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# Study on the Use of Polymer 3D-Printed Material for the Verification Process of a Metal Topology-Optimized Bracket

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**Abstract:** The article proposes a cost-effective and rapid method for the preliminary verification of an optimized metal air brake bracket using a 3D-printed polymer model. The original bracket, used in light jet aircraft, is made of the aluminium alloy Al 2024 T351 and manufactured using conventional CNC machining technology. The study presents a structural optimized bracket, intended to be produced using 3D printing technology with AlSi10Mg material to reduce weight. The bracket is presented along with its static load, stress-strain analysis, and the weight structural optimization procedure using ANSYS Workbench. Modifications to the bracket's shape were made to meet the static stress-strain and buckling characteristics of the original bracket, resulting in a 32% weight reduction. The complex model of the optimized bracket was verified both numerically using ANSYS Workbench and experimentally using 3D-printed bracket models made from substitute polymer ASA material, printed with the Prusa Mk3 printer. The article also presents the results of basic tensile material tests on ASA material coupons printed in various positions to determine the semi-isotropic characteristics necessary for numerical analysis. The substitute material bracket provides potential for indicative verification of the numerically optimized model, though its usage is limited. Finally, the article offers recommendations for further research.

**Keywords:** STRUCTURAL OPTIMIZATION, ADDITIVE MANUFACTURING, ANSYS, AIRPLANE AIR BRACKET, ASA

## 1. Introduction

The aircraft structures are characterized by the efforts to use materials weight-efficiently [1-2]. One of the modern weight-reduction tools of the components are the combinations of structural optimization and additive manufacturing [3-5]. The technology of the structural optimization is used in many applications in a variety of industrial branches, including aerospace [4-11]. This technology enables a reduction in the weight of several components produced by conventional technologies and a formation a shape with more economical use of material; thus, it can transmit the original load. This is true for the aerospace structures, where the total aircraft weight is one of the crucial factors affecting almost all airplane operation characteristics. In commercial aerospace, it is estimated to reduce the airframe weight by 5-7% in combination with additive manufacturing [4]. 3D printing, falling into the additive technology category, allows forming an almost any – no matter how complicated – shape of a component from different materials by the gradual layering of the material, which could not be produced through conventional technologies or would be unprofitable or lengthy to produce [12].

The article presents the study of a left inner braking shield bracket for the light jet training aircraft further development (see Figure 1) that has achieved a significant weight reduction using the structural optimization in the ANSYS Workbench environment. The original bracket, which is located on the underside of the central part of the wing as a part of the support system of two air brake shields each supported by two brackets of a different size, is made of the aluminium alloy Al 2024 T351 using the conventional machining technology on a CNC device with respect to its small-scale production. For the purpose of this study, the bracket load is only static and the structural optimization is applied only to the external shape of the component.

Finally, the optimized component is presumed to be produced using the 3D printing technology using the material AlSi10Mg. A weight saving of 32% was achieved based on simulation and FEM verification.

A key element design parameter is verification of FEM results. This is done experimentally by measuring the deformation behaviour on original and optimized brackets made of polymer material Acrylic Styrene Acrylonitrile (ASA) using 3D printing. This study evaluates the hypothesis that measurements obtained from polymer models can be used to verify the static behavior of complex metallic components. These would make the design process of metal parts significantly cheaper and faster.



Fig. 1 Air brake bracket location on jet airplane and bracket CAD model.

The first step is a numerical stress-strain static analysis of the original bracket to set the deformation and stress limits for the proposed bracket. Subsequently, a structural optimization of the bracket is performed to achieve a significant reduction in its weight. The method uses the Solid Isotropic Material with the Penalization interpolation scheme (SIMP) [3, 6, 13-15] with a simple compliance objective that uses the mass constraint [16]. To maintain the ability to transfer the same load as the original bracket, the optimized bracket is afterwards modified and reinforced. To verify experimentally the optimized bracket model, the bracket is made of the substitute ASA polymer material using the 3D printing and its stiffness behaviour is verified using experimental static loading. The stiffness results are compared to the numerical model of this bracket, whose load is in accordance with the experiment performed. In addition, the fundamental material properties of ASA have been determined to enable its use as an isotropic material in FEM analyses. The goal of the article is to present the methodology of the structure design utilizing the structural optimization and the low-cost verification preceding the final production using the metal additive manufacturing.

## 2. Finite Element Analysis of the Bracket

The analysis uses a given CAD model of a bracket loaded at the bottom fork by a pin in three axes according to Figure 2. The top approximately flat surface of the bracket is attached to the bottom wing supporting system by seven steel shoulder fasteners. The material of the original bracket is the aluminium alloy 2024 T351, the approximate dimensions of the bracket are 220 × 122 × 92 mm and the weight is 659 g.

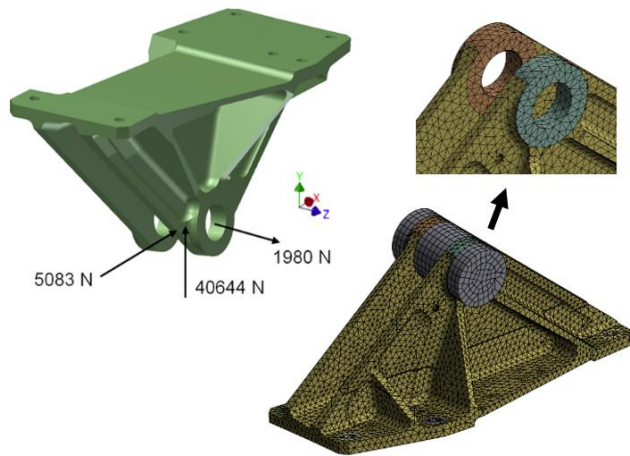


Fig. 2 Bracket load and mesh.

The bracket model is analysed in the ANSYS Workbench 2025 R1 environment using Static Structural analysis. The mesh model is illustrated in Figure 2. Tetrahedron elements with a size of 4 mm were used for the bracket, while the pin was meshed using the Multi-Zone method with elements of the same size. The boundary conditions are simplified by representing the pre-tensioned shoulder fasteners through the application of fixed constraints to all five annular regions on the bracket beneath the bolt washers. In addition, the Compression Only Support condition is applied to the upper flat bracket surfaces attached on the wing system. The primary load from the three force components specified by the aircraft manufacturer as ultimate static load is transmitted to the center of the steel pin located within the bracket fork. The pin features shoulders that provide support against the adjoining components. This configuration represents a pre-tensioned shoulder bolt connection with the air brake system. The contact between the pin and the bracket fork is simulated using a Rough friction condition. The results of the analysis are shown in Figure 3.

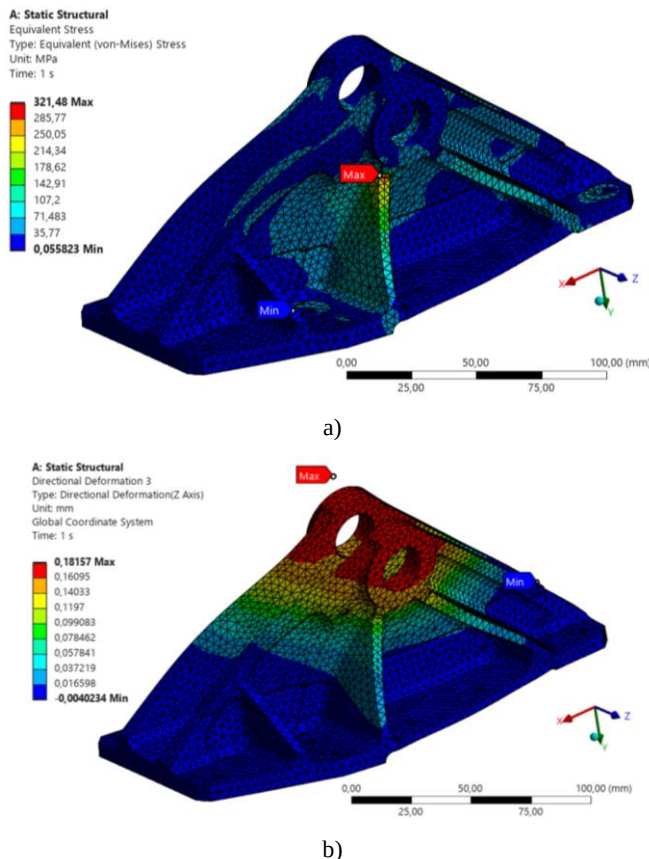


Fig. 3 Results of original bracket analysis: a – von Mises stress, b – deformation along z-axis.

Von Mises stress in Figure 3a has its maximum value 321 MPa in rib fillet and its location is marked with a red arrow. Deformation along the z-axis is in Figure 3b with maximum value 0.18 mm. The steel pin is not shown. Deformation along the x and y axes are shown in Table 1. The yield limit of the bracket material 325 MPa is not exceeded, the strength limit is 470 MPa, the modulus of elasticity is 73 GPa and the Poisson number is 0.33 [17-18]. In the bracket model with a refined mesh of 1 mm in the region of maximum stress, the von Mises stress increased to a value of 326 MPa, which is also acceptable. The area of stress peak is small, and these results set the ultimate limits for stress and stiffness behaviour for the optimized bracket. Moreover, the optimized bracket geometry will be modified to reduce the mentioned stress concentration at this point; thus, enabling the desired weight reduction.

### 3. Structural Optimization of the Bracket

The aim of the proposed structural optimization is to reduce the bracket weight while preserving the ability to transfer the specified load without exceeding the ultimate stress and stiffness limits of the original bracket. The structural optimization employs a Mass Response Constraint, targeting a 40% reduction in weight. Exclusive regions are taken from boundary conditions – seven fasteners annular regions and two hollows for the pin. The condition Compression Only Support used in Static Structural analysis should be suppressed due to the impossibility to support such a non-linear condition for structural optimization analysis in used version of ANSYS, other settings including mesh remain the same. Manufacturing constraints are applied in form of Member Size min 2 mm and AM Overhang Constraint Angle 45° in direction –Y. Figure 4a shows the structural optimization analysis result.

The resulting bracket geometry respects the specified weight-reduction criterion as well as the chosen size of the mesh. However, such geometry cannot be used directly because it requires editing and smoothing. In this article, the geometry of the weight-reduced bracket is created "manually" following the pattern of the analysis results by trimming the original bracket model in the CAD Autodesk Inventor environment. This procedure is chosen because it is considered faster, simpler and enabling further geometry modifications. Moreover, the two left fasteners appear to be unnecessary for load-bearing and are therefore removed in the modified bracket design.

The optimized bracket is subsequently verified for stress and stiffness limits, in comparison to the original bracket design, using Static Structural analysis in ANSYS. If it does not comply, additional modifications are required in the form of reinforcing and strengthening the bracket, or vice versa, possibly lightening in the appropriate bracket areas. Therefore, it was necessary to redistribute the material to reinforce the bracket in view of the mentioned von Mises stress concentration that occurred with the original bracket in Figure 3a.

However, the targeted weight reduction could no longer be achieved through these modifications. The final design, which achieved a 32% reduction in weight, is shown in Figure 4b.

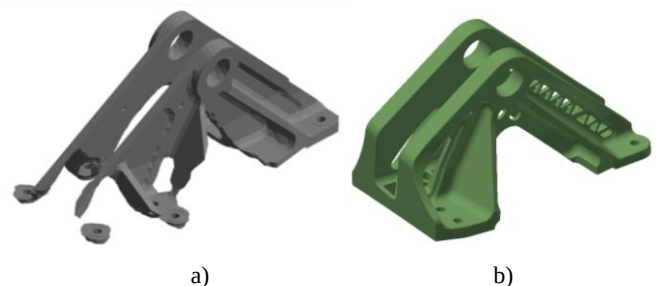
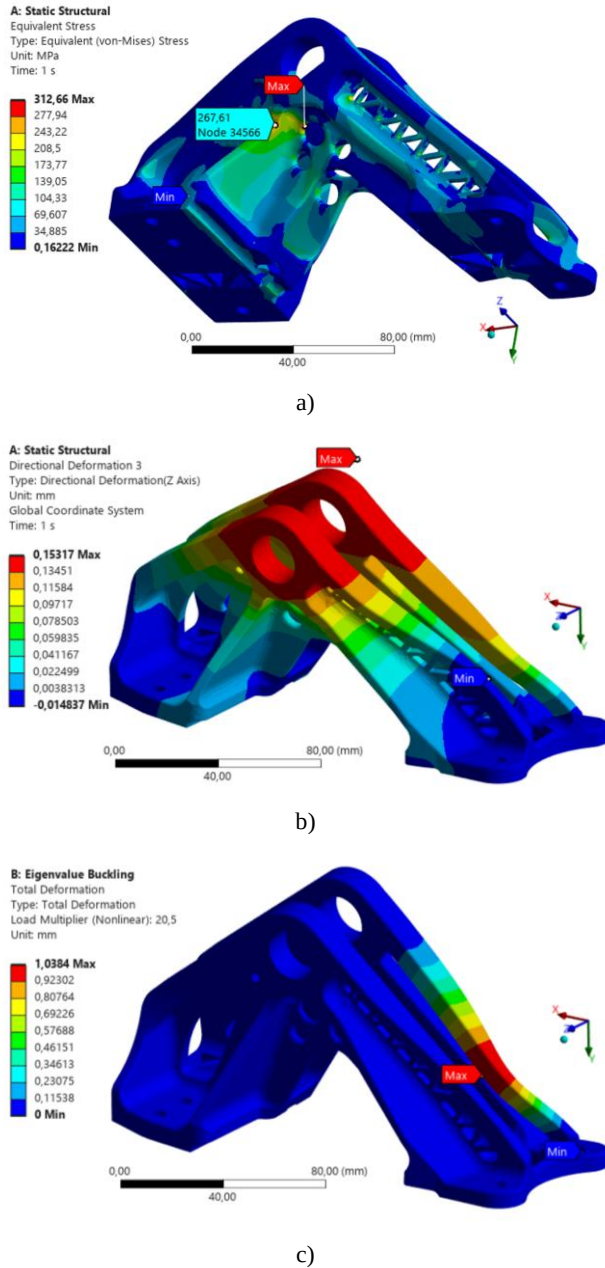


Fig. 4 Structural optimization analysis result for mass reduction 40% and Retained Threshold 0.3 (a) and modified optimized bracket (b).

The results of stress-strain analysis are shown in Figure 5 (the pin is not shown) and the comparison of results is shown in Table 1.



**Fig. 5** Results of stress-strain analysis: a – von Mises stress, b – deformation along z-axis, c – buckling analysis.

**Table 1:** Comparison of bracket parameters

| Parameter        | Origin bracket | Optimized bracket |
|------------------|----------------|-------------------|
| Deformation X    | 0.01 mm        | 0.06 mm           |
| Deformation Y    | 0.12 mm        | 0.14 mm           |
| Deformation Z    | 0.18 mm        | 0.15 mm           |
| von Mises Stress | 321 MPa        | 313 MPa           |
| Weight           | 0.659 kg       | 0.450 kg          |
| Weight reduction |                | 32%               |

Von Mises stress is slightly lower for the optimized bracket and its maximum value 313 MPa occurs in relief opening below the pin. Moreover, the critical stress concentration in the rib fillet under the bracket's pin hollow has been significantly reduced to the value 268 MPa. Stress values for refined mesh 1 mm are 314 / 273 MPa.

