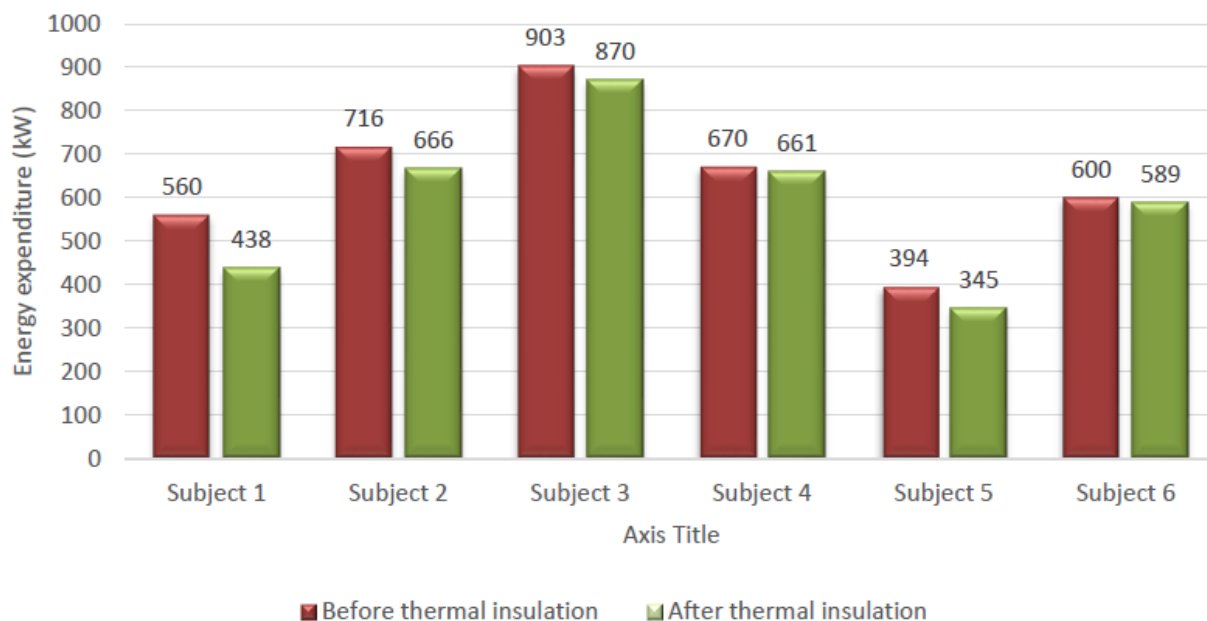
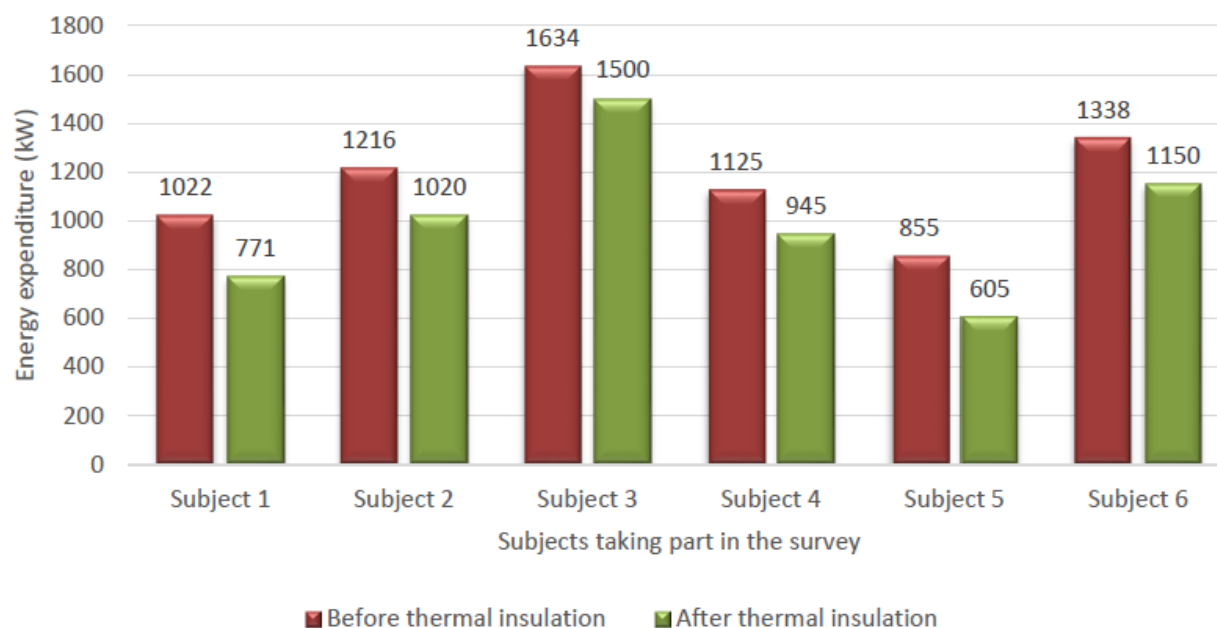
The economic aspect is also crucial in the life of every average household as it heavily impacts the quality of all their daily activities. This paper interprets official data retained from OSHE for the same subjects that collaborated above. The data represent the yearly expenditure on electrical energy, and this research focuses on two critical years, the year before the thermal insulation and the year after. This selection was made to prove the difference in expenditure and, as a result, in cost during this timeframe. Data was compiled and formatted graphically. (See Graph 1-4)

Graph 1: Cost representation Spring 2017 - 2019**Graph 2: Cost representation Summer 2017 - 2019**

The data in each of the four graphs correspond to each subject's average expenditures for each season. There is a difference between the respective values before and after the thermal insulation works. From the graphs, it is clear that in spring and autumn, when the need for heating - cooling is very low, the difference between these two values is not very large, although it is present.

When the need for heating - cooling is at the highest levels in the winter and summer periods, the difference between these two values is much more significant.

We also see that the opinions obtained during the interview are in sync with the statistical data presented in the graph.

Graph 3: Cost representation Autumn 2017 - 2019**Graph 4: Cost representation Winter 2017 - 2019**

Conclusion

Through this research, certain conclusions were put on evidence. The research subjects felt the impact of thermal insulation in their everyday lives. They were physically feeling an increase in energy and health as having a comfortable interior and avoiding excessive temperatures in both directions, warm and cold, reduced their chances of getting sick and suffering from the seasonal flu and cold. The constant state of health also affected their psychological and emotional state as they were feeling more motivated to stay active during the day and even increased the amount of time they spent at home instead of avoiding it. From the obtained data, it is evident that the economic impact of thermal insulation has a positive impact on the household's savings in energy-related costs. Furthermore, the investment becomes profitable in a 4–5-year period if the investment was undertaken privately by the inhabitants

of the building.

Literature Review

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Statistical analysis of modification of joints of metals and composites by thermal drilling

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Abstract: The paper presents an innovative method for joining Al alloy sheets and polymer fibre-reinforced composites by thermal drilling. A proposal for modifying the joint geometry by reverse drilling with a larger diameter tool is presented. The proposed modification demonstrated a statistically significant increase in the failure energy of the resulting joints.