Deformation values are comparable for the optimized bracket. In two cases, the deformation of the optimized bracket slightly exceeds the original values – the deformation in the direction of the

x and y axes. In the case of the x-axis deformation, the optimized value is greater by 0.05 mm and in the case of y-axis deformation, it is by 0.03 mm, which is not considered to be a major exceeding as these are very small deformation values. In the case of the largest z-axis deformation, the optimized bracket deformation is slightly reduced, based on the simulation analysis.

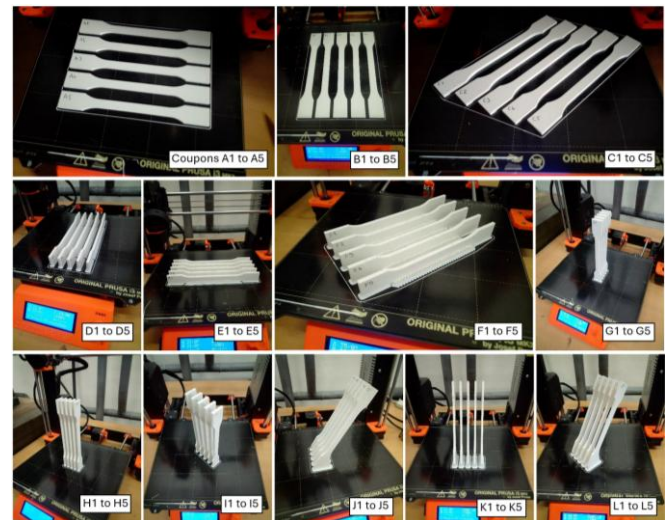
The optimized bracket model has also been checked for the loss of stability using Eigenvalue Buckling analysis, see Figure 5c. The used criteria are the Load Multiplier as the magnification factor by which the loads applied in a previously specified static analysis would have to be multiplied to produce the critical buckling load [19-20]. Its value is 20.5 which complies. It can, therefore, be concluded that the optimized bracket has met the goal with approximately one-third weight reduction.

#### 4. Characteristics of Substitute Material ASA

The experimental verification of the original and optimized models was carried out on the manufactured components using the 3D printing, but from a substitution polymer material ASA of manufacturer Prusa with filament diameter 1.75 mm and nozzle diameter 0.4 mm. This also required a verification of the used material characteristics, especially the modulus of elasticity to achieve proper stiffness behaviour of the bracket.

In order to determine the basic mechanical characteristics, a tension test on coupons was conducted according to the CSN EN ISO 527, Type II (coupon length 170 mm, rectangular cross section 10 × 4 mm) using the test machine Shimadzu AGX-V2 100 kN. The test enabled to set the elasticity modulus and the strength of the material as the essential parameters for the static loading of the bracket in the elastic region. A mechanical extensometer (MFA 25) was used to measure deformation, attached to the specified region of the test specimen. The loading rate was 1 mm/min.

The ASA material specimens were fabricated using Fused Deposition Modelling (FDM) technology on a Prusa i3 MK3 printer, utilizing filament from the same spool. Twelve distinct printing orientations were employed, with each orientation comprising five individual specimens. This configuration was designed to encompass a broad spectrum of printing orientations in order to investigate the anisotropic behavior of the printed material (see Figure 6).



**Fig. 6** Printing orientation of ASA coupons using Prusa i3 Mk3 printer; the coupons are designated from A to L.

Coupons A, E, G, and J were positioned longitudinally along the printing bed; coupons B, D, H, and K were oriented transversely; and coupons C, F, I, and L were arranged diagonally. Coupons A, B and C were printed flat on the bed, D, E and F on their edge, G to L were printed vertically; while J, K and L were printed vertically at a 60° angle due to print stability and the

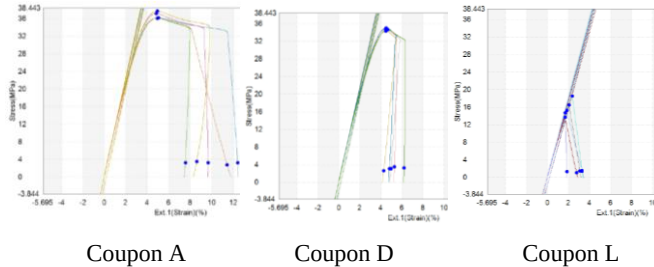
elimination of the need for support structures. The default printer settings recommended by filament vendor for this material were applied to both the sample coupons and the substitution brackets. These settings included a layer thickness of 0.15 mm, a heated temperature of 110 °C (105 °C for the first layer), an extruder nozzle temperature of 260 °C, a material infill density of 100%, print speed for perimeters 60 mm/s and for infill 200 mm/s.

The results for the elasticity modulus with standard deviation are presented in Table 2.

**Table 2: Modulus of elasticity of ASA coupons**

| Coupon type                     | Modulus of elasticity [GPa] | Coupon type | Modulus of elasticity [GPa] |
|---------------------------------|-----------------------------|-------------|-----------------------------|
| A                               | $1.12 \pm 0.013$            | G           | $0.929 \pm 0.026$           |
| B                               | $1.11 \pm 0.031$            | H           | $0.943 \pm 0.007$           |
| C                               | $1.13 \pm 0.011$            | I           | $0.892 \pm 0.007$           |
| D                               | $1.08 \pm 0.017$            | J           | $0.902 \pm 0.010$           |
| E                               | $1.10 \pm 0.005$            | K           | $0.923 \pm 0.011$           |
| F                               | $1.08 \pm 0.008$            | L           | $0.896 \pm 0.015$           |
| Average value: $1.01 \pm 0.097$ |                             |             |                             |

The moduli of elasticity exhibit a high degree of consistency across the five samples as well as within printing orientation types – flat (A, B, C), on edge (D, E, F), vertical (G, H, I) and vertical with an angle (J, K, L). The flat configuration exhibits the highest average modulus of elasticity (1.12 GPa), while the lowest value is observed in the vertical configuration with an angle (0.907 GPa). The average modulus of elasticity including all configurations has the value  $1.01 \pm 0.097$  GPa. This corresponds to a deviation of approximately 10%, which is considered acceptable for preliminary and rapid assessments of the isotropic stiffness behaviour of printed ASA material. An example of the stress-strain relationship is presented in Figure 7. The results indicate an acceptable level of isotropy in the material, which is assumed in the subsequent analysis and allows for a simplified isotropic definition of ASA's material properties for stress-strain evaluation.



**Fig. 7 Stress-strain characteristics of coupons A, D and L.**

Note – the modulus of elasticity E drawn from the mentioned coupons testing does not represent the true modulus of elasticity of the ASA material. The produced samples contain a non-homogenous structure with a different distribution of a filament located on rims with respect to the inside region of the printed part according to chosen printer parameters [21]. On the other hand, achieved non-homogenous structure modulus of elasticity represents to some extent the behaviour of real parts produced by 3D printing using FDM technology and material ASA.

According to the manufacturer [22], the modulus of elasticity is 1.6 GPa for the horizontal printing direction and 1.7 GPa for the vertical direction, both determined in accordance with the same standard. However, the manufacturing parameters of the test specimens are not disclosed, and factors such as nozzle speed, layer height and filament condition may have influenced the results. The investigation of the filament material characteristics is also described in [23-26] and needs to be further investigated.

The results for ultimate tensile strength are presented in Table 3. Significant differences can be observed. Greater differences were observed in the ultimate tensile strength. The consistency among the

five specimens varied, with higher uniformity found in horizontally printed samples (A to F) and lower consistency in vertically printed ones (G to L). Notably, samples B and G deviated from their respective groups, exhibit significantly higher deviation. Regarding the magnitude of ultimate tensile strength, the horizontally printed samples (A to F) demonstrated more than twice the strength – ranging from 34.8 to 37.3 MPa – compared to the vertically printed samples (G to L), which ranged from 12.8 to 18.1 MPa. These results clearly indicate that printing orientation has a substantial impact on the mechanical strength of the material.

**Table 3: Strength of ASA coupons**

| Coupon type                     | Strength [MPa]  | Coupon type | Strength [MPa]  |
|---------------------------------|-----------------|-------------|-----------------|
| A                               | $36.7 \pm 0.74$ | G           | $17.8 \pm 3.72$ |
| B                               | $35.5 \pm 1.93$ | H           | $18.0 \pm 0.98$ |
| C                               | $36.3 \pm 0.72$ | I           | $12.8 \pm 1.65$ |
| D                               | $34.8 \pm 0.31$ | J           | $18.1 \pm 1.46$ |
| E                               | $37.3 \pm 0.22$ | K           | $12.9 \pm 1.41$ |
| F                               | $35.9 \pm 0.27$ | L           | $15.7 \pm 1.87$ |
| Average value: $26.0 \pm 10.42$ |                 |             |                 |

## 5. Experimental Verification of the Bracket using Substitute Material ASA

The aim is to create experimental cases that are subsequently verified on a simulation model, where the mentioned homogeneous and isotropic substitute ASA material is assumed. The brackets were manufactured from the substitute ASA material using the same production parameters as the coupons used for determining mechanical properties in Chapter 4. The set includes three brackets with the original geometry and three with the optimized design, see Figure 8. The material exhibits relatively high deformation during the printing process, which partially alters the geometry and necessitates compensation using shims during the experiment.



**Fig. 8 Experimental brackets made from ASA material.**

The experimental verification of all brackets has the character of a stiffness test in the weakest bracket direction, which is the direction z, using a special device representing bracket pin made from the PETG material enabling to apply the load and measuring the deformation. The load was applied using a 5 kg and 10 kg calibrated weight through a steel bolt at room temperature. The load is chosen with respect to the used material and the elastic (linear) area of bracket deformation.

A 5 kg load is gradually applied individually to each bracket arm, while a 10 kg load is applied simultaneously to both arms, in both directions along the z-axis. This results in a total of six loading cases for each bracket, which are illustrated in Figure 9.

The desired vertical deformation along the direction of load is measured at the bolt head using digital indicators MarCator 1086. An example of the measurements for cases 1-1 and 2-6 is shown in Figure 10. Each case was tested six times, and the reported value was calculated as the arithmetic mean of the last five measurements with standard deviation. The first measurement was excluded from the evaluation due to potential assembly clearances and material hysteresis. The measurement results are presented in Table 4 and 5.

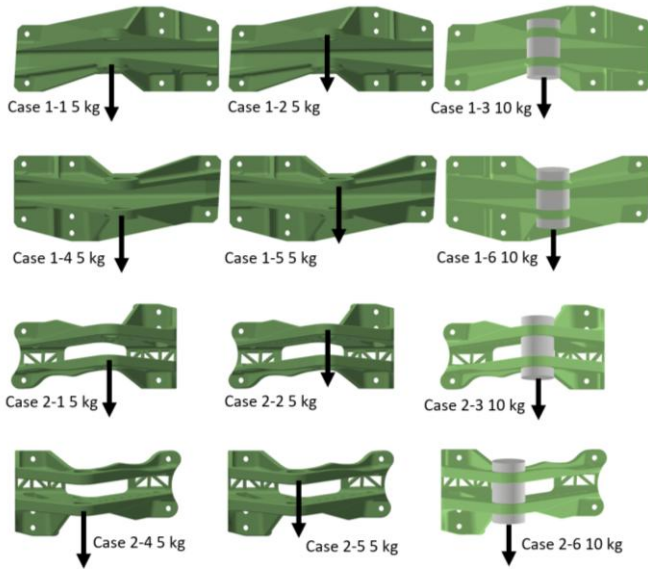


Fig. 9 Experimental load cases.

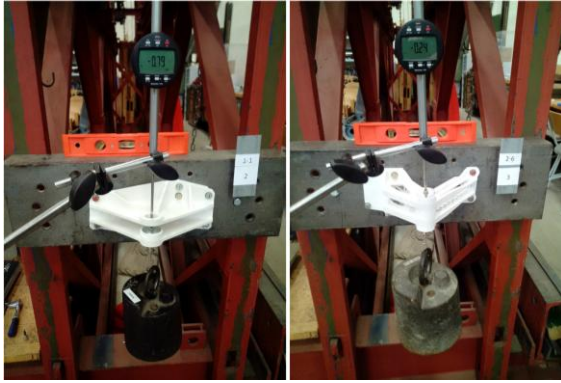


Fig. 10 Experimental setup for cases 1-1 (loaded is only the lower bracket arm by weight 5 kg) and 2-6 (loaded are both arms by weight 10 kg).

Table 4: Experimental results for brackets deformation along z-axis

| Bracket type | Load case | 1 [mm] | 2 [mm] | 3 [mm] | Result [mm]     |
|--------------|-----------|--------|--------|--------|-----------------|
| Original     | 1-1       | 0.65   | 0.71   | 0.57   | $0.65 \pm 0.06$ |
|              | 1-2       | 0.17   | 0.27   | 0.21   | $0.22 \pm 0.04$ |
|              | 1-3       | 0.11   | 0.13   | 0.12   | $0.12 \pm 0.01$ |
|              | 1-4       | 0.27   | 0.32   | 0.26   | $0.28 \pm 0.03$ |
|              | 1-5       | 0.64   | 0.62   | 0.67   | $0.64 \pm 0.02$ |
|              | 1-6       | 0.09   | 0.15   | 0.13   | $0.13 \pm 0.03$ |
| Optimized    | 2-1       | 0.94   | 0.92   | 0.97   | $0.94 \pm 0.02$ |
|              | 2-2       | 0.22   | 0.22   | 0.21   | $0.22 \pm 0.00$ |
|              | 2-3       | 0.16   | 0.16   | 0.13   | $0.15 \pm 0.02$ |
|              | 2-4       | 0.31   | 0.32   | 0.30   | $0.31 \pm 0.01$ |
|              | 2-5       | 0.96   | 0.96   | 0.97   | $0.96 \pm 0.01$ |
|              | 2-6       | 0.19   | 0.21   | 0.20   | $0.20 \pm 0.01$ |

The results presented in the table indicate that the optimized brackets demonstrate notably consistent performance, with arithmetic deviations ranging from 0.00 to 0.02. In contrast, the original brackets exhibit greater variability, with deviations between 0.01 and 0.06, highlighting the need for testing a larger sample size to ensure statistical reliability.

## 6. Simulation Verification of the Bracket using Substitute Material ASA

Finally, FEM simulations were conducted to validate all experimental cases for both the original and optimized bracket designs, using ASA material. The model accurately reflects the

experimental bracket assembly, and the deformation along the z-axis at the bolt head was evaluated. Assembly and mesh of the simulation model is shown in Figure 11.