Keywords: METAL-COMPOSITE JOINING, THERMAL DRILLING, BUSHING GEOMETRY, REVERSE DRILLING, STATISTICAL ANALYSIS, p-VALUE

1. Introduction

Thermal drilling represents a technique for joining dissimilar materials through the formation of bushings, even without fastener. In recent years, significant progress has been made in addressing the challenges associated with joining materials possessing fundamentally different physical and mechanical properties, such as thin-walled metallic and fiber reinforced composite substrates [1–7]. These hybrid material configurations are increasingly utilized in the design of ultralight structures, particularly within the automotive and aerospace sectors. Typical applications of metal–composite joints include structural elements such as A-pillars, engine covers, load-bearing plates, and front stretchers. Joints between thin-walled metal sheets and composite plates with a thermoplastic matrix are characterized by the preservation of fiber continuity, thereby maintaining their reinforcing function. To ensure this, the composite material must be heated above the melting temperature of the thermoplastic matrix during the joining process. Common thermoplastics used for the matrix include polypropylene, polyamide 6, polyamide 66, polyamide 12, polycarbonate, thermoplastic polyurethane, and polyphenylene sulfide. During the heating and formation of the metal bushing, the fibers within the composite are deflected, allowing the bushing to form without damage to the fibers.

The joint between the metal sheet and the composite, created through thermal drilling, may appear as shown in Fig. 1.



Fig. 1 Schematic representation of a possible joint failure

As seen in Fig. 1, the joint is mechanical; however, due to the heating of the polymer matrix and the mutual compression of the materials during the joining process, adhesive bonding also occurs between the materials. The end of the bushing is used for hemming flange the joint, which prevents it from opening under stress. The outer surface of the bushing is conical, while the inner surface is cylindrical. Fig. 1 also highlights the potential modes of failure of the joint under tensile loading. In an ideal case, the joint should fail by shear of the bushing, but practical experience has shown that due to the conical shape of the bushing, failure occurs more often by the composite slipping off the conical bushing, straightening of the hem, or shearing of the hem, leading to the composite being pulled out of the bushing. As a result, the materials separate without fully utilizing the material properties of the metal (bushing), and the joint fails.

The aim of this paper is to present the proposed change in the geometry of the bushing and its effect on the effective use of the material properties of the metal parts of the joint.

2. Materials and methods

The metal sheet used for the joint formation is made of EN AW 6082 T6 alloy with a thickness of 1 mm. This is a precipitation-hardened aluminum alloy, commonly used in the manufacturing of lightweight structures in the automotive industry or construction.

For the composite, polypropylene with a melting temperature of 165°C, reinforced with glass fibers (GF) and carbon fibers (CF), was used. The fibers are continuous and laid in two mutually perpendicular directions in the form of a mat. The thickness of the composite panels was 1.5 mm, with the thickness of the glass fiber panels achieved by consolidating three layers of prepreg, while the carbon fiber panels consisted of seven layers.

The joint was created by thermal drilling using a Flowdrill Long tool $\varnothing 5.3$ mm, with the following process parameters: RPM 4800 min^{-1} , feed rate 60 $\text{mm} \cdot \text{min}^{-1}$. During drilling, the materials (Al-CF, Al-GF) were overlapped on a length of 30 mm, and the composite was heated to 175°C, as shown in Fig. 2. Forty joints were produced for each material combination to allow for a detailed statistical analysis of the results.

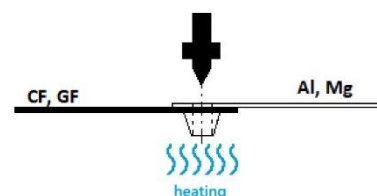
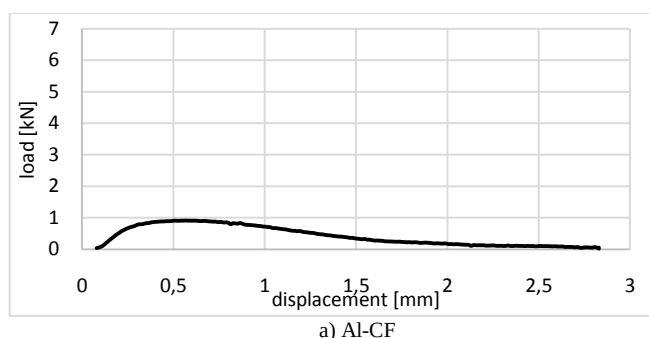


Fig. 2 Principle of joint formation by thermal drilling

Load-displacement dependence was recorded when testing the load-carrying capacity of the connections.

Results

Selected load-displacement curves for Al-CF and Al-GF joints are shown in Fig. 3.



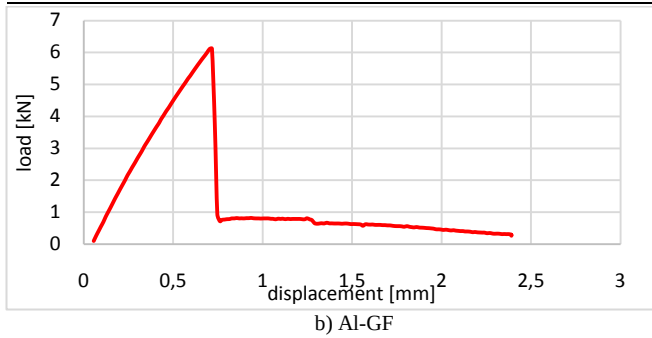


Fig. 3 Load-displacement curves when testing load-bearing capacity of joints

In Al-CF joint, there was no adhesive bonding, only mechanical joining through the bushing. In the case of Al-GF joints, the curve first shows an increase in force up to F_{max} , when the adhesive part of the joint was broken and the force dropped sharply. At this point, the load was transferred to the joint bushing which deformed and the composite was gradually pulled out of the joint, Fig. 4.

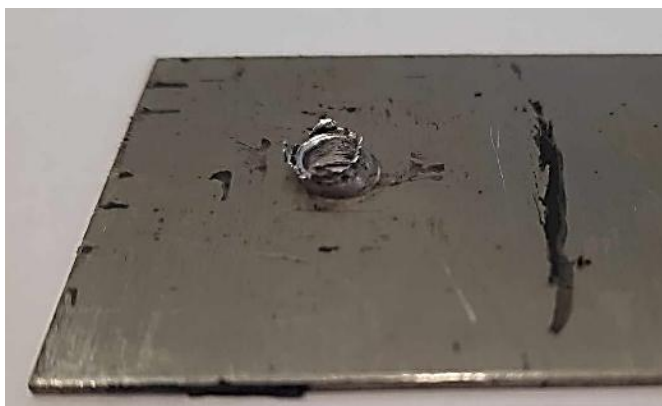


Fig. 4 Mechanism of bushing failure in joints

To prevent the composite from sliding out of the bushing, a geometric modification of the bushing was proposed by forming an inverted cone with a tool of larger diameter (9.3 mm) than the original bore (5.3 mm), which would eliminate the tangential component of the force that leads to the composite sliding out of the bushing, Fig. 5. The process of modifying the geometry of the bushing will be referred to as reverse drilling (RD) in this context.

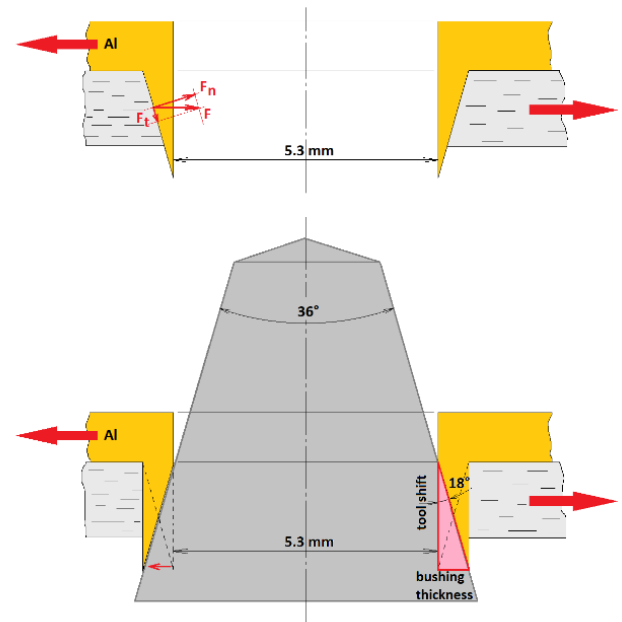


Fig. 5 Design of the bushing geometry modification to increase the load carrying capacity of the connections (F - loading force, F_n - normal, F_t - tangential component of the force F)

In reverse drilling the shape of the bushing changes to the opposite - the outer shape is cylindrical, the inner conical, Fig. 5 and 6.

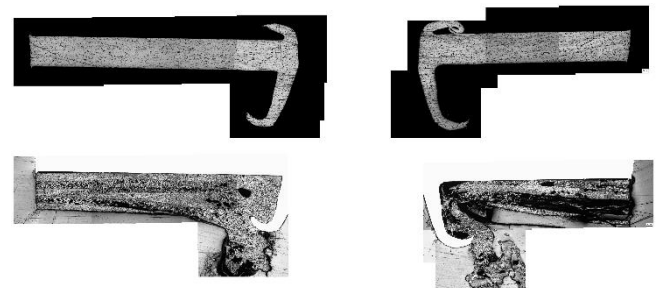
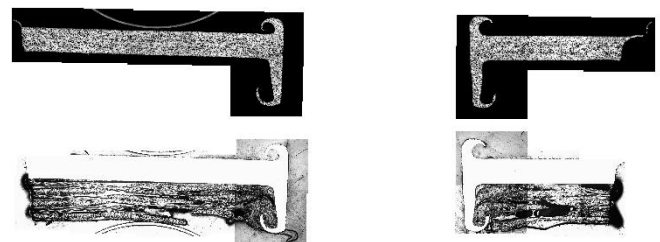
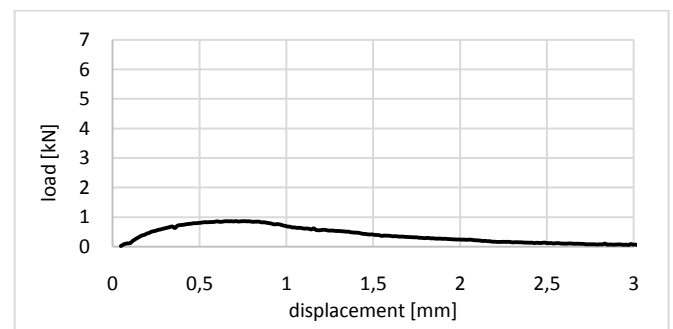


Fig. 6 Metallographic section of Al-GF joint

The joints, modified by reverse drilling (RD) were also stressed in tension, Fig. 7.



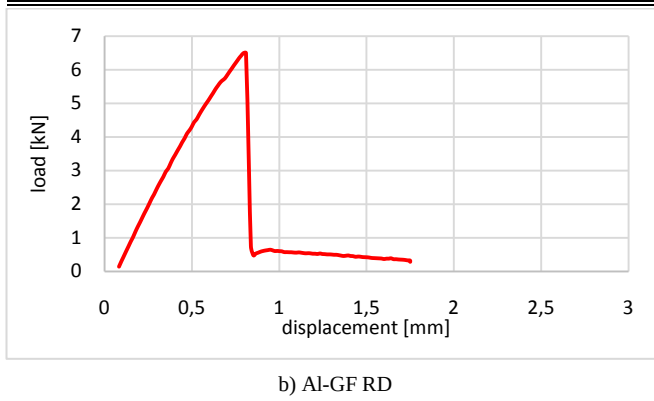


Fig. 7 Load-displacement curves when testing load-bearing capacity of joints with improved bushing geometry by reverse drilling

At first glance, the load-displacement curves appear very similar, which is why it was necessary to analyze the resulting dependencies in more detail using statistical methods. The load-displacement relationships also serve as the basis for calculating another indicator, beyond just the maximum force F_{max} , namely the energy W dissipated at the failure of the joint. It is desirable for the joint to absorb as much energy W (in joules) as possible during failure, thereby contributing to the overall impact absorption during a vehicle collision in the vehicle's deformation zones and joints. The dissipated energy is calculated using the following formula:

$$W = \int_0^{s_{max}} F(s)ds \approx \sum_{i=1}^n F_i(\bar{s}_i)\Delta s = \Delta s[F_1(\bar{s}_1) + F_2(\bar{s}_2) + \dots + F_n(\bar{s}_n)]$$

where F_i is the instantaneous value of the load in N and s_i is the instantaneous value of the displacement in m .

Additionally, it can be seen that the load-displacement curve can be divided into two parts – the adhesive and mechanical part of joint, Fig. 8, and the dissipated energy for both components of the joint can be calculated separately, as shown in Table 1.

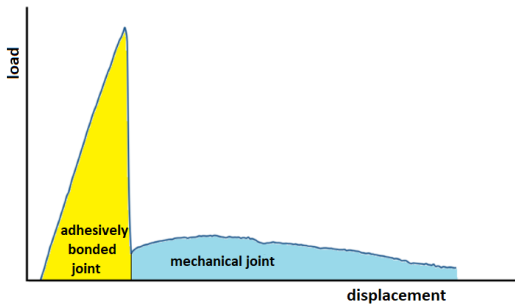


Fig. 8 Typical load-displacement curve for a hybrid, adhesion-mechanical joint

Tab. 1 Energy dissipated in the particular areas of the hybrid joints

Joint	Adhesive part		Mechanical part		Total energy		Change in energy [%]
	[J]	[%]	[J]	[%]	[J]	[%]	
Al-CF	0.00	0.00	1.07	100.00	1.07	100.00	+37.33
Al-CF RD	0.00	0.00	1.47	100.00	1.47	100.00	
Al-GF	1.81	79.23	0.48	20.77	2.29	100.00	+27.96
Al-GF RD	2.13	71.66	0.80	28.34	2.93	100.00	

As seen in Table 34, modifying the bushing geometry resulted in an increase in the total energy consumed during failure for all joint types, as well as an increase in the partial energies in the adhesive and mechanical parts of the joint. The failure mode of the joint also changed, from bushing deformation to bushing shear (Fig. 9), which is desirable for the efficient utilization of the material properties of the aluminum alloy.



a) Al-GF RD, partial shear of the bushing (approx. 1/3 of the circumference), the bushing remains part of the Al plate



b) Al-CF RD, partial shear of the bushing (approx. 2/3 of the circumference), the bushing remains wedged in the CF



c) Al-CF RD, total shear of the bushing, the bushing remains wedged in the CF

Fig. 9 Mechanism of bushing failure in Al-composite hybrid joints with bushing geometry modification by reverse drilling

The percentage representation of the failure modes of the joints before and after the geometry modification through reverse drilling, based on testing 40 joints in each group, is shown in Fig. 10.