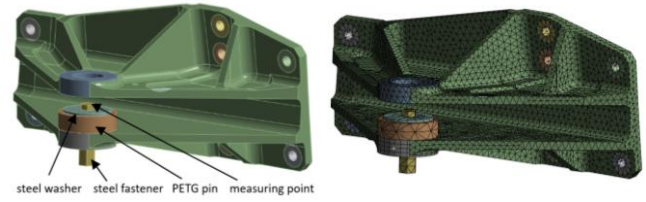


Fig. 11 Simulation assembly and mesh.

The material properties of the brackets are based on an average elastic modulus of 1.01 GPa, as determined from the coupon experiments, and the material is assumed to be isotropic. Poisson's ratio of 0.38, representing the average of reported anisotropic values, was adopted from reference [25].

The PETG pin is assumed to exhibit the same material properties as the brackets due to similar reported material characteristics [27]. The fasteners are made of steel, and their pretension is not considered. Pin connections are bonded.

The applied load consists of two experimental weights – 5.0005 kg (49.055 N) and 10.0025 kg (98.125 N) – selected according to the specific load case (see Figure 9). The load exerted by the spring in the digital indicator, ranging from 0.25 to 0.35 kg depending on indicator deflection, is neglected due to the use of tare at the beginning of the case measurement.

An example of the simulation results is shown in Figure 12.

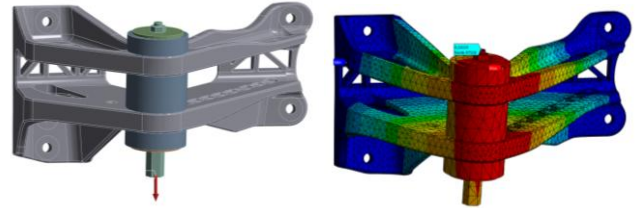


Fig. 12 Simulation result of deformation along z-axis for case 2-6.

The results of the FEM simulations are presented in Table 5 for comparison with the experimental data.

Table 5: Comparison of experimental and simulation deformation results of original and optimized brackets made of substitute ASA material

| Bracket type | Load case | Exp [mm] | Sim [mm] | Deviation [%] |
|--------------|-----------|----------|----------|---------------|
| Original     | 1-1       | 0.65     | 1.41     | 54            |
|              | 1-2       | 0.22     | 0.60     | 63            |
|              | 1-3       | 0.12     | 0.29     | 59            |
|              | 1-4       | 0.28     | 0.53     | 47            |
|              | 1-5       | 0.64     | 1.54     | 58            |
|              | 1-6       | 0.13     | 0.23     | 43            |
| Optimized    | 2-1       | 0.94     | 1.85     | 49            |
|              | 2-2       | 0.22     | 0.54     | 59            |
|              | 2-3       | 0.15     | 0.28     | 46            |
|              | 2-4       | 0.31     | 0.51     | 39            |
|              | 2-5       | 0.96     | 1.96     | 51            |
|              | 2-6       | 0.20     | 0.23     | 13            |

The deviation relative to the simulation results indicates a considerable discrepancy between the simulations and the experimental data. A satisfactory result was obtained only for the optimized bracket variant 2-6, where the difference was 13%. The results for the optimized bracket are slightly better than those for the original design. The average deviation for the original bracket is 54%, while for the optimized bracket it is 52%.

In our opinion, the results demonstrate the potential for indicative evaluation of the air brake bracket optimization process, owing to the low cost, speed, and simplicity of experiments using substitute material. However, the analysis procedure requires further refinement. To enhance the accuracy of the results, it is recommended to conduct an extended series of material characterization experiments, incorporating various printing parameters and additional loading conditions such as compression, bending, and torsion. Furthermore, enhancing the modeling of the pin-bracket interface in the FEM analysis is essential, along with considering the use of alternative polymer materials and verifying the geometry of the printed coupons and brackets. Applying the verification method to a larger number of complex components would also increase the reliability and generalizability of the proposed approach.

## 7. Conclusion and Recommendations

Verification of proposed components is a critical phase in the aerospace design process. Streamlining this step can yield substantial savings in both time and cost. However, the use of substitute polymer materials for verifying metallic components presents inherent limitations. The verification methodology presented in this study – utilizing a 3D-printed bracket made from ASA polymer – exhibits only indicative correlation with experimental results. Despite its limited precision, this approach can be recommended for rapid, cost-effective preliminary validation during early design stages.

For practical implementation, it is necessary to address and refine the simplifications adopted in this study. Furthermore, the mechanical properties of metal components produced via additive manufacturing must be rigorously validated to ensure their structural integrity and suitability for aerospace applications. Since materials fabricated through 3D printing may differ significantly from those produced by conventional methods – particularly in terms of homogeneity and isotropy – it is essential to verify the optimization outcomes using components printed from duralumin. A comprehensive suite of mechanical tests, including assessments of dynamic loading, fatigue resistance, and thermal performance, should be conducted to ensure reliability under operational conditions.

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# Development of an acoustic emission signal recording system

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**Abstract:** The objective of this study is to develop a system for recording and processing acoustic emission signals. The research focuses on designing cost-effective experimental equipment for investigating acoustic emission processes under laboratory conditions, with the capability of being reconfigured for specific applications depending on loading conditions and methods, material properties, environmental conditions, etc. A laboratory rig for recording and analysing acoustic emission data has been developed and experimentally tested. This paper presents the system's block diagram and its operational algorithm. Furthermore, the correlation between the results of statistical processing of the recorded data and the physical characteristics of the input signals is demonstrated using model acoustic signals, incorporating various components of the developed rig.

**Keywords:** non-destructive testing, acoustic emission method, acoustic emission signal recording, laboratory test rig, acoustic emission source modelling, impulse signal.

## 1. Introduction

The acoustic emission (AE) method is highly sensitive and effective for monitoring the early stages of defect development. It enables real-time identification of the damage zone, improving the speed and accuracy of inspection while reducing the scanning volume and monitored area. The key informative parameters that characterise the AE signal include amplitude, energy, signal count, oscillation count, count rate, cumulative count, activity, arrival time, rise time, leading edge slope, first half-wave duration, and others.

Each AE signal parameter is associated with a specific parameter of the destruction process and serves as its acoustic representation. The ability to overlay the loading diagram onto the time dependencies of the main informative AE signal parameters allows for the assessment of their dynamic changes in relation to the load level [2]. In the study of physical properties and material structures, the acoustic emission method of non-destructive testing plays a crucial role. This method is based on measuring the velocity and attenuation coefficient of elastic waves. Its key advantage is that it enables the acquisition of information about the internal structure of materials.

The technology of the AE testing method is based on the acoustic emission effect. Acoustic emission (AE) is the process of a material emitting mechanical waves caused by a local dynamic reconfiguration of its internal structure under external influence. As these waves reach the material's surface, they propagate further in the form of surface waves, inducing mechanical vibrations with amplitudes ranging from  $10^{-14}$  to  $10^{-7}$  m. The detection of such minute vibrations is carried out using piezoelectric sensors.

An important aspect is the analysis of recorded data and the selection of useful information. Despite noise suppression using the frequency method, noise can still make up 99% of the recorded data. This is because the destruction process during the operation of a structure usually occurs slowly, whereas the presence of acoustic noise is an inherent feature of the technological process. Noise reduction after data recording is carried out within the system's software.

Although filtering algorithms may be specific to each application, several general approaches can be identified. Firstly, correlation analysis is applied to examine the relationships between measured AE signal parameters. There are well-established parameter ratios for real AE signals that differ from those of noise signals. The use of parameter correlation is highly effective. The aim of this study is to develop a system for recording and processing acoustic emission signals. The research focuses on designing cost-effective experimental equipment for studying acoustic emission processes

under laboratory conditions, with the flexibility to be reconfigured for specific, more specialised tasks, depending on the loading method, material type, and other factors. The primary objective of experimental planning is to achieve maximum measurement accuracy with the minimum number of tests while maintaining the statistical reliability of the results.

Experimental design methods help minimise the number of necessary tests, establish a rational order, and determine the conditions for conducting studies based on their type and the required accuracy of results [1]. To ensure the desired measurement accuracy of input parameters, it is essential to define the range of possible input parameter measurements and refine the types of external influences.

The selection of sample types or test objects should consider their similarity to the actual product in terms of condition, structure, shape, size, and other characteristics for the registration, processing, and analysis of AE signals. Since AE sensors are piezoelectric sensors with high output impedance and a broad frequency range, and given the low amplitude of AE signals during the plastic deformation stage, the primary requirement for the AE signal recording rig is high sensitivity and low intrinsic noise levels.

## 2. Main stages of developing an acoustic emission system

The development of such equipment involves the following key stages:

- selection of hardware components with sufficient sensitivity, high speed, and low noise levels;
- calibration procedures for the developed device;
- testing using model signals;
- carrying out experimental studies employing the developed rig;
- analysis of informative parameters and identification of new parameters for the analysis of recorded acoustic emission data;
- interpretation of results, both in comparison with known data and within the framework of scientific concepts.

The main requirements for acoustic emission recording equipment are determined by the characteristics of AE signals, which include their complex nature, low energy level, wide frequency range, significant dynamic variations, etc. Therefore, the receiving transducer and the subsequent electronic units must introduce minimal distortion to the signal shape, possess high sensitivity and

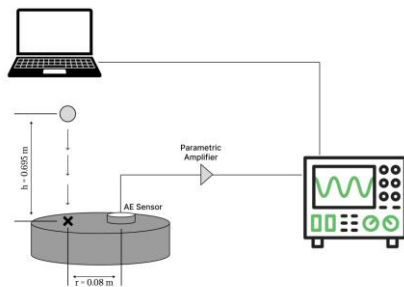
a high amplification factor, and maintain a low level of intrinsic noise [2]. Due to the low energy of AE pulses, resonance piezoelectric transducers are commonly used to enhance sensitivity. These transducers have extremely high output impedance, a broad operational frequency range, and a low level of intrinsic noise. The main components of the developed laboratory system for recording acoustic emissions include:

- AES sensor (Acoustic Emission Sensor)
- broadband low-noise amplifier
- ADC unit (Analog-to-Digital Converter)
- personal computer
- software

During the testing of the acoustic emission equipment, the following conditions were maintained:

- ambient air temperature in the room: 21 °C
- relative air humidity: 70%
- atmospheric pressure: 102 kPa (720 mmHg)
- power supply voltage: 220 V
- power supply frequency: 50 Hz

Before conducting the laboratory tests, all devices were properly grounded.



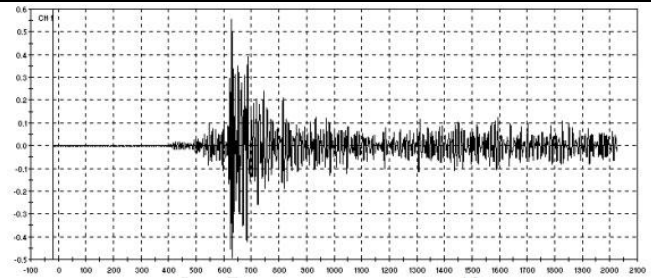
**Fig.1** Laboratory system for acoustic emission recording

The functionality of the developed rig was tested using various signal sources with parameters that to some extent resemble those of real acoustic emission sources. To validate the method, a series of experiments was conducted using model excitation of different types of AE signal sources. As different types of signal sources, the pencil lead break was used (Hsu-Nielsen source).

The essence of the invention is considered using the example of processing AE signals excited by the specified Hsu-Nielsen type sources and recorded during the propagation of acoustic waves in a steel plate at various distances from the receiver, as well as AE signals generated by the impact of a bearing ball.

### 3. Modelling of an AE signal source through pencil lead break

This method is recommended for calibrating AE sensors. The acoustic signal generated during the pencil lead break also serves as a model signal [6]. In the experiments, a 0.5 mm diameter pencil lead was used. A 5 mm thick steel plate was employed as the acoustically conductive medium. The AE sensor was mounted 80 mm from the signal source. To ensure optimal contact between the sensor and the plate, a layer of epoxy resin was applied. A typical signal recorded by the rig during the pencil lead break, along with its spectrum, is shown in the figure below.



**Fig.2** Typical AE pulse signal

### 4. Modelling of an AE signal source by bearing ball impact

The model signal was generated by the impact of a falling steel ball, producing an acoustic wave. Assuming that most of the ball's potential energy is converted by the sensor into an electrical signal, similar to waves generated by real AE sources, it follows that the ball's mass is proportional to the signal energy. The free fall of the ball onto a metallic base was conducted from a height of 695 mm into an area located 80 mm from the mounted AE sensor.

Each ball was dropped at least five times. A piezoelectric transducer was used to record AE signals, functioning as a broadband acoustic emission transducer. The transducer was connected to a preamplifier with a gain of 40 dB, the output of which was linked to the AE recording system with analog-to-digital signal conversion. The positions of the transducer, serving as the AE signal receiver, and the AE sources on the surface of the plate are shown in Figure 1.

The analysis of the obtained data showed that the energy of the signal (elastic wave) generated by the impact of the steel ball on the plate varies linearly with the increase in the ball's mass. Thus, not only was a previously known method of AE sensor calibration applied, but a linear relationship between the energy of the spectrum and the mass of the ball was also demonstrated. This finding enables the future use of this methodology as a rapid calibration method for the device before conducting measurements [3,4].

In addition to the factors already mentioned, the sensor itself has a significant influence on the signal shape. When a broadband emission signal interacts with a resonant sensor, it produces a "bell effect", where the sensor resonates at a specific frequency regardless of the excitation method. As a result, multiple factors simultaneously affect the signal shape at the sensor's output, including paths of wave propagation, the presence of different signals traveling at varying speeds, and the transformation of the input signal by the sensor.

### Conclusions

A laboratory rig for recording and analysing acoustic emission data has been developed and experimentally tested. The block diagram of the system and its operational algorithm have been presented. The relationship between the results of statistical processing of the recorded data and the physical characteristics of the input signals is demonstrated using model acoustic signals with various components of the developed rig. The functionality of the laboratory rig was verified through experimental testing.

A model signal was generated by the impact of a falling steel ball, producing an acoustic wave. In the experiments, steel balls of varying masses from rolling bearings were used. Assuming that most of the ball's potential energy is converted by the sensor into an electrical signal, similar to waves generated by real AE sources, it was considered that the mass of the ball would be proportional to the energy of the signal.

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# Multi-Method Statistical Analysis of Factors Influencing Predictive Maintenance of Electric Vehicle Fleets

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**Abstract:** Accurate estimation of predictive maintenance is important for effective electric vehicle fleet management. Existing approaches often fail to account for the complex relationships between diverse influencing factors. In this study, we propose a multi-method statistical analysis framework that integrates Spearman correlation, Mutual Information, and ElasticNet regression to quantify these relationships. The findings show that charge cycles and load weight exhibit the strongest positive correlations with Remaining Useful Life (RUL), while route roughness and battery temperature demonstrate significant negative impacts. Additionally, the Mutual Information analysis identified battery temperature as having the strongest non-linear relationship with RUL, underscoring its unique predictive relevance. Interestingly, maintenance records were found to have small predictive value across all analytical methods. The ElasticNet regression also refined the analysis by identifying 11 critical predictive factors, successfully eliminating redundant variables, and showing how corresponding statistical methods can improve predictive maintenance. These results can help the fleet operators to prioritize monitoring efforts on the most impactful factors and develop more precise RUL prediction models.