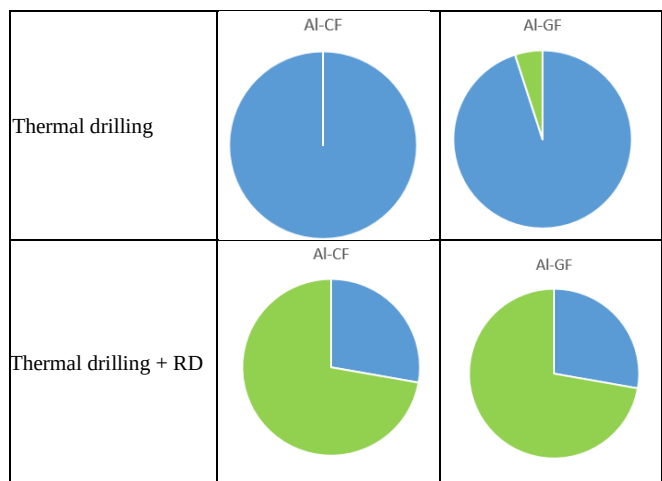


Fig. 10 Change in the joint failure mode (blue - deformation of the bushing, pulling out of the composite, green - shearing of the bushing)

By modifying the bushing geometry, the proportion of joints failed by bushing shear significantly increased, which was the objective of the proposed bushing modification.

To compare the data sets (maximum force F_{max} , energy W consumed during joint failure), statistical tests were used. The normality condition was verified using the Shapiro-Wilk test (SW) to determine whether it is appropriate to use a parametric or non-parametric test. The Shapiro-Wilk normality test evaluates the validity of the following hypotheses:

H_0 : the data set has a normal distribution

H_1 : the data set does not have a normal distribution

Subsequently, Fisher's F-test was used to test the hypothesis regarding the equality of variances of two independent data sets. The hypotheses tested were:

H_0 : the two independent data sets have equal variance

H_1 : the two independent data sets do not have equal variance

Based on the results of the F-test, the Student's t-test for two independent samples was used for the comparison, either assuming equal variances or unequal variances. This test evaluates the hypothesis about the difference in the means of two data groups and is used to determine whether the observed difference in means from the samples is due to chance or is statistically significant.

Tested hypotheses:

H_0 : the difference in the means of two independent data sets is not statistically significant

H_1 : the difference in the means of two independent data sets is statistically significant

There are various ways to test the hypotheses H_0 against H_1 at the significance level α (in our case $\alpha=0.05$), and although these methods may differ, the conclusion remains the same. The acceptance or rejection of the null hypothesis is based on the p-value as follows:

- if $p < \alpha$, the null hypothesis H_0 is rejected at the significance level α in favor of the alternative hypothesis H_1 ,
- if $p > \alpha$, the null hypothesis H_0 cannot be rejected.

The statistical tests mentioned above were used to compare the different categories of joints created by thermal drilling and reverse drilling with modified bushing geometry, both in terms of the achieved maximum force F_{max} during joint load testing and in terms of the energy W dissipated during joint failure, as shown in Tab. 2 and 3.

Tab. 2 Statistical comparison of Al-composite joints in terms of F_{max}

Joints	AI-CF	AI-CF RD	AI-GF	AI-GF RD
SW test				
p-value	0.2815	0.1619	0.2530	0.0547
conclusion	p> α normal distribution, parametric tests	p> α normal distribution, parametric tests	p> α normal distribution, parametric tests	p> α normal distribution, parametric tests
F-test				
p-value	0.000621184		0.041717792	
conclusion	p< α data sets do not have equal variance, unequal variances T-test		p< α data sets do not have equal variance, unequal variances T-test	
t-test				
p-value	0.062563566		0.074745448	
conclusion	p> α The difference in means is not statistically significant		p> α The difference in means is not statistically significant	

Tab. 3 Statistical comparison of Al-composite joints in terms of W

Joints	Al-CF	Al-CF RD	Al-GF	Al-GF RD
SW test				
p-value	0.8878	0.548	0.9638	0.9547
conclusion	$p > \alpha$ normal	$p > \alpha$ normal	$p > \alpha$ normal	$p > \alpha$ normal

	distribution, parametric tests	distribution, parametric tests	distribution, parametric tests	distribution, parametric tests
F-test				
p-value	0.0592		0.5301	
conclusion	p> α data sets have equal variance, equal variance T-Test		p> α data sets have equal variance, equal variance T-Test	
t-test				
p-value	0.0000		0.000373	
conclusion	p< α The difference in means is statistically significant		p< α The difference in means is statistically significant	

The statistical tests confirmed that, although the maximum force at joint failure F_{max} does not change statistically significantly with the modification of the bushing geometry, the increase in the total energy W dissipated during the failure of joints with modified bushing geometry—across all tested material combinations—is not random, but statistically significant at the 0.05 significance level.

Conclusion

Experimental and statistical tools have confirmed that by modifying the tool geometry through reverse drilling with a larger diameter tool, it is possible to achieve a more efficient utilization of the mechanical properties of metallic parts when joining metals and composites using the thermal drilling technology.

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Correlation-Based Sensor Pruning and Malfunction Detection in Multi-Sensor Condition Monitoring

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Abstract: This study presents a correlation-based approach for both detecting sensor malfunctions and identifying redundant sensors in a multi-sensor condition monitoring system. Sensor malfunctions were detected using a threshold-based method that flagged correlation drops, with persistence criteria applied to eliminate false positives. While no persistent malfunctions were observed during the study, the developed algorithm remains suitable for real-time deployment. Correlation analysis also revealed that the 3axis_Y signal exhibited the highest average correlation with others, indicating redundancy. Five machine learning models were trained and evaluated with the Leave-One-Run-Out strategy to guarantee generalization across acquisition sessions. The findings demonstrated that correlation-driven sensor selection and anomaly detection are effective tools for optimizing predictive maintenance systems, improving model generalization, and simplifying sensor networks without sacrificing reliability.

Keywords: PREDICTIVE MAINTENANCE, SENSOR MALFUNCTION DETECTION, CORRELATION ANALYSIS, SENSOR REDUNDANCY, VIBRATION ANALYSIS

1. Introduction

Modern condition monitoring systems rely on a wide array of sensors to capture real-time data on machine and process states. Ensuring the reliability of such multi-sensor setup is essential for the success of Predictive Maintenance (PdM) strategies. However, sensor malfunction - whether - resulting from drift, noise, or signal loss (Fig. 1) - can compromise model accuracy and system safety [1]. An increasingly adopted approach to detect such faults relies on monitoring the correlation between sensors, either from raw time domain data or from condition indicators extracted from those signals. Sensors that typically show strong functional relationships should maintain high correlation across time. A malfunctioning sensor often deviates from these established relationships, resulting in a measurable drop in correlation. This makes correlation a useful unsupervised indicator for detecting anomalies in multi-sensor environments [2].

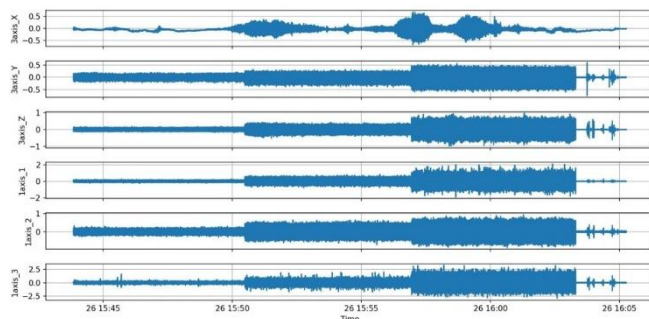


Fig. 1 Sensor malfunction encountered during one of the measurements.