**Keywords:** PREDICTIVE MAINTENANCE; ELECTRIC VEHICLE FLEET; REMAINING USEFUL LIFE

## 1. Introduction

Electric vehicle (EV) fleets are becoming an increasing component of modern transportation infrastructure, where accurate maintenance estimation facilitates cost-effective predictive maintenance (PdM). Maintenance prediction requirements in EVs present challenges because of complex interactions between operational parameters (e.g., charge cycles, load weight), environmental conditions (e.g., temperature, route roughness), and component-specific degradation patterns. Unlike traditional combustion engine vehicles, EV fleet maintenance is influenced by battery and electric drivetrain degradation. PdM has emerged as an important strategy for optimizing operational efficiency and reducing downtime. PdM strategy relies on several main metrics: Remaining Useful Life (RUL), which estimates the time until a component fails; Failure Probability (FP), quantifying the possibility of failure within a given timeframe; Time to Failure (TTF), predicting the exact failure time; and Component Health Score (CHS), which provides a continuous measure of component degradation. Traditional approaches to estimating these metrics can be classified into three main categories: (1) physics-based models, which use first principles and domain knowledge for interpretability, (2) data-driven models which learn patterns from operational data, and (3) hybrid approaches combining both. Together, these approaches aim to address the complexities of real-world EV fleet maintenance.

Modern EV fleets present unique predictive maintenance challenges due to their complex temporal data streams, which exhibit non-stationary patterns across vehicles and operational windows [1, 2]. Incorporating driving and charging patterns has been shown to improve reliability in real-world applications [3]. Recent studies show significant growth in EV infrastructure and IoT-enabled charging systems, with edge computing enhancing real-time data processing [4] and system-wide approaches are proving important for large-scale monitoring [5]. A key area of focus within EV maintenance research is battery health management, particularly the prediction of metrics such as State of Health (SOH) and Remaining Useful Life (RUL). Approaches have concentrated on battery factors, including charging and discharging profiles (C-rate), depth of discharge (DoD), temperature extremes, and cycle count, as extensively reviewed in [6-8].

Recent surveys on prediction maintenance methods [9] have emphasized the increasing relevance of statistical approaches in predictive maintenance, particularly for RUL. Traditional statistical approaches in this area have primarily focused on time-to-failure analysis and degradation modeling, employing techniques such as parametric survival analysis and stochastic process models [9, 10]. Data-driven degradation model calibration has recently been shown to improve the accuracy of RUL predictions [11]. At the fleet level,

statistical methods have proven particularly useful for grouping vehicle-specific degradation patterns while accounting for operational variability across various usage scenarios. Machine learning approaches have complemented these efforts by optimizing charging schedules to extend fleet-wide RUL [12]. For EV-specific applications, statistical methods have demonstrated strong performance in analyzing battery degradation [13]. While these methods provide interpretability, they are often limited by model assumptions and parameter selection challenges [14]. In contrast, deep learning approaches like those proposed by [15] can capture complex patterns but require large, labeled datasets and often lack interpretability. Hybrid approaches that integrate statistical methods with machine learning have shown promise in achieving a balance between interpretability and predictive performance [16, 17]. Recent work on statistical methods for EV component RUL prediction [18] has demonstrated the effectiveness of correlation and regression-based approaches in this domain, offering a balance between interpretability and predictive power. Unlike deep learning models, these methods focus on deriving actionable and interpretable insights for EV fleet maintenance, addressing the need for practical fleet-wide insights.

This paper examines data-driven statistical techniques to understand the factors influencing PdM metrics in EV fleets, particularly in contexts where abundant operational data compensates for incomplete physical models. Estimating RUL in EV fleets presents three main aspects: (1) high-dimensional telemetry data generated by numerous sensors, (2) non-linear relationships between operational factors and component degradation, and (3) interdependence among various operational parameters. To address these challenges in this study, we use a multi-method framework combining: (1) Spearman correlation for linear relationships; (2) Mutual Information for non-linear dependencies; (3) ElasticNet regression to assess feature importance within a regularized linear model, for evaluating interdependence. This analysis explored the relationships between various operational, environmental, and system-monitoring factors and four key predictive maintenance targets: Remaining Useful Life (RUL), Failure Probability (FPS), Time Till Failure (TTF), and Component Health Score (CHS). The primary contributions of this research include: (1) a quantitative comparison of statistical methods for RUL analysis, (2) identification of key predictive factors using ElasticNet regression, and (3) practical insights to guide the design of EV fleet monitoring systems. Presented framework provides both methodological accuracy (handling non-linearity and multicollinearity) and practical value (focusing monitoring on the most influential factors).

## 2. Data and Methodology

The analyses conducted in this study utilize the open-source "EVIOT - Electric Vehicle IoT Predictive Maintenance Dataset",

which was obtained from the Kaggle repository [19]. This dataset consists of time-series data from Internet of Things (IoT)-enabled EVs operating in a variety of environments. The main purpose of EVIOT dataset is to enable research into predictive maintenance applications.

The dataset contains 175,393 records capturing telemetry and contextual information related to EV component health and potential failure modes. Key features within the dataset include:

- **Battery System Monitoring:** Includes metrics such as State of Charge (SoC), State of Health (SoH), battery voltage, battery current, battery temperature, and total charge-discharge cycles,
- **Electric Motor and Drivetrain Monitoring:** Features data on motor temperature, motor vibration levels, motor torque, motor RPM, and power consumption by the drivetrain system,
- **Brake System Monitoring:** Contains information on brake pad wear, brake pressure, and regenerative braking efficiency,
- **Tire and Suspension Data:** Includes tire pressure, tire surface temperature, and suspension load,
- **Environmental and Usage Data:** Encompasses ambient (external) temperature, ambient humidity, load weight (cargo or passenger), and current driving speed.,
- **Telematics and Fleet Data:** Provides cumulative distance travelled, idle time duration, and route roughness,
- **Maintenance Records:** Details maintenance type categories: None (0), Preventive (1), Corrective (2), and Predictive (3),
- **Target Variables:** The dataset include data for target variables relevant for predictive maintenance tasks: RUL estimates, TTF data, FP scores, CHS indices.

This dataset was chosen for the present study because it contains diverse factors that influence EV component degradation and failure. The EVIOT dataset provides an appropriate basis for conducting multi-method statistical analysis to investigate these relationships.

### Problem setting

Let  $X \in \mathbb{R}^{n \times d}$  be the feature matrix for  $n$  vehicles with  $d$  operational parameters, and  $y \in \mathbb{P}dM^n$  the predictive maintenance targets: RUL, FP, TTF, and CHS. We assume: (1) sampling frequency captures degradation trends ( $\Delta t \ll \tau_{\text{degradation}}$ ), (2) current state suffices for PdM targets estimation ( $y_t = f(x_t)$ ), and (3) feature-PdM targets relationships are stationary ( $\nabla_t f(x_t) \approx 0$ ).

This analysis examined the relationships between various operational, environmental, and system-monitoring factors and four key predictive maintenance targets (RUL, FP, TTF, and CHS). Three statistical methods were employed to examine these relationships: Spearman correlation (to identify monotonic linear/non-linear trends) [20], Mutual Information (to capture complex non-linear relationships) [21], and ElasticNet regression (to assess feature importance within a regularized linear model, while addressing potential multicollinearity) [22].

### Implementation

The EVIOT dataset was imported using the Pandas Python library and preprocessed to remove rows where all values were missing, handling potential empty lines. Feature columns were identified, categorized into logical groups (battery system, motor monitoring, environmental data), along with the four target variables (RUL, FP, TTF, CHS). Three distinct methods were employed to assess the relationship between individual features and the target variables: (1) The non-parametric Spearman rank correlation coefficient ( $\rho$ ) was used to calculate pairwise correlations between each feature and target variable, assessing the strength and direction of monotonic relationships (linear or non-linear). Calculations were conducted using the “spearmanr” function from the SciPy library. Cases with insufficient data pairs ( $<2$ ) or constant feature/target values were excluded from the analysis; (2) Mutual Information (MI), a measure of mutual dependence, was used to capture non-linear relationships. The Scikit-learn feature selection module was employed, with

“mutual\_info\_regression” used for continuous targets (RUL, TTF, CHS) and “mutual\_info\_classif” for the binary target (FP). A fixed random state (42) ensured reproducibility, and the number of neighbors for MI estimation was adjusted adaptively (3 neighbors for sufficient samples, 1 for smaller subsets). Similar to Spearman, calculations were skipped for features with insufficient or constant data; (3) To evaluate feature importance within a multivariate linear context while addressing potential multicollinearity, an ElasticNet regression model was implemented the Scikit-learn “ElasticNet” class. A separate model was trained for each target variable, using the standardized feature set relevant to that target. The model parameters were set as follows: regularization strength  $\alpha=0.01$ , L1/L2 mixing parameter  $l1\_ratio=0.5$  (balancing Lasso and Ridge penalties), maximum iterations (2000), and random state (42) for reproducibility. Feature importance was determined based on the magnitude and sign of the fitted model coefficients.

### 3. Results

Table 1 presents the features showing the strongest positive and negative associations with each target variable, as determined by Spearman correlation ( $\rho$ ), Mutual Information (I), and ElasticNet regression ( $\beta$ ). Together, these methods provide a broad view of factor influence.

One notable observation across all target variables is the generally low magnitude of the top Spearman correlation coefficients and MI scores. For example, the highest absolute Spearman  $\rho$  reported is -0.007 (Battery Temperature vs. TTF), and the highest MI score is 0.005 (Tire Temperature vs. TTF and SoH vs. Component Health Score). These results indicate that most features show relatively weak or non-linear relationships with the predictive targets in this dataset when evaluated individually with these methods.

**Table 1.** Features showing the strongest positive and negative associations with each target variable

| Target | Method      | Top Positive                                    | Top Negative                                   |
|--------|-------------|-------------------------------------------------|------------------------------------------------|
| RUL    | Spearman    | Power Consumption ( $\rho=0.006$ )              | Route Roughness ( $\rho=-0.006$ )              |
| RUL    | Mutual Info | Battery Temperature ( $I=0.003$ )               | -                                              |
| RUL    | Elasticnet  | Load Weight ( $\beta=0.445$ )                   | Route Roughness ( $\beta=-0.380$ )             |
| FP     | Spearman    | SoC ( $\rho=0.005$ )                            | Regenerative Brake Efficiency ( $\rho=0.004$ ) |
| FP     | Mutual Info | Motor Vibration ( $I=0.001$ )                   | -                                              |
| TTF    | Spearman    | Regenerative Brake Efficiency ( $\rho=0.003$ )  | Linear/Monotonic Trends                        |
| TTF    | Mutual Info | Tire Temperature ( $I=0.005$ )                  | Joint/Multivariate Analysis                    |
| TTF    | Elasticnet  | Regenerative Brake Efficiency ( $\beta=0.140$ ) | Non-linear Effects                             |
| CHS    | Spearman    | Charge Cycles ( $\rho=0.004$ )                  | Ambient Temperature ( $\rho=0.005$ )           |
| CHS    | Mutual Info | State of Health ( $I=0.005$ )                   | -                                              |

In contrast, the ElasticNet model, which evaluates features jointly while applying regularization, identifies factors with significantly higher implied importance for predicting RUL and TTF. This is evident from the magnitude of the top  $\beta$  coefficients (e.g., Load Weight  $\beta=0.445$  for RUL; Battery Temperature  $\beta=-$

0.397 for TTF). Notably, ElasticNet often highlights different top features compared to Spearman correlation or MI, underscoring the aspects of multivariate analysis in revealing relationships that might be missed in simpler pairwise comparisons. Additionally, for the FP and CHS targets, ElasticNet assigned zero coefficients to all features (indicated by "-" in Table 1). This result indicates that, in this linear framework, none of the input features showed important predictive power for these specific results.

### Remaining Useful Life

ElasticNet identified load weight ( $\beta=0.445$ ) as the most significant positive predictor and route roughness ( $\beta=-0.380$ ) as the most significant negative predictor, emphasizing their roles as key factors within the multivariate model. Spearman analysis provided weak confirmation of the negative relationship of route roughness ( $\rho=-0.006$ ), and identified power consumption ( $\rho=0.006$ ) as the strongest positive factor (see Fig. 1). Mutual Information indicated battery temperature ( $I=0.003$ ) as the most informative single feature, suggesting at a potential non-linear relationship that was not strongly reflected in the rankings of the other methods. The divergence shows how different analytical techniques can prioritize distinct factors.

### Failure Probability

The analysis faced challenges in identifying strong predictors for this binary target. Spearman correlation indicated weak associations with the state of charge ( $\rho=0.005$ ) and regenerative brake\_efficiency ( $\rho=-0.004$ ) (see Fig. 2). Mutual Information indicated that motor vibration ( $I=0.001$ ) provided the most non-linear information, though this contribution was minimal.

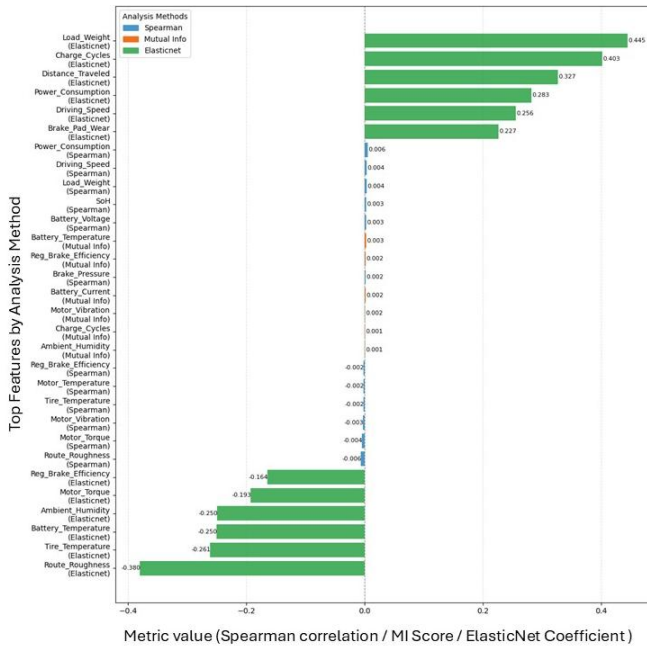


Fig. 1 Predictive features for remaining useful life across analysis methods.

ElasticNet found no features with sufficient predictive power to retain non-zero coefficients after regularization. This absence of strong signals suggests that predicting failure probability may require non-linear models, interaction terms between features, or variables not included in this dataset. Alternatively, failure events may be too sparse for these methods to identify reliable patterns.