Redundant sensors are frequently used in industrial setups for fault tolerance and system reliability. By comparing their outputs, a faulty sensor can be detected when its readings diverge from the correlated group. For example, in [3], voting and correlation-based approaches were used to detect faulty sensors by identifying values that no longer aligned with their peers. In another study [4], the Piecewise Aggregate Approximation (PAA) technique was used to aggregate the data in fixed intervals of time, followed by the creation of a correlation matrix from baseline data. An anomaly was detected when the correlation between typically aligned sensors dropped below a defined threshold. If such events occurred in sequence, the data was labeled abnormal.

Various methods further leverage correlation-based methods to detect sensor faults. In [5], variables with correlation coefficients ranging from 0.5 to 0.95 were organized into two-dimensional clusters. Anomalies were then identified using Mahalanobis distance to detect deviations from the established normal behavior. In Wireless Sensor Networks (WSNs), multi-variable correlation is used in ensemble methods to enhance detection reliability in

complex or high-volume systems [6]. An outlier was confirmed if at least two methods agreed. A sensor reading was considered anomalous if two or more models agreed. This approach has been shown to maintain high detection accuracy and low false alarm rates. In [7] correlation method was applied to differentiate between events (true incidents) and noise (sensor errors). After detecting anomalies using exponential moving averages, a correlation matrix determined whether anomalies in correlated sensors were due to a real event or just isolated sensor noise.

Simultaneously, correlation analysis can be used to identify redundant sensors and indicators. By examining pairwise correlations among sensor signals or performance indicators, variables carrying overlapping information can be identified. High correlations indicate overlapping (redundant) information. Removing such redundancy can simplify system complexity, improve computational efficiency, and lower deployment and maintenance costs without significant loss of information [8]. While correlation-based feature reduction is commonly applied to condition indicators [9], it can be extended to entire signal channels or even physical sensors. Authors of [8] demonstrated a correlation-driven method for optimal sensor placement in structural monitoring: they computed a correlation matrix of all candidate sensor locations and used a clustering algorithm to choose a subset of sensors with minimal redundancy. If two sensors consistently yield highly similar indicator patterns across time windows, they can be considered functionally redundant. In such cases, removing or consolidating one of the sensors can reduce system complexity, minimize computational overhead, and even lower the system's overall risk - fewer sensors mean fewer components that can fail. Only a few well-placed sensors can often capture most of the variability if chosen intelligently [10]. This type of sensor pruning or fusion is gaining interest in industrial PdM applications, where data volume and sensor failure management are growing challenges.

The dual use of correlation - both as an anomaly signal and a redundancy measure, represents a powerful and interpretable tool for sensor network optimization.

2. Pearson's and Spearman's correlation

Both Pearson's and Spearman's correlation coefficients are used in sensor-based data analysis for feature/sensor selection, but they have different assumptions and strengths.

- Pearson's correlation - measures linear association between sensor readings [11] and is widely used to identify collinear (redundant) sensors or features. In [12] Pearson's correlation coefficient was deployed to identify the most relevant meteorological inputs, from which Machine Learning (ML) models should learn.

- Spearman's correlation - nonparametric measure based on data ranks, which captures the strength of any monotonic (not necessarily linear) relationship [11]. Spearman's method is often chosen for sensor data that exhibit nonlinear trends or outliers – for instance, it has been used to select sensors in a machine tool monitoring setup by detecting nonlinear dependencies (reducing 16 sensors to 7) [13]. It's also useful when comparing different sensor types or calibrations, focusing on the agreement in ranked trends rather than exact values [14].

The key difference is that Pearson assumes a straight-line relationship and works best with continuous, normally-distributed data, whereas Spearman makes no normality assumption and is robust to non-linear monotonic patterns. Consequently, Pearson is preferred when a clear linear relationship is expected, while Spearman is preferred for capturing monotonic correlations in skewed or ordinal sensor data and in detecting trend-like relationships that Pearson might miss.

3. Methodology

The measurements for this study were conducted on the experimental setup shown in Fig. 2. Vibration data was collected from four accelerometers: one triaxial sensor and three uniaxial sensors, resulting in a total of six signal channels. The sampling frequency was set to 30 kHz. All sensors were rigidly mounted to the bearing housings and machine table to ensure stable and representative signal acquisition across different mechanical components.

Measurements were performed under three different servomotor speeds: 745, 750, and 755 rpm, to simulate slight process variability. The training and validation datasets included several independent acquisition runs to ensure robustness against data distribution shifts between sessions. This approach was designed to reflect real-world operating conditions and enhance model generalization.

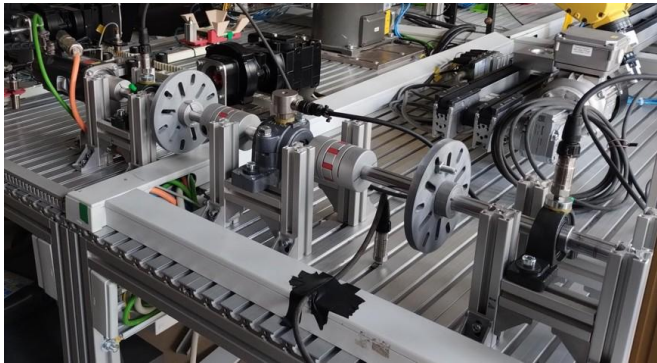


Fig. 2 Experimental measurement stand.

In this study, two fault classes were considered, as shown in Table 1. Class 0 represents healthy operation, while Class 1 corresponds to shaft imbalance. The imbalance fault was simulated by attaching an additional weight to the disks mounted on the rotating shaft, which introduced characteristic vibration patterns.

Table 1. Fault Type to the Classes Mapping.

	Fault type
0	No fault
1	Unbalanced shaft

3.1. Data analysis

In the preprocessing phase, the raw vibration signals were divided into time windows of 1.5 seconds each. Each segment was filtered using a 5th-order Butterworth bandpass filter with the following cutoff frequencies:

- 0.5 - 5000 Hz for the triaxial accelerometer,
- 0.8 - 13000 Hz for the uniaxial accelerometers.

In addition, the envelope of each signal was calculated using the Hilbert transform to enable demodulation. Filtering in the kilohertz range (to capture the machine's resonance) is beneficial because the impulsive events due to bearing faults are more pronounced in that band [15]. Prior to envelope extraction, signals were high-pass filtered above 3 kHz to isolate machine resonances. The filtered signals were then transformed into the frequency domain (from both time domain and envelope) using the Fast Fourier Transform (FFT).

From each signal window, a wide range of time and frequency domain condition indicators were calculated in order to assess the machine's operational state. These include the following indicators, which were described in [16]:

- Peak-to-Peak (PP),
- Root Mean Square (RMS),
- Crest Factor (CF),
- Standard Deviation (STD),
- Kurtosis,
- Shape Factor (SF),
- Mean Frequency (MF),
- Frequency Center (FC),
- 3 maximum amplitudes and their corresponding frequencies,
- Energy Operator (EO),
- Fourth Order Figure of Merit (FM4),
- Sixth-Order Figure of Merit (M6A),
- Eight-Order Figure of Merit (M8A),
- Clearance Factor (CIF),
- Impulse Indicator (II),
- Root Mean Square Frequency (RMSF),
- Standard Deviation Frequency (STDF),
- Fourth Order Normalized Power (NP4).