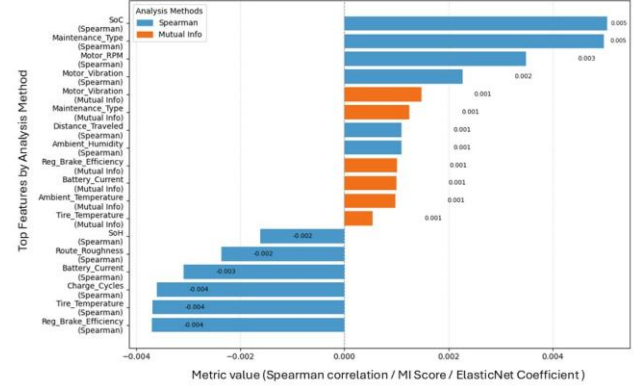


Fig. 2 Predictive features for failure probability across used methods.

### Component Health Score

As with failure probability, identifying strong predictors for this composite score proved difficult. Spearman correlation revealed weak relationships to charge cycles ( $\rho=0.004$ ) and ambient temperature ( $\rho=-0.005$ ). Mutual Information identified state of health ( $I=0.005$ ) as the most informative feature. ElasticNet coefficients for all features were again reduced to zero. This result suggests that the CHS, currently defined and measured, is not well-predicted by individual features in a linear framework. This limitation may reflect the complex nature of the CHS or its dependence on complex feature interactions.

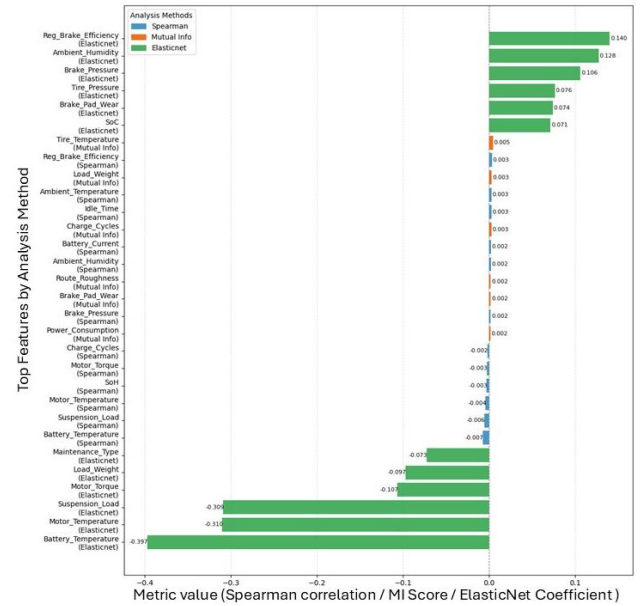


Fig. 3 Predictive features for time till failure across analysis methods.

### Time Till Failure

ElasticNet identified regenerative brake efficiency ( $\beta=0.140$ ) as the strongest positive factor and battery temperature ( $\beta=-0.397$ ) as the strongest negative, with the latter demonstrating a substantial negative association (see Fig. 3). Spearman correlation supported these top factors, but showed much smaller effect sizes (regenerative brake efficiency  $\rho=0.003$ ; battery temperature  $\rho=-0.007$ ). The convergence between Spearman and ElasticNet on the top factors, despite differences in magnitude, shows confidence in their functions.

#### 4. Conclusions

This study introduces and evaluates a multi-method statistical framework that integrates Spearman correlation, Mutual Information, and ElasticNet regression to analyze both linear and non-linear relationships between diverse factors and EV target-specific results. By combining these methods, the proposed framework provides insights, identifies key predictive factors (including operational ones like load and route roughness) and battery-related parameters, and offers a robust approach for feature selection and understanding factor importance in EV fleet predictive maintenance. The comparative analysis shows the advantages of using the complementary value of employing multiple statistical techniques. Specifically, univariate methods such as Spearman correlation and Mutual Information identified statistically significant but relatively weak individual relationships, the multivariate. In contrast, the multivariate ElasticNet regression revealed feature importance within a joint predictive context, exposing potentially stronger associations, particularly for RUL and TTF.

Factors related to operational load (e.g., load weight), usage patterns (e.g., power consumption and charge cycles), environmental conditions (e.g., route roughness and temperature variations), and specific component states (e.g., battery temperature and regenerative brake efficiency) appeared as potentially influential, particularly in the ElasticNet regression results for RUL and TTF. The consistent negative associations of route roughness and battery temperature across statistical methods and targets show their importance as candidates for monitoring in predictive maintenance strategies. The difficulty in identifying impactful predictors for FP and CHS using these methods suggests that these outcomes may be influenced by more complex, non-linear dynamics, feature interactions, or factors not captured in the current dataset. Future works related to these specific targets could explore advanced non-linear algorithms (e.g., tree-based ensembles or neural networks) and potentially incorporate time-series specific approaches to better capture these complex relationships.

#### 5. Acknowledgment

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# Detection of fibre continuity in joints of metallic and composite thin-walled materials formed by thermal drilling technology by computed tomography

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**Abstract:** This paper presents the results of scanning fiber continuity in the joints of thin sheets made of aluminum and magnesium alloys with bi-directionally glass and carbon fiber-reinforced composites formed by thermal drilling technology using computed tomography. The scans show the progression of the bushing forming and the closure of the fibres in the hem joint. Little delamination, but no fiber fracture are visible in metal-composite joints.

**Keywords:** METAL-COMPOSITE JOINING, THERMAL DRILLING, FIBER FRACTURE, COMPUTED TOMOGRAPHY

## 1. Introduction

The joining of metals and composites in the form of thin-walled materials is a current subject of research [1-4]. The need to join such dissimilar materials arises from the needs of the automotive and aerospace industries, where the combination of ultra-lightweight materials and the production of tailored parts is required. The largest group of composite materials suitable for automotive applications are polymer composites with a thermosoftening or thermosetting matrix. Thermoset composites provide higher mechanical properties and can be bonded to other materials by means of press-fit fasteners, since once cured, a change in their shape and possible further bonding without breaking the fibres is no longer possible. Thermosoftening matrix composites can be purchased in the form of organosheets formed by consolidating several layers of prepregs to achieve the desired panel thickness. The forming of such organosheets, heated above the melting temperature of the polymer matrix, can be carried out using a pair of flexible membranes, a rubber die or in conventional metal split moulds. Composite organosheets can also be processed by combined technologies, short or long fibre plastics with the same type of matrix can be injection moulded to form reinforcing or stabilising ribs, force transfer elements, functional elements or additional contours on the edges of the component, Fig. 1.



Fig. 1 Rib structure and edge overmolding

By choosing appropriate matrices and process parameters, a homogeneous connection between two different cross-sections is achieved. In particular, the temperature of the two materials must be high enough to form a reliable fusion bond. For a good fusion of the materials, the highest possible injection speed is preferred (because at high injection speeds there are high shear stresses in the injected mass and thus too rapid cooling is prevented), especially in areas away from the inlet, and also a high clamping force helps to fuse the materials. The joining of polymers and polymer composites with compatible matrices can also be achieved by welding. Welding is mainly used for joining thermosoftening composites, bonding and mechanical joining can be used for joining different material combinations, even plastics with metals.

In addition to the aforementioned technologies, the issue of joining composites with other materials, especially metals, is also a challenge. Composite components are often part of complex assemblies that, in extreme cases, combine a variety of materials including steel, lightweight metals such as aluminum or magnesium

alloys, polymers reinforced with short or long glass fibers, or carbon fiber composites.

According to the physical principle, joining processes can be divided into:

- homogeneous joints (welded, bonded)
- non-homogeneous joints (mechanical joints)
  - o non-positive joints (screw, pressure, riveted joints)
  - o positive joints (latches, locks, handles)

According to their demountability they are divided into:

- demountable joints (using screws, pins, wedges)
- non-demountable joints (bonded, welded, riveted).

Typical mechanical joining techniques, such as bolting and riveting, cause the fibres in the composite to break when making metal-to-composite joints, which significantly reduces the load-bearing capacity of the joint. This may underutilize the high potential of lightweight composite components in highly loaded multi-material systems. In addition, often multi-step manual operations, such as pre-drilling of the parts to be joined and subsequent insertion of additional fasteners, represent time-consuming and costly preparatory work in the joining process [5-9].

Flowdrill technology is used in joining thin-walled materials, it uses frictional heat between the tool and the material, which softens the material and deforms it plastically by the movement of the tool [4]. The plasticized material is displaced below the level of the material being drilled, forming a bushing into which sufficient threads can be created to make a mechanical connection to another material with a screw. The bushing is very advantageous when joining thin workpieces because it locally increases the thickness of the material.

The aim of the work is to experimentally verify the possibility of using the side effect of thermal drilling technology (flowdrill) for joining two overlapped thin-walled materials (metal-composite) without using a screw, just by forming a metal bushing penetrating through the fiber composite without breaking the integrity of the reinforcing fibers. The integrity of the fibres is analysed by computed tomography (CT).

## Materials and methods

The joints were made of the following materials:

- Aluminium alloy EN AW-6082 T6 (AlSi1MgMn) – Al alloy supplied in a precipitation-hardened state with relatively high mechanical properties. The alloy was supplied in the form of a 1 mm thick rolled sheet. Hereinafter Al.
- AZ 91 magnesium alloy with the main alloying elements Al and Zn. The alloy was supplied in the form of a 2 mm thick rolled sheet. Hereinfter Mg.
- Composite with polypropylene (PP) matrix reinforced with continuous glass fibres in two perpendicular directions. The thickness of the consolidated composite organosheet is 1.55 mm, which is the result of the compaction of three layers of prepregs.

Hereinfter GF.

- Composite with polypropylene matrix (PP) reinforced with continuous carbon fibres in two perpendicular directions. The thickness of the consolidated composite orgaanosheet is 1.55 mm, the result of the compaction of seven layers of prepregs. Hereinfter CF.

The basic characteristics of the materials are shown in Tab. 1-3.

**Tab. 1** Chemical composition of alloys in wt.%

| alloy | Si   | Mg      | Mn   | Fe    | Zn   | Cu   | Al      |
|-------|------|---------|------|-------|------|------|---------|
| Al    | 1.0  | 0.7     | 0.44 | 0.4   | 0.08 | 0.06 | balance |
| Mg    | 0.09 | balance | 0.14 | 0.004 | 0.93 | 0.02 | 8.9     |

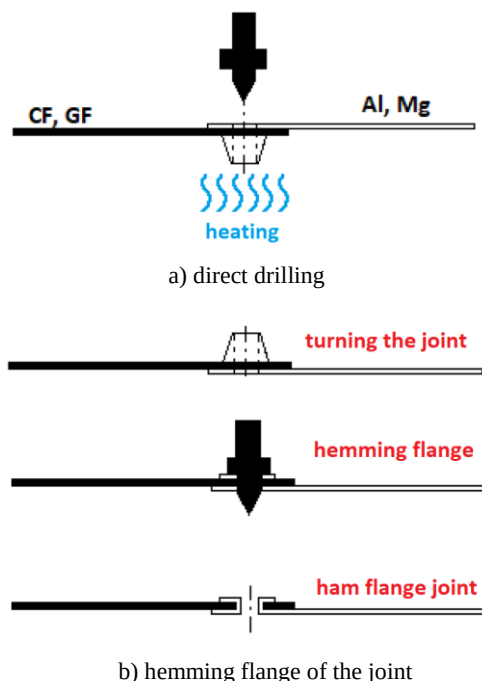
**Tab. 2** Mechanical and physical properties of alloys

| alloy | Re [MPa] | Rm [MPa] | A <sub>50</sub> [%] | density [g·cm <sup>-3</sup> ] |
|-------|----------|----------|---------------------|-------------------------------|
| Al    | 295      | 340      | 15                  | 2.71                          |
| Mg    | 280      | 200      | 24                  | 1.81                          |

**Tab. 3** Properties of composite organosheets

| Composite                      | PP CF50 T200 OS                      | PP GF45 T600 OS                     |
|--------------------------------|--------------------------------------|-------------------------------------|
| Matrix                         | polypropylene                        |                                     |
| Reinforcement                  | Carbon fibre                         | E Glass fibre                       |
| Weaving                        | Twill 2/2                            | Twill 2/2                           |
| Surface mass. mats             | 200 g·m <sup>-2</sup>                | 600 g·m <sup>-2</sup>               |
| Density of weaving             | 3K                                   | 1200 tex                            |
| Fibre content in the composite | 51%                                  | 47%                                 |
| Weight of finished product     | 301 g·m <sup>-2</sup>                | 887 g·m <sup>-2</sup>               |
| Prepreg thickness              | 0.22 mm                              | 0.5 mm                              |
| Specific weight of composite   | 1.46 g·cm <sup>-3</sup>              | 1.68 g·cm <sup>-3</sup>             |
| Melting temperature            | 165°C                                | 165°C                               |
| CTE (23-80°C)                  | 3.2×10 <sup>-6</sup> K <sup>-1</sup> | 11×10 <sup>-6</sup> K <sup>-1</sup> |

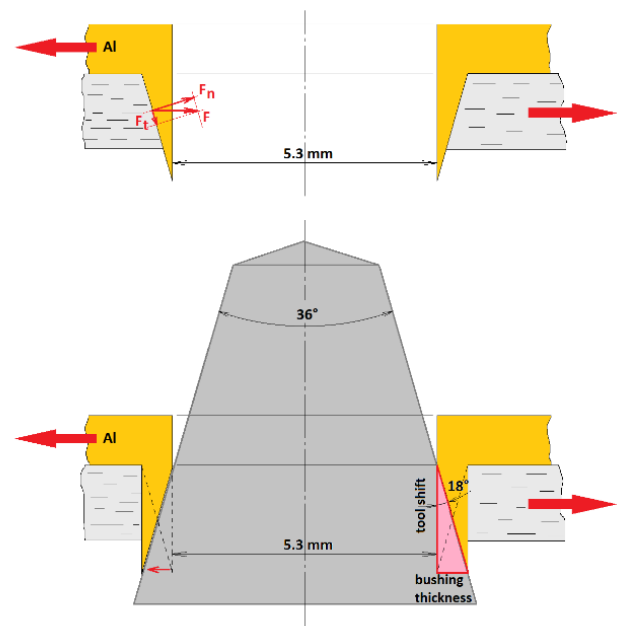
The philosophy of joint formation is that the tool, as it feeds into the material, comes into contact with the metal sheet, begins to penetrate it by means of friction-assisted rotation, whereby an opening is created and the material from the opening is transformed into a bushing. As it is formed, the bushing penetrates through the heated composite, deflecting its fibres off the axis of the opening without breaking it. This creates a mechanical interlocking of the two materials. However, when conducting the experiments, we divided the process into two steps - first, a hole was formed in the preheated composite, and in the second step, a metal sheet was placed on the composite and the drilling was carried out once more.