In total, 276 indicators were computed per time window across all six sensor channels, resulting in a comprehensive condition vector for each time segment. These vectors were subsequently used for both sensor malfunction detection and sensor selection based on correlation analysis.

3.2. Sensor malfunction detection

The correlation between sensors was monitored across time windows to detect deviations indicative of sensor malfunctions. For each time window, Pearson (Fig. 4) and Spearman (Fig. 3) correlation coefficients were calculated between all pairs of sensors based on their computed condition indicators. The average of both correlation types was used to increase robustness, as Pearson captures linear relationships while Spearman captures monotonic trends and is more resistant to outliers.

A sensor was flagged as malfunctioning in a time window if its mean of Pearson and Spearman correlation with at least four other sensors dropped below predefined threshold of 0.85. To avoid false positives, a sensor was considered definitively malfunctioning only if this behavior occurred in at least 4 windows and showed signs of persistence (i.e., occurred in a sequence of consecutive or near-consecutive windows, within the duration of 6 seconds in summary). Tab. 2 shows the number of windows where each sensor was flagged and whether a persistent failure was detected.

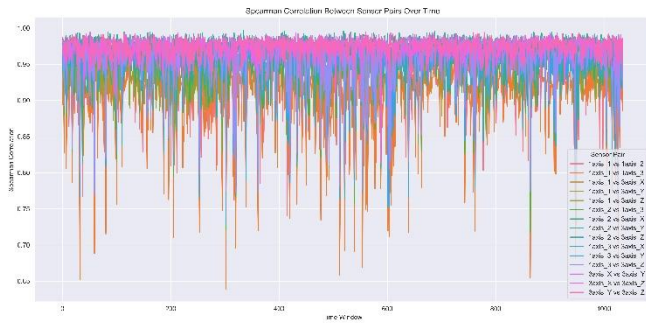


Fig. 3 Spearman's correlation between sensors across time windows.

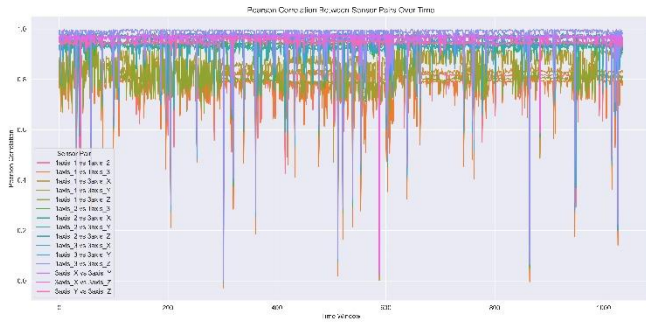


Fig. 4 Pearson's correlation between sensors across time windows.

Table 2. Sensor malfunction.

Sensor	Malfunction windows	Persistent failure
1axis_3	34	False
1axis_2	5	False
3axis_X	4	False
1axis_1	0	False
3axis_Y	0	False
3axis_Z	0	False

3.3. Sensor selection

To reduce redundancy in the sensor network and improve model generalization, correlation-based sensor selection was applied. The average correlation of each sensor with all other sensors was calculated using the mean of Pearson and Spearman coefficients across all time windows. The sensor exhibiting the highest average correlation to others was considered the most redundant and thus a candidate for removal.

This method assumes that a highly correlated sensor contributes less unique information to the condition monitoring system and may be safely excluded without significant loss of predictive power. In this case, the 3axis Y sensor had the highest mean correlation, suggesting it could be omitted from model training to reduce dimensionality (Tab. 3).

Table 3: Mean correlation of each sensor with others (averaged across all windows).

Sensor	Avg mean correlation
3axis_Y	0.9494
3axis_X	0.9432
3axis_Z	0.9418
1axis_2	0.9301
1axis_3	0.9221
1axis_1	0.8785

3.4. Machine Learning models

Models were trained using BayesSearchCV with 5-fold cross-validation to optimize hyperparameters and reduce the risk of overfitting. For final evaluation, the Leave-One-Run-Out (LORO) strategy was employed to ensure the models generalized well across independent measurement runs. During hyperparameter tuning, a subset of the training data was held out for internal validation.

The dataset consisted of measurements collected for two fault classes at different time intervals using a dedicated test stand. Since models tend to overfit to specific noise patterns or temporal characteristics of a single acquisition session, special care was taken to test their robustness on data gathered during entirely separate sessions. Without this precaution, models can perform well on cross-validation but generalize poorly to new conditions, particularly in time-sensitive applications.

In this study, the following machine learning models were trained and evaluated: K-Nearest Neighbors (KNN), Decision Tree (DT), Random Forest (RF), Support Vector Machine (SVM), and XGBoost. All models were initially trained and tested using the full set of measurement signals. Subsequently, the process was repeated after removing the most redundant signal, identified through correlation analysis, to assess the impact of dimensionality reduction on model performance.

3. Results and Discussion

The most correlated sensor was 3axis Y, with an average mean correlation of 0.9494 when compared to all other sensors (Tab. 3). This indicates that 3axis Y provides highly redundant information and may not contribute significantly to model generalization. Based on this redundancy analysis, the sensor was excluded from a second round of model training and evaluation.

No persistent sensor malfunction was detected in any of the six accelerometers used in this study. While some sensors, such as 1axis_3, showed correlation drops in several windows, none met the criteria for persistent failure. The absence of malfunction events indicates that all sensors operated reliably throughout the data acquisition period (Tab. 2).

All five classifiers were trained using BayesSearchCV and evaluated using both cross-validation and the Leave-One-Run-Out method. The results before and after sensor reduction are summarized in Tab. 4 and Tab. 5, respectively.

Before removing 3axis Y, all models performed well on the validation set, with SVM achieving perfect accuracy. However, when evaluated on the test set using unseen data from different acquisition sessions, KNN exhibited a noticeable drop in performance, highlighting its limited generalization capability. In contrast, the remaining models—Decision Tree, Random Forest, SVM, and XGBoost—achieved equal or even higher accuracy on the test set compared to their cross-validation results during BayesSearch optimization.

Table 4. Comparison of Accuracy of Models on Validation and Test Datasets.

	KNN	DT	RF	SVM	XGBoost
Validation	96.63%	98.08%	99.04%	100.00%	99.52%
Test	74.30%	99.53%	100.00%	100.00%	100.00%

After removing the 3axis Y sensor, the accuracy of most models on validation dataset remained high. On Leave-one-run-out test dataset, KNN and SVM showed slight improvements in generalization, with test accuracy increasing to 77.57% and 99.53%, respectively. However, Decision Tree performance dropped significantly on the test set after sensor removal, highlighting its sensitivity to feature reduction. Importantly, the best-performing

model – XGBoost – maintained high accuracy, demonstrating robustness even with reduced input dimensionality.

Table 5. Comparison of Accuracy of Models on Validation and Test Datasets after reduction of 3axis Y sensor.

	KNN	DT	RF	SVM	XGBoost
Validation	97.12%	96.63%	99.04%	100.00%	99.52%
Test	77.57%	43.93%	97.66%	99.53%	100.00%

5. Conclusion

This study addressed both sensor malfunction detection and sensor selection using correlation-based analysis within a machine learning framework for fault classification. Pearson's and Spearman's correlation coefficients were calculated between all sensor pairs over time windows to monitor system behavior and identify redundancy.

None of the sensors exhibited persistent signs of malfunction. However, the malfunction detection algorithm will be integrated into the measurement stand for real-time monitoring (to prevent occurrences as shown in Fig. 1). This mechanism can serve as an early warning system, identifying potential underperformance in the measurement chain and reducing the risk of invalid predictions and false alarms.

The Leave-One-Run-Out (LORO) strategy proved its relevance for evaluating model generalization. While models often perform very well on validation data derived from the training set, they may perform significantly worse on data collected in separate acquisition sessions. This confirms the importance of building comprehensive and diverse datasets—including multiple experimental runs—to develop noise-resistant and robust models.

After feature selection, most models maintained high accuracy on validation dataset, with XGBoost continuing to achieve 100% performance. Notably, the Decision Tree classifier suffered a significant, above 50%, drop in test accuracy after sensor reduction, highlighting its sensitivity to input dimensionality. In contrast, models like SVM, XGBoost and Random Forest remained stable, suggesting that carefully chosen models can operate effectively even with a reduced sensor set.

In summary, correlation-based sensor selection can maintain model performance while simplifying the sensor setup. Combined with ongoing malfunction detection and robust evaluation strategies, this approach provides a reliable pathway toward efficient and trustworthy machine learning-based condition monitoring systems.

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Regarding cybersecurity in Bulgarian educational institutions at the K–12 level

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Abstract: Cybersecurity studies increasingly prioritize empirical methodologies to understand and alleviate security risks arising from human behavior, organizational practices, and the advancement of technologies used to perform cyberattacks. This research paper explores how the school management and key educators in Bulgarian K-12 schools comprehend cybersecurity within the academic framework of the Bulgarian education system. Our survey of 927 Bulgarian K–12 educational institutions revealed that a very small number of them assess their level of cybersecurity as extremely low. Respondents see cybersecurity training as essential for ensuring information security within their institutions. Our findings indicate that only 25% of K-12 employees are able to incorporate this training into their qualification programs.

KEYWORDS: HUMAN FACTOR IN SECURITY, K-12 EDUCATION, BULGARIA

1. Introduction

Cybersecurity establishes policies, procedures, and technical methods to protect, detect, correct, and defend against harm, illegal use or modification, or exploitation of information and communication systems and the data they contain. The rapid speed of technical progress and innovation, along with the rapidly developing nature of cyber threats, exacerbates the situation, [1].

The European Union underlines the significance of the science and research sector, categorizing it as a vital infrastructure sector subject to distinct cybersecurity rules. The NIS 2 Directive (EU 2022/2555) establishes a revised framework for cybersecurity inside the European Union, superseding the original NIS Directive (2016). It aims to improve cybersecurity within the European Union by creating a uniform high standard of security for network and information systems. While K–12 level educational institutions are not covered by NIS 2 Directive, their cybersecurity must not be overlooked. The rapid growth of digital educational infrastructures, combined with the rise of cloud computing, is introducing new risks that established security frameworks are struggling to manage.

A recent article from 2024 delineates and elucidates the primary elements of cybersecurity protection in Bulgaria. The rules for adopting and implementing effective measures to avoid cybercrime are substantiated based on the ideas of "information security," "cyber security," and "cyber resilience." An analysis has been conducted on the principal administrative documents and legal instruments pertaining to national cyber security protection. A legal analysis was performed for the purpose of examining potential vulnerabilities, dangers, and risks to cybersecurity in Bulgaria, [2].

A study conducted in Bulgaria presents findings from a survey of Cybersecurity Experts aimed at collecting and synthesizing extensive information about the challenges of ensuring cybersecurity in the country, with particular emphasis on the critical role of human factors (HF) in this field. The survey was executed as a component of a project funded by the Bulgarian Institute of Public Administration in 2019. The survey inquiries relate to three specific sectors: public administration, academia, and the business sector, each of which supports the functioning of e-government in Bulgaria. The study results corroborated the prevailing consensus among experts that the human element may represent the 'weakest link' in cybersecurity as a socio-technical system. Therefore, experts believe that the majority of cybersecurity breaches are attributable to human error or other HF vulnerabilities. The predominant issues associated with successful assaults are spam and ransomware. Nonetheless, authors observed a propensity among SMEs to regard HF as a potentially robust method for identifying and alleviating cyber hazards. Consequently, they deem it essential to focus on the significance of the human element in the realm of cybersecurity in Bulgaria. Simultaneously, authors highlighted the competency level and inadequate capacity (knowledge and skills) of IT personnel as the primary issue. The research indicates that, despite the acknowledged significance of HF in cybersecurity, the training remains inadequate, [3].

2. The Research Backgrounds

The educational institutions at the K–12 level are frequently targeted by cyber threats. K-12 schools and districts are confronting numerous formidable risks as contemporary cyber-attacks get increasingly sophisticated and astute. A suitable starting point for our analysis can be found in [4]. An analysis of the Cybersecurity and Infrastructure Security Agency of the U.S. Department of Homeland Security indicates that K–12 organizations require simplicity, prioritization, and resources tailored to their unique needs. [4] aims to advance the response to this call by offering clear recommendations and resources to assist K–12 organizations in effectively mitigating their evolving cybersecurity risks. The report's key findings and recommendations are summarized as follows:

Table 1: Key findings and recommendations, Source[2]

	FINDING	RECOMMENDATION
1	With finite resources, K–12 institutions can take a small number of steps to significantly reduce cybersecurity risk.	Invest in the most impactful security measures and build a mature cybersecurity plan by taking these three steps: • Implement highest priority security controls. • Prioritize further near-term investments in alignment with the full list of CISA's Cross-Sector Cybersecurity Performance Goals (CPGs). • Over the long-term, develop a unique cybersecurity plan that leverages the NIST Cybersecurity Framework (CSF).
2	Many school districts struggle with insufficient IT resources and cybersecurity capacity.	Recognize and actively address resource constraints: Work with the state planning committee to leverage the State and Local Cybersecurity Grant Program (SLCGP). • Utilize free or low-cost services to make near-term improvements in resource-constrained environments. • Expect and call for technology providers to enable strong security controls by default for no additional charge. • Minimize the burden of security by migrating IT services to more secure cloud versions.
3	No K–12 entity can singlehandedly identify and prioritize emerging threats, vulnerabilities, and risks.	Focus on collaboration and information sharing: • Join relevant collaboration groups, such as MS-ISAC and K12 SIX. • Work with other information-sharing organizations, such as fusion centers, state school safety centers, other state and regional agencies, and associations. • Build a strong and enduring relationship with CISA and FBI regional cybersecurity personnel.

Alongside cybersecurity issues, the proliferation of digital content and the ever-improving access to it have heightened pupils' vulnerability to a broader spectrum of online dangers and unsuitable material. Consequently, the necessity for cybersecurity and school child cybersecurity has become imperative. Given the evolving digital landscape, it is crucial to implement safeguards to protect kids from online risks, including cyberbullying, improper content, sexting, sextortion, and online predation. In this context [5]

proposes a novel education-specific K-12 Cyber Protection Framework (CPF) that provides industry-led cybersecurity and cybersecurity standards.

Other current thorough research analyzes the fundamental principles and procedures involved in the formulation and execution of information security management policies inside educational institutions, with a particular focus on "Dr. Ivan Bogorov" Vocational High School of Economics in Varna. The development of an information security policy within the framework of rules and international standards is discussed. The research presents an overview of the primary steps for implementing information security policies in educational settings, specifically within "Dr. Ivan Bogorov" Vocational High School of Economics, [6].