**Fig. 2** Joining of metals and composites by thermal drilling

This sequential joining method was designed to facilitate the shaping of the metal bushing in the prepared hole in the composite plate. The joint was then further secured against opening from the opposite side with a hem flange, Fig. 2. The above materials were then used to form the joints with the metal plate in the top position when drilled and the composite in the bottom position. The material combinations of the joints formed were Al-CF, Al-GF, Mg-CF, Mg-GF.

The resulting metal bushing has an outer surface that is conical and an inner surface that is cylindrical in shape, Fig. 3 top. However, the outer conical shape of the bushing can cause the composite to slide away from the metal sheet when the joint is loaded, causing the joint to open and its load carrying capacity to depend on the thickness of the hem flange instead of the thickness of the bushing. Therefore, a geometric modification of the bushing was proposed by widening the bushing from the flange side with a larger diameter tool (Flowdrill Long 9.3 mm), Fig. 3 bottom. This results in an inverted bushing and the elimination of the tangential component of the force that causes the joint to open.

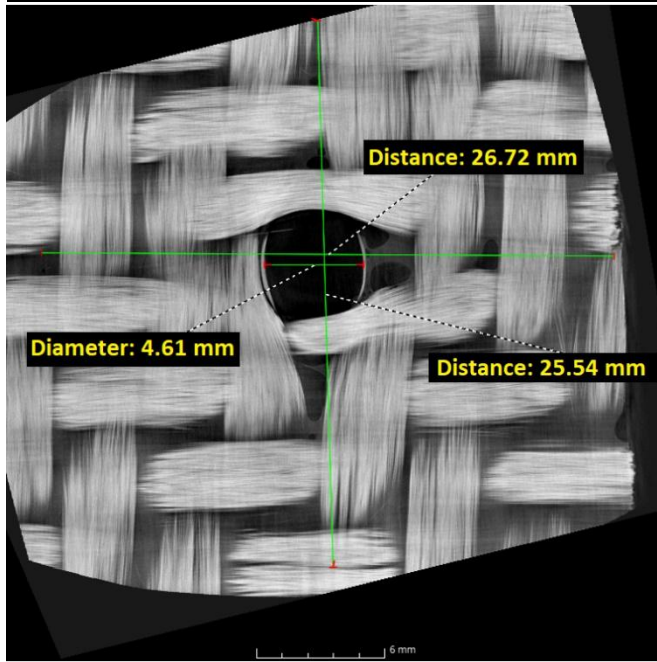


**Fig. 3** Design of the bushing geometry modification to increase the load carrying capacity of the connections ( $F$  - loading force,  $F_n$  - normal,  $F_t$  - tangential component of the force  $F$ )

After the joints were made, the entire area was scanned using CT. The fiber distribution around the opening in the composite as well as around the bushing in joints was visualized by Carl Zeiss Metrotom 1500 Gen1. The scanning parameters were different when scanning the composites alone and when scanning the metal-composite joints. The scanning parameters for the composites were: voltage 100 kV, current 230  $\mu$ A, integration time 1000 ms, resolution 27.04  $\mu$ m, no filter applied. Scanning parameters for metal-composite joints: voltage 120 kV, current 250  $\mu$ A, integration time 1000 ms, resolution 40,29  $\mu$ m, Cu filter 0,5 mm.

## Results

First, the prepared openings in the composite were scanned, which is actually the first step in sequential joining, Figs. 4 and 5.



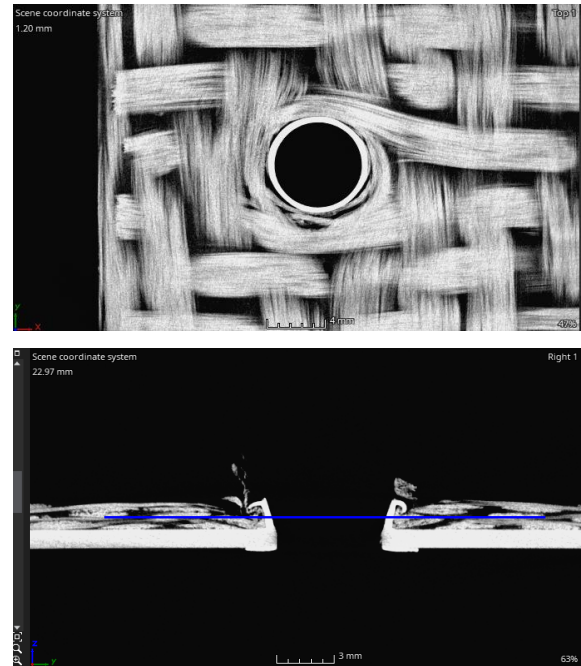
**Fig. 41** Fibre distribution around the opening in the GF composite



**Fig. 5** Fibre distribution around the opening in the CF composite

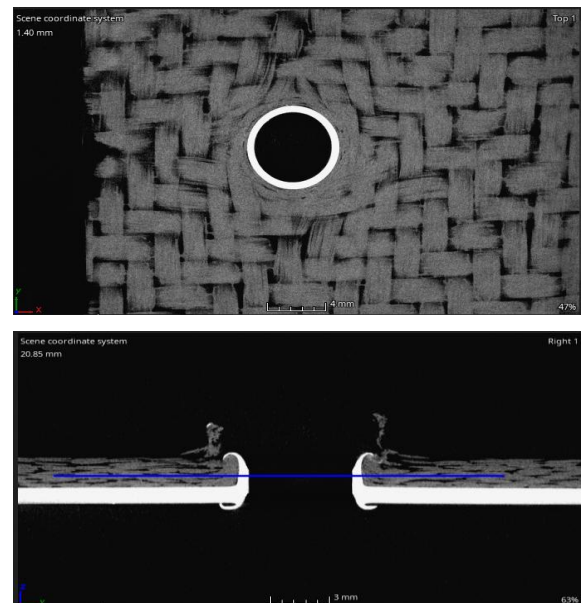
From CT scans of the openings made with the Flowdrill 5.3 mm tool in the GF and CF composite, fiber displacement is visible. Heating the composite to temperatures above 165°C caused the polypropylene matrix to melt and allowed the fibres to be displaced from their position to a greater distance from the opening, up to 22-25 mm in diameter. Fiber breakage is not detected. The opening in the preheated composite, created by the 5.3 mm diameter tool, shrank to 4.6 mm after the tool returned to its initial position due to the tensile stress in the fibres. However, the opening is still large enough to facilitate the forming of the metal bushing after subsequent overlapping with metal sheet. It is also clear from the scans that the glass fibers are thicker, as are the bundles that make up the glass fabric. The carbon fibers are thinner, the fiber bundles are thus also thinner, and the weaving density of the fiber mat is greater. The higher weaving density may resist the penetration of the forming metal bushing. However, this need not be negative. It can help in the forming of the Al bushing in particular, which would not have a suitable shape without the resistance of the fibers. We consider a slightly conical bushing with a sharp end to be a suitable bushing shape for joining purposes.

CT scans of the joints of Al and Mg plates with GF and CF composites are shown in Figs. 6-9.



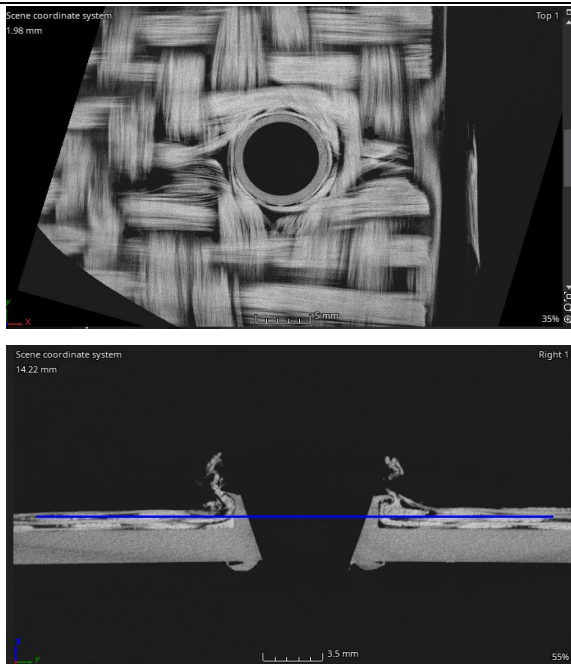
**Fig. 6** CT scan of Al-GF joint

The scan (Fig. 6) shows the displacement of the glass fibers during the formation of the bushing. Significant fiber breakage is not visible. The hem prevents delamination of the composite. The bushing has the shape of an inverted cone as a result of modifying the joint opening from the opposite side with a 9.3 mm tool.



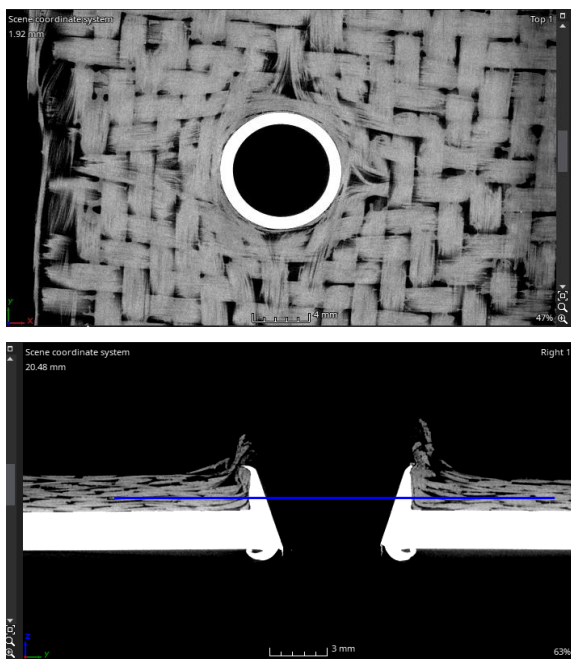
**Fig. 7** CT scan of Al-CF joint

The Al hem (Fig. 7) is well formed, trapping and fixing the fibres around the joint opening, thus preventing significant composite delamination. There is a visible fiber rich zone around the bushing, indicating fiber displacement during thermal drilling and fiber accumulation at the periphery of the bushing.



**Fig. 8 CT scan of Mg-GF joint**

At the Mg-CF joint (Fig. 8), the importance of modifying the geometry of the bushing is more apparent. The Mg bushing is cylindrical outside and conical inside, which eliminates the composite from sliding off the bushing when the joint is subjected to load and could lead to desirable bushing failure by shear. The hem is relatively small and so there was local pulling of the fibers out of the composite.



**Fig. 9 CT scan of Mg-CF joint**

The Mg-CF joint (Fig. 9) again exhibits the desired inverted cone geometry. Widening the hem with the 9.3 mm tool leads to a reduction of the hem, as a result of which a slight pulling out of the fibers from the composite around the joint opening is again evident.

## Conclusion

Computed tomography is an essential non-destructive technique that makes it possible to monitor the behaviour of a composite around a joint with a metal sheet formed by thermal drilling technology. CT confirmed the displacement of the fibers out of position during penetration of the flowdrill tool without breaking

the fibers while maintaining their reinforcing effect. Due to the undisturbed continuity of the fibres and also due to the geometrical modification of the shape of the resulting bushing, the mechanical properties of the two materials involved in the joint can be effectively used for increasing the load carrying capacity of the joint.

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## Development of flexible auger working bodies designs to improve the performance of bulk materials transport

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**Abstract.** The article presents a scheme of a new combined screw conveyor, which makes it possible to improve the performance of conveyors. To eliminate the identified disadvantages in the operation of flexible screw conveyors, new types of sectional working bodies hinged to each other have been developed, which will increase the reliability and durability of conveyors.

**KEYWORDS:** SCREW CONVEYOR, AUGER, FLEXIBLE WORKING BODY.

### Introduction

The transportation of grain material using flexible helical spirals provides high mobility in various technological processes. However, the existing solid flexible spirals are rapidly destroyed by alternating cyclic loads when transporting bulk materials of agricultural production along curved routes, and the use of combined working bodies is characterised by high material consumption, which leads to increased energy consumption and damage to the transported material. Theoretical and experimental studies in the area of bulk material overloading for double-track screw conveyors [1–3], as well as material intake by active loading nozzles [4–6], have made it possible to select rational design and kinematic parameters of working bodies, as well as their operating modes.

To increase the productivity of flexible screw conveyors, continuous strip spirals were used, which were placed in elastic casings. However, experimental studies have shown that they are destroyed rather quickly when transporting materials at small radii of curvature, due to the occurrence of alternating cyclic deformations [7].

In this regard, it is necessary to improve and develop new designs of screw working bodies, which are made of separate sections and pivotally attached to each other to ensure a high service life of productivity during the transportation of bulk materials of agro-industrial production [8, 9].

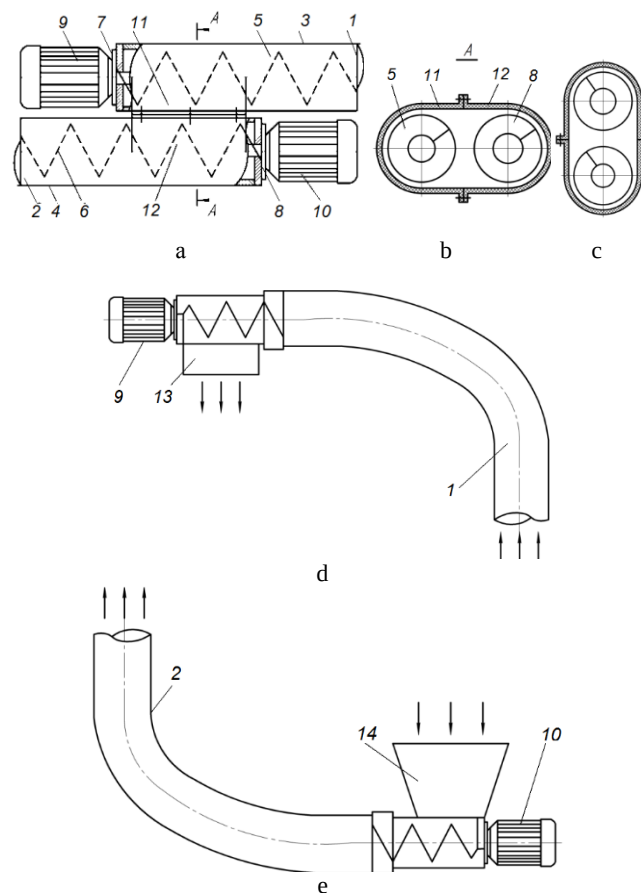
### Results and discussion

To improve the operational parameters, we have developed a layout diagram of a combined screw conveyor [10], which contains a loading 1 and an unloading 2 line, as shown in Fig. 1, a. They are made in the form of closed casings 3 and 4 of circular cross-section, in which helical spirals 5 and 6 are located, which are connected to the drive shafts 7 and 8 of electric motors 9 and 10.

In the area of the drive shafts, the lines are interconnected by means of two sections 11 and 12 of the overload pipe, which are fixed in the openings of the closed casings 3 and 4 on one side and interconnected on the other side. The helical spirals are installed in such a way that their central axes coincide with the axes of the drive shafts of the electric motors. The pipelines in the area where the sections of the discharge pipe are connected can be located in both horizontal (Fig. 1, b) and vertical (Fig. 1, c) planes.

During operation, the bulk material is fed into the intake area of the feed line and transported by the spiral 5 in the casing towards the discharge nozzle. The material in the nozzle is then transferred to the spiral 6 and transported to the unloading zone. The conveyor can also be used as a single-main conveyor. In this case, an unloading window 13 is attached to the sections of the reloading spigot, namely, the loading line, and a hopper 14 is attached to the unloading line.

In the first case, the single-mainline conveyor operates in the pulling or loading mode (Fig. 1, d), and in the second – in the feeding or unloading mode (Fig. 1, e).

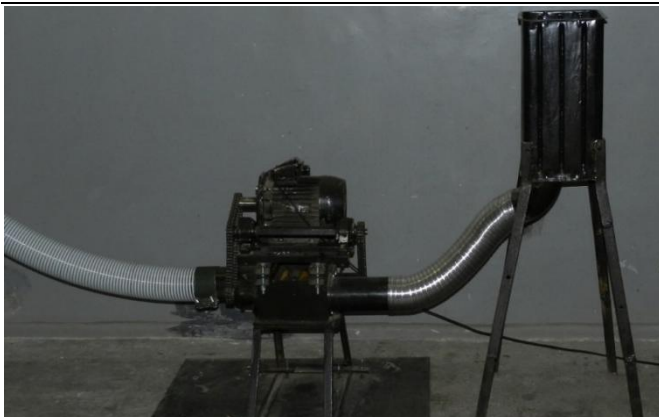


**Figure 1.** Scheme of a flexible screw conveyor:  
a – general view; b – horizontal arrangement of lines; c – vertical arrangement of lines;  
d – version of a single-main loading conveyor; e – version of a single-main unloading conveyor

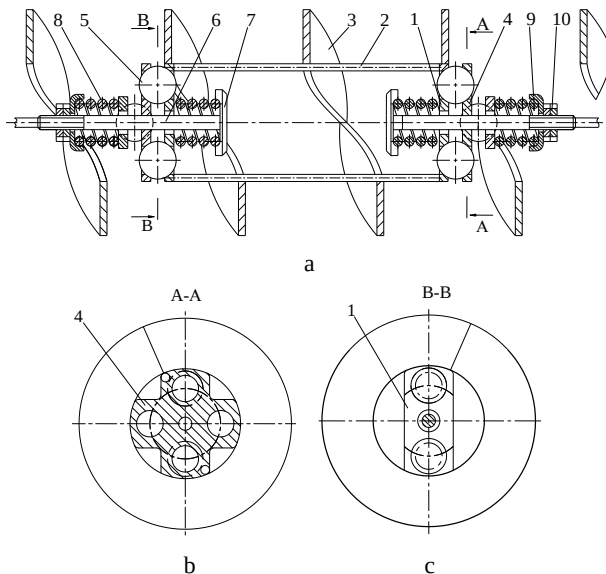
A general view of a flexible screw conveyor is shown in Fig. 2.

To solve this problem, a screw working body was developed, which is made of hinged sections with an autonomous elastic ball engagement, shown in Fig. 3.

Each section is made in the form of a pair of end washers 1 connected by rods 2, to which a screw rib 3 is attached. Between adjacent sections, an intermediate washer 4 is installed, in which four holes are made, evenly spaced in the circular direction. Two holes are diametrically opposite in the end washers, in which balls 5 are located, which on the other hand are installed in a pair of holes of the intermediate washers, and the lines connecting the centres of the holes of adjacent end washers are mutually perpendicular.



**Figure 2.** General view of the flexible screw conveyor



**Figure 3.** Schematic diagram (a), cross-section A-A (b), cross-section B-B (c), and general view (d) of an articulated working body with elastic ball engagement

The spiral sections are pressed together by an elastic mechanism, which is made in the form of a central rod 6 with a flange 7. The rod is installed in the hole of the intermediate washer, and on the inside of the adjacent end washers there are springs 8, the amount of deformation of which is regulated by the pressure washer 9 and nuts 10.

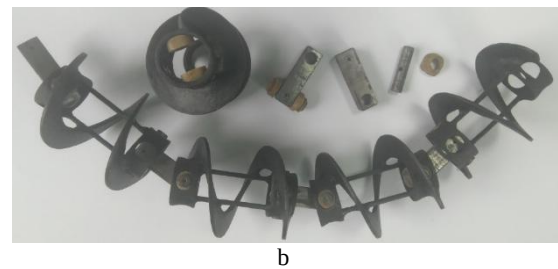
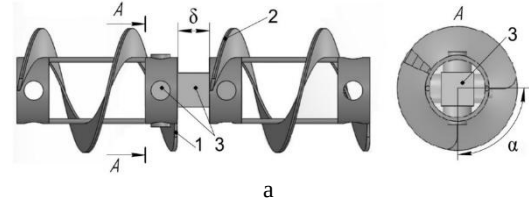
During operation, the working body, which is located in an elastic casing, rotates to transport bulk material to the unloading zone. Since the pairs of balls that connect the end and intermediate washers are located mutually perpendicular, this ensures relative rotation of the screw sections when transporting bulk materials along curved routes.

To improve the reliability of the flexible screw conveyor, it is proposed that its working body be made of separate screw sections that are hinged together. Fig. 4, a shows the location of the edges of adjacent sections, the helical ribs 1 and 2 of which are located in the axial direction with a gap  $\delta$  (inactive zone).

The helical sections are connected to each other by means of a hinge mechanism 3, which is made on the principle of a cardan with

spaced axes that are mutually perpendicular. In the circular direction, the edges of adjacent helical ribs are offset by an angle  $\alpha$ . The idea of the construction of such a working body consists in the fact that when the bulk material descends from the edge of the helical rib 1, it must travel a distance  $\delta$  in a certain time  $t_1$ . At the same time, the edge of the helical rib 2 should be rotated by an angle of  $\alpha$  at least (the angle of departure of the material must be taken into account) in time  $t_2$  in order to capture the transported material.

A general view of the sections of the working body located on the curved section and its individual elements is shown in Fig. 4, b.

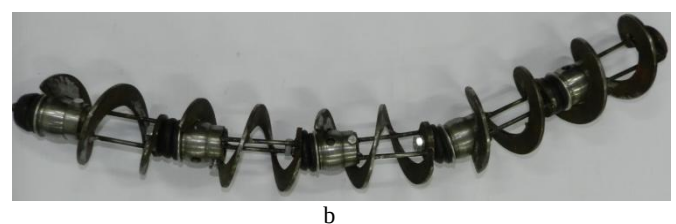
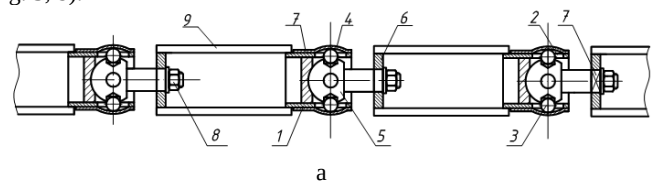


**Figure 4.** Structural and design scheme of a screw impeller, the sections of which are pivotally connected to each other:

a – image of two sections;  
b – general view of the sections of the working body located on the curved section and its individual elements

Fig. 5, a shows the design of a flexible sectional auger working body with a radial ball joint connection of the sections. A cylindrical sleeve 1 is rigidly attached to the sections at the right end. The latter is made with a system of parallel axial grooves 2, which are located evenly around the circumference and interact with rolling elements 3. On the other hand, the rolling elements 3 are located in the inner spherical surface of the sleeve 4 with the possibility of axial and angular rotation of the spherical pin 5.

At the opposite end of the cylindrical section, a connecting sleeve 6 with an internal square or shaped hole 7 is rigidly and perpendicularly mounted in the inner hole, which interacts with the corresponding end of the spherical pin of the adjacent section and with the nut 8 rigidly fixing it. Bridges 9 are fixed to the outer surface of the connecting sleeve 6 evenly around the circumference, and at the other end, the bridges are connected to the outer surface of the sleeve 1. A screw section is fixed to each cylindrical section (Fig. 5, b).



**Figure 5.** Schematic diagram (a) and general view (b) of the flexible sectional auger

To eliminate the identified disadvantages in the operation of flexible screw conveyors, new types of sectional working bodies hinged to each other have been developed, which will increase the reliability and durability of conveyors.

### **Conclusions**

To increase the productivity of flexible screw conveyors for transporting bulk materials in agro-industrial production, it is proposed to use new designs of flexible screw working bodies made of separate sections and hinged to each other.

On the basis of the study, a hinged working body with elastic ball engagement was developed, which, by unloading the screw ribs during torque transmission, ensures increased reliability and durability of conveyors. In addition, to improve the functioning of the flexible screw conveyor, it is proposed that its working body could be made of separate screw sections that are hinged together. To ensure increased reliability and durability of the conveyors, it is proposed to use a flexible sectional screw working body with a radial ball joint of the sections.

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# New trends in road traffic safety with better environmental protection

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**Abstract:** About a hundred young lives are lost on Serbian roads every year. Since the beginning of 2025, eight young people have died in traffic accidents in Serbia. According to Norwegian statistics, the share of traffic accidents involving electric cars more than tripled between 2018 and 2023, but the increase in the accident rate is still proportional to the number of electric cars. The subject of many debates in recent years is the fact that electric cars are very quiet. Electric cars are more likely to be involved in accidents with pedestrians. At least compared to diesel and gasoline engines. In March 2025 at the International Motor Show in Belgrade, the new all-electric "Fiat Grande Panda" produced in Serbia was presented. The launch of serial production at the factory in Kragujevac will affect the economic development of Serbia. The fight for environmental protection is a process that requires long-term commitment, large investments, and active cooperation between governments, the private sector, and citizens.

**Keywords:** ROAD TRAFFIC SAFETY, ELECTRIC CARS, ENVIRONMENTAL PROTECTION

## 1. Introduction

The war conflicts are not abating in Ukraine, new mobilization is being sought. The chance for peace is still waited for.

In Germany, Volkswagen is reporting the closure of at least three of its ten car factories, with wage cuts announced.

The largest market for electronic vehicles - 60% of global sales come from China, but China still remains the world's largest emitter of carbon dioxide and rapid industrialization is making environmental change more difficult.[1] The experiences of the EU and China show that large investments in solar and wind energy are key to the long-term sustainability of the energy sector. Serbia should accelerate projects in this area in order to reduce dependence on coal.

Although environmental protection is recognized as a universal need, approaches to addressing it vary significantly between countries. [2] Smart traffic systems in Singapore use digital technology to optimize traffic, reduce congestion and reduce emissions. One of the most important approaches to reducing traffic pollution is the transition to environmentally friendly vehicles. The European Union has adopted the Euro 6 standard, which sets high standards for emissions from diesel vehicles, obliging manufacturers to implement advanced technologies to reduce harmful emissions.

## 2. International experience

Volkswagen will cut more than 35,000 jobs. The decision is part of a cost-cutting plan as the company faces tougher competition outside Europe. In February 2025 Audi was closing a large electric car factory in Brussels. The decline in demand and high production costs are the reason for the factory closure.

Electric Lamborghini was postponed to 2029, as they believe the market is not ready yet. Starting this year, Lamborghini's Urus SE SUV, Revuelto and Temerario models are offered as hybrids. The company is also waiting for decisions from regulators. The ban on the sale of internal combustion cars from 2035 will be reviewed again in two years. It may also be postponed.

Car manufacturer Porsche has recalled 27,527 of its electric sedans in the US due to a risk of battery short circuits. The US National Highway Traffic Safety Administration said the recall applies to Porsche Taycan models manufactured between 2021 and 2024. A potential short circuit in the high-voltage battery increases the risk of a fire in the car. Porsche customers will have vehicle diagnostic software installed and free repairs performed if necessary.

Nine out of ten new cars sold in Norway last year were fully electric, as data from the Norwegian Transport Federation (OFV) show, bringing the country to its goal of adding only electric cars to the road by 2025. Despite being a major oil and gas producer, Norway aims for all new cars sold to be "zero-emission" starting in 2025, 10 years ahead of the target of the European Union, of which Norway is not a member.

In 2012, electric cars represented only 2.8 percent of sales, while almost all (88.9%) of new cars sold in Norway last year were electric. Explanation for this are various incentives. They received exemptions from higher taxes, making them competitive with highly taxed internal combustion cars. They had also exemption from paying road tolls, had free parking in public lots, and could use public transportation lanes. Although some tax breaks and incentives have been eliminated over the years, electric cars have become customary. Tesla is the leading electric car manufacturer in Norway with 19 percent of the market, followed by Volkswagen, Toyota, Volvo and BMW.

However, Tesla vehicle sales in the European Union halved in February! Tesla vehicle sales in the EU fell by 47.1% in February, the European Automobile Manufacturers Association (ACEA) announced. Looking at the data for the first two months of 2025, Tesla sales in the European Union fell by 49% compared to the same two-month period last year to 19,046 vehicles.

Still sales of electric cars of all brands in the EU increased by 23.7 percent year-on-year in February to 131,275 vehicles, and by 28.4 percent in the first two months to 255,489 vehicles, representing a 15.2 percent market share. The latest data is in line with an analysis by JATO Dynamics, which concluded that sales of Tesla vehicles in Europe are declining. In February, Tesla was surpassed by Volkswagen, BMW and rivals from China in sales of battery electric vehicles (BEVs) in Europe.

According to Norwegian statistics, the share of traffic accidents involving electric cars more than tripled between 2018 and 2023, but the increase in the accident rate is still proportional to the number of electric cars. However, when it comes to serious accidents, there are differences. Electric cars were overrepresented in pedestrian accidents during the study period, indicating a particular risk in this category.

On the other hand, electric cars are less frequently included in fatal accident statistics, compared to diesel and gasoline cars, according to an analysis by Statistics Norway (SSB). The study, which covers the period from 2018 to 2023, focused on traffic accidents with injuries. Specifically, the share of electric cars in accident statistics has increased from 7 to 25 percent. But this is primarily due to the fact that the number of electric cars has generally increased over the same period.

The subject of many debates in recent years is the fact that electric cars are very quiet. In 2019, for the same reason, it became a requirement that Acoustic Vehicle Alert System (AVAS) must be installed in all electric cars. The system emits an artificially created sound as soon as the electric car is moving at a speed of 20 km/h or more. Electric cars are more likely to be involved in accidents with pedestrians. At least compared to diesel and gasoline engines.

Environmental protection is a key goal of all modern societies, as its survival directly affects the quality of life, human health and the sustainability of ecosystems. [3]

Among the most important international initiatives are the Paris Agreement on Climate Change [4], the Convention on Biological Diversity and the 2030 Agenda for Sustainable Development, which aim to eliminate poverty, inequalities and preserve the environment. These international initiatives encourage countries to take concrete measures to preserve the ecological balance and reduce global warming.