An intriguing study was undertaken from April 2024 to September 2024 with the participation of 56 Bulgarian citizens employed in higher education. The study aimed to evaluate the state of information security in higher education institutions by collecting the views, attitudes, and perceptions of professionals in the field. The queries were classified according to three fundamental principles: demographic characteristics, occupational features, and individual viewpoints. The main finding is that respondents feel secure regarding the performance of their work duties and the protection of personal data in an information security environment, [7].

3. Data and Methodology

In order to have a better knowledge of how to enhance security and make schools more resistant to cyber-attacks, the first logical step is to investigate the comprehension of individuals in educational institutions with regards to cybersecurity.

The survey was conducted online from March 31, 2024, to May 3, 2025, involving a poll of 927 school principals, teaching staff, administrative and other staff from Bulgarian K-12 institutions. This study aimed to compare individual differences, evaluate the availability of systematic cybersecurity training, analyze decision-making styles, and assess behavioral intentions related to cybersecurity for the protection of educational and administrative platforms, software, hardware, and computer networks, along with proactive awareness and knowledge enhancement. The survey was designed and distributed via Microsoft Forms within the internal Microsoft 365 environment of the Bulgarian Ministry of Education.

The survey consisted of 22 questions designed to assess individuals' understanding of cybersecurity within their K-12 educational institutions and to gather their viewpoints on the impact of cybersecurity risks on their daily tasks. No incentives were given out, and participation was completely voluntary and anonymous.

Table 2, Table 3 and Table 4 illustrate the structure of the schools involved in the study.

Table 2: Distribution of survey-participating schools by type and kind of ownership.

type and kind of ownership	In numbers	percentage of respondents
State	317	34.20%
Municipal	592	63.86%
Private	4	0.43%
(blank)	14.00	1.51%

Table 3: Distribution of survey-participating schools by category.

School category	In numbers	percentage of respondents
Gymnasiums	14	2%
Primary school	31	3%
Integrated school	20	2%
Basic school	321	35%
Profiled gymnasiums	114	12%
Vocational gymnasiums	22	2%
Secondary school	400	43%
(blank)	5	1%

Table 4: Distribution of survey-participating schools by size.

School size	In numbers	percentage of respondents
With up to 50 students	23	2%
Between 50 and 100 students	98	11%
Between 100 and 200 students	134	14%
Between 200 and 500 students	329	35%
Over 500	332	36%
(blank)	11	1%

This structure of the schools involved in the study gives us reason to believe that the results obtained from our survey are representative only of the different types and sizes of public K-12 schools. Only four private schools participated in the study, rendering the data unrepresentative of this group of K-12 institutions.

Table 5 illustrates the distribution of survey participants by position.

Table 5: Distribution of survey participants by position.

Participants' position	In numbers	percentage of respondents
Teaching staff	750	80.91%
Director	103	11.11%
Deputy director	43	4.64%
Administrative and other staff	27	2.91%
(blank)	4	0.43%

The distribution of survey participants by their positions suggests that the results are indicative of the many roles within K-12 institutions.

Table 6 illustrates the distribution of survey participants by age.

Table 6: Distribution of survey participants by years old.

Participants' age (years old)	In numbers	percentage of respondents
Up to 25 years old	23	2.48%
Between 24 and 40 years old	210	22.65%
Between 40 and 60 years old	611	65.91%
Over 60	79	8.52%
(blank)	4	0.43%

The age distribution of survey participants corroborates the trend of an aging teaching workforce in Bulgarian K-12 institutions.

4. Key Results

Based on the assessments of the K-12 educational institutions surveyed, only 3.34% indicate that they have faced cybersecurity incidents in the past five years. The results are presented in Table 7.

Table 7: Has your school had any cybersecurity incidents in the past five years?

Answer	In numbers	percentage of respondents
Yes	31	3.34%
No	884	95.36%
(blank)	12	1.29%

For comparison, according to data from the USA, [8], 82% of K-12 organizations experienced cyber incidents, nearly 14,000 security events were observed, over 9,300 are confirmed incidents. Cyber threat actors target human behavior 45% more often than technical vulnerabilities. We believe that the significant difference in reported cybersecurity incidents between our data and the US data comes from the absence of established and easy-to-follow procedures for reporting every cybersecurity incident in K-12 educational institutions. In many cases, prevalent cybersecurity incidents like spam, fishing and ransomware often go unreported.

This observation is corroborated by our survey data, which reveals a significant lack of personnel accountable for cybersecurity in K-12 schools. Only 5.39% of the respondents who participated in the survey indicated that their school had personnel accountable for cybersecurity, (See Table 8).

Table 8: Do you think it is necessary to have a separate position for cybersecurity activities in your school?

Answer	In numbers	percentage of respondents
There is a position in the school that handles cybersecurity activities.	50	5.39%
Yes, it is important to have such a position.	235	25.35%
I can't say.	361	38.94%
Not really	215	23.19%
Definitely NOT.	50	5.39%
(blank)	16	1.73%

At the same time, the majority of respondents, (48.87%), are unable to assess the state of cybersecurity at their institution, (See Table 9). The positive aspect was that a very small percentage of answers identified significant cybersecurity deficiencies in their K-12 institutions.

Table 9: What do you thinking about the level of cybersecurity at your school?

Answer	In numbers	percentage of respondents
Very low	16	1.73%
Relatively low	100	10.79%
Can't tell	453	48.87%
Relatively high	293	31.61%
Very high	61	6.58%
(blank)	4	0.43%

A considerable number of respondents in our poll indicated substantial resources and personnel challenges. The most commonly identified essential components of cybersecurity in K-12 schools are cybersecurity training (staff training, selected by 24.77% of respondents, student training, selected by 20.43% of respondents, parent training, selected by 15.61% of respondents), and technological tools and software, selected by 26% of respondents, (See Table 10). At the same time, a very small percentage of respondents (8.00%) refer to the presence of regulations governing cybersecurity as a significant factor.

Table 10: In your experience, what are the most crucial parts of cybersecurity in your school?

Answer	In numbers	percentage of respondents*
Technical tools and software for cybersecurity	480	26.02%
Staff training	457	24.77%
Student training	377	20.43%
Parent training	288	15.61%
Regulations	148	8.02%
Other	95	5.15%
(blank)	37	3.99%

* The cumulative percentages surpass 100% as participants were permitted to select several answers.

Despite the recognition of cybersecurity training as a critical element, only 35% responded positively to the question, "Have you participated in any cybersecurity-related training in the past five years?". Additionally, merely 12.73% of respondents confirmed that their K-12 institutions provide annual cybersecurity training, and 11.76% of respondents confirmed that their K-12 institutions provide a rather general cybersecurity training, (See Table 11).

Table 11: Do you expect that your qualification plans will include cybersecurity and computer security training?

Answer	In numbers	percentage of respondents*
Not planned	143	15.43%
Somewhat unlikely	127	13.70%
Can't tell	368	39.70%
Somewhat likely	109	11.76%
Annually	118	12.73%
(blank)	62	6.69%

5. Conclusions

Our survey of 927 Bulgarian K–12 educational institutions indicates that a insignificant number of workers employed within, define the level of cybersecurity in their institutions as very low. They believe that cybersecurity training, technological instruments, and software are essential components for maintaining information security within their institutions. Simultaneously, our research indicates that fewer than ¼ of those employed in K-12 institutions can rely on such training as an integral component of their qualification plans. We deem it necessary to do further our investigation into the remarkably low number of cybersecurity events observed in our study.

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