Key environmental measures of the European Union are:

- European Green Deal – The goal is climate neutrality by 2050;
- Emission Trading System (ETS) – Limits carbon dioxide emissions through a system of permit trading;
- Subsidies for electric vehicles and renewable energy sources;
- Low Emission Zones (LEZ) in large cities.

In London, a Low Emission Zone (ULEZ) has been introduced, which charges a fee for vehicles that do not meet emission standards, thereby reducing pollution in the city center itself.

Good is the example of Amsterdam, where bicycle traffic makes up a significant portion of total traffic, thereby reducing greenhouse gas emissions.

### 3. Serbia

In March 2025 at the International Motor Show in Belgrade, the new all-electric "Fiat Grande Panda" produced in Serbia was presented. The launch of serial production at the factory in Kragujevac will affect the economic development of Serbia.

A representative of Jiangling Group Electric Vehicle (JMEV) in Serbia reported in March 2025 that the Chinese company had chosen a factory location in Sremska Mitrovica to produce an electric car in our country. They call themselves a "pure green company", as all electricity consumption in the production of electric cars comes from renewable sources. Now, we need to comply with EU regulations regarding this type of production in the automotive sector.

In November 2024, the OSCE and EECL organized a roundtable discussion within the ELC Hub at the Faculty of Law in Belgrade. The Jean Monnet Chair for European Environmental and Climate Change Law of the Faculty of Law, University of Belgrade, in cooperation with the OSCE Mission to Serbia, organized a roundtable discussion on the topic "Electric Cars and Sustainable Fashion in the Formula of Environmental Sustainability". It was held as a platform for connecting alumni of the Environmental Law Clinic and the Master's Degree in Environmental Law and environmental lawyers, in order to stimulate discussion on current issues in the field of environmental law and climate change law in domestic practice.

The main problems in Serbia are: limited resources and slow implementation of environmental applications. These days focus is put on harmonization with EU legislation. We also insist on increasing participation and investment in renewable energy sources. Constant work on raising environmental awareness is necessary.

About a hundred young lives are lost on Serbian roads every year. Since the beginning of 2025, eight young people have died in traffic accidents in Serbia. The Traffic Safety Agency in Serbia is implementing the "In the car without alcohol" campaign this year, during which it conducts preventive activities aimed at responsible behavior in traffic. Statistics show that every ninth person killed in traffic loses their life due to drunk driving.

In 2024, 65 motorized two-wheelers, 13 moped riders, and 53 motorcycle riders died on Serbian roads. Their share in the total number of traffic fatalities is 13%, which is an extremely high number, especially when we consider their number in our country.

A comparative analysis shows that Serbia lags behind developed countries in implementing environmental measures, but is gradually introducing reforms to align with European Union standards. [5] The biggest challenge remains dependence on coal and insufficient investment in renewable energy and transport infrastructure.

### 3. Conclusion

Environmental protection is a key goal of all modern societies. Electric vehicles (EVs), hydrogen-powered vehicles, hybrid vehicles, and vehicles with lower carbon emissions are key technologies that can significantly reduce greenhouse gas emissions, as well as other pollutants such as nitrogen oxides and particulate matter.

Setting stricter fuel economy standards for new vehicles can reduce overall carbon dioxide production. Investing in "green" buses (biogas, electric or hydrogen) can further reduce the negative environmental effects of traffic. Example: Cities like Copenhagen and Amsterdam are developing green public transport systems, while Sweden is known for using biogas in buses as a sustainable fuel.

The fight for environmental protection is a process that requires long-term commitment, large investments, and active cooperation between governments, the private sector, and citizens.

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# Green logistics - a condition for the country's sustainable development

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**Abstract:** Transport and logistics services play a crucial role in the economic development of any country, especially in Georgia, as they contribute to the growth of other sectors of the economy. However, as a significant energy consumer, it also has a very negative impact on the environment. The aim of the study is to learn the relationship between green logistics and sustainable development, investigate the impact of transport and logistics services on the environment from an economic, ecological, and social perspective, and identify possible ways to achieve sustainable development in the country through green logistics. Based on the analysis of scientific literature and empirical data, we can conclude that to achieve sustainable development goals, it is necessary to create transport systems that are capable of optimal use of resources and high environmental responsibility. Green logistics just is the practice that responds to these requirements. Meanwhile, Georgia's geographical location as a transport corridor between Europe and Asia highlights the particular need for sustainable logistics solutions for the benefit of the country.

**Keywords:** TRANSPORT AND LOGISTICS SERVICES, GREEN LOGISTICS, SUSTAINABLE DEVELOPMENT

## 1. Introduction

The concept of sustainable development appeared in the scientific literature as early as the 1960s and 1970s. However, it was popularized in 1987 in the Brundtland Report (World Commission on Environment and Development (WCED, 1987). [1. P. 108.] In this report, sustainable development was defined as development that meets the needs of the present without compromising the ability of future generations to meet their own needs. [2. P. 41.]. The concept of sustainable development implies a balance between interrelated social, ecological and economic dimensions. (Fig. 1). [1. P.108.]. In essence, it emphasizes the rational use of limited resources and the introduction of environmentally friendly, energy-efficient and resource-saving technologies.

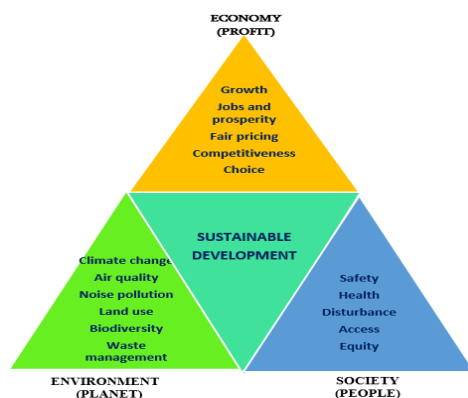


Fig. 1 The concept of sustainable development

Source: Adapted from [1].

There is a direct connection between sustainable development and green logistics. The principles of green logistics are based on the development of environmentally friendly transport systems and the decarbonization of production and transport processes. With such approaches, green logistics addresses the most critical challenge of modernity - environmental degradation - by promoting economic growth and improving social well-being. By its very nature, it is the basis for building a sustainable economy, as it supports environmental protection, promotes the efficient use of resources and optimizes transport flows. As a result, green logistics plays a crucial role in the ecological transformation of supply chains. Moreover, the introduction of environmental standards in logistics processes lays the foundation for long-term, balanced and sustainable economic growth.

For a deep understanding of the theoretical foundations of green logistics, it is very important to analyze the relevant scientific literature and consider the research of various scientists and practitioners. Among them, it is worth noting:

McKinnon, A., Browne, M., Whiteing, A., & Piecyk, M. (Eds.). (2015). [1], which covers the environmental aspects of transport, warehousing, processing, supply chains, opportunities for improving the use of transport vehicles, guidelines for carbon footprint accounting, etc.;

Grant, D. B., Trautrim, A., & Wong, C. Y. (2017) [3], which extensively presents the ecological and social aspects of supply chain management, discusses in detail global freight transport trends, emissions, fuel consumption issues, and the development of technologies that create cleaner transport alternatives.

Sarkis, J. (2006) [4], focuses on the development of the concept and principles of green supply chain management. presents practical examples of green supply chains, describing the challenges that arise in this process and the ways to overcome them.

The results of scientific publications by foreign authors [5; 6; 7] emphasize the importance of implementing green logistics practices and sustainable development strategies in the economy. They show that the integration of environmental aspects into logistics contributes to the efficient use of resources, reducing environmental impact and ensuring economic sustainability in the long term.

It should be noted that the level of scientific research on green logistics issues in Georgia is relatively low, although interest in this topic from scientists and practitioners is gradually increasing.

The heads of leading foreign companies consider and use green logistics practices. Using energy- and resource-saving technologies, they try to reduce the negative impact of logistics and the supply chain on the environment. Unfortunately, we cannot say the same about the example of our country. This problem still remains one of the important challenges for Georgia, and its solution requires targeted actions. In order to study this problem, we developed a questionnaire and conducted a study to assess the extent to which transport and logistics companies in Georgia use sustainable practices, as well as collected and analyzed data published in various reports that reflect the impact of transport and logistics services on the environment.

## 2. Main part

Globalization has led to large flows of goods around the world. However, the production, transportation, storage, and consumption of all these goods have created significant environmental problems.

In the face of growing environmental challenges, governments and stakeholders are increasingly focusing on the importance of sustainable development and are calling on companies to take actions to combat this threat. [6]. This challenge is has of a strategic importance for Georgia as well. Given its geographical location, our country is a transit corridor connecting Asia with Europe, and its effective use is a necessary condition for the country to strengthen its role in regional and global supply chains and ensure competitive advantages in various sectors of the national economy, especially in logistics and transport. Despite its strategic geographical location, Georgia cannot fully use the transit corridor effectively, nor are its logistics systems efficient. Today, the logistics sector in Georgia faces significant obstacles that hinder its sustainable development. The main ones:

- 1) The underdeveloped logistics and intermodal infrastructure contribute to the low efficiency, high cost, and relatively low reliability of the logistics system. [8.p.9].
- 2) High levels of air pollution, especially in cities, also negatively affect the health of the population. The SWD (2023) report notes that Georgia is at an early stage of environmental and climate change preparedness. [9, p. 99]. Climate change and its adverse effects on ecosystems and the economy pose a serious threat to the sustainable development of Georgia. [10, p. 16].
- 3) The need to raise awareness about internationally recognized green logistics standards. We also want to raise awareness of environmental issues and green logistics. According to a study conducted within the framework of the United Nations Development Program (UNDP) (Vardosanidze K. & Kiss C. 2023), Georgian society is relatively less involved in environmental issues or discourse.

Green logistics is, by its very nature, the basis for building a sustainable economy, as it supports environmental protection, promotes the efficient use of resources and optimizes transport flows. As a result, green logistics plays a crucial role in the ecological transformation of supply chains.

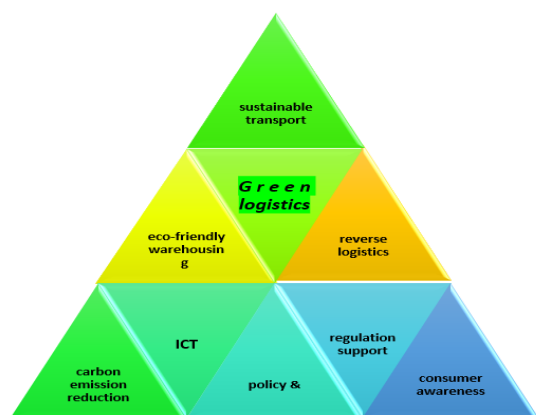


Fig. 2 Core Elements of Green Logistics

Source: Developed by the author

As it is known, worldwide, transport is responsible for approximately one billion tons of carbon dioxide emissions, which corresponds to 3% of total human-caused CO<sub>2</sub> emissions. In addition, it accounts for approximately 15% of global nitrous oxide emissions and 13% of sulfur dioxide emissions, and this trend is still increasing, which is accompanied by significant damage to the environment and health. [12] Therefore, it is essential that the transport sector operates smoothly and efficiently, especially in Georgia, where the country's economic growth and sustainable development largely depend on this sector.

The data from Georgia's Fourth National Communication to the United Nations Framework Convention on Climate Change reflect the environmental challenges facing the country and point to dangerous trends. [13]

Table 1.: Greenhouse gas emissions from the transport sector and types of transport

| Road transport |       |                     |       |                     |       |                                      |       |
|----------------|-------|---------------------|-------|---------------------|-------|--------------------------------------|-------|
| Year           | Total | CO <sub>2</sub> eq. |       | CO <sub>2</sub> eq. |       | CH <sub>4</sub> and N <sub>2</sub> O |       |
|                |       | Total               | Share | CO <sub>2</sub>     | Share | CO <sub>2</sub> eq.                  | Share |
| 1990           | 3,901 | 3,678               | 94,3% | NE                  | -     | 43.58                                | 1.12% |
| 1995           | 863   | 844                 | 97,8% | NE                  | -     | 0,89                                 | 0,10% |
| 2000           | 965   | 945                 | 97,9% | NE                  | -     | 0,04                                 | 0,00% |
| 2005           | 1,571 | 1,537               | 97,8% | NE                  | -     | 0                                    | 0,00% |
| 2010           | 2,630 | 2,390               | 90,9% | NE                  | -     | 0,02                                 | 0,00% |
| 2015           | 4,208 | 3,965               | 94,2% | 3,855               | 91,6% | 110                                  | 2,60% |
| 2016           | 4,500 | 4,239               | 94,2% | 4,125               | 91,7% | 114                                  | 2,50% |
| 2017           | 4,472 | 4,240               | 94,8% | 4,128               | 92,3% | 112                                  | 2,50% |
| 2018           | 4,153 | 3,875               | 93,3% | 3,772               | 90,8% | 103                                  | 2,48% |
| 2019           | 3,995 | 3,669               | 91,8% | 3,571               | 89,4% | 97                                   | 2,44% |

Table 1 continuation: Greenhouse gas emissions from the transport sector and types of transport

| Year | Total | Civil aviation  |       | Railway         |       | Inland Navigation   |       | Pipeline        |       |
|------|-------|-----------------|-------|-----------------|-------|---------------------|-------|-----------------|-------|
|      |       | CO <sub>2</sub> | Share | CO <sub>2</sub> | Share | CO <sub>2</sub> eq. | Share | CO <sub>2</sub> | Share |
| 1990 | 3,901 | NE              | -     | 101             | 2,59% | 78                  | 2,00% | NE              | -     |
| 1995 | 863   | NE              | -     | NE              | -     | 18                  | 2,09% | NE              | -     |
| 2000 | 965   | NE              | -     | NE              | -     | 20                  | 2,07% | NE              | -     |
| 2005 | 1,571 | NE              | -     | NE              | -     | 34                  | 2,16% | NE              | -     |
| 2010 | 2,630 | NE              | -     | 190             | 7,22% | 50                  | 1,90% | NE              | -     |
| 2015 | 4,208 | 2               | 0,05% | 18              | 0,43% | 2                   | 0,05% | 221             | 5,3%  |
| 2016 | 4,500 | 3               | 0,08% | 34              | 0,75% | 2                   | 0,05% | 222             | 4,9%  |
| 2017 | 4,472 | 2               | 0,04% | 34              | 0,77% | 6                   | 0,14% | 19              | 4,3%  |
| 2018 | 4,153 | 1               | 0,02% | 34              | 0,83% | 2                   | 0,05% | 240             | 5,8%  |
| 2019 | 3,995 | 2               | 0,05% | 32              | 0,80% | 1                   | 0,03% | 292             | 7,3%  |

According to the data presented in the table, the share of greenhouse gas emissions from road transport accounts for more than 90% of emissions from the transport sector. Accordingly, road transport is one of the main environmental challenges in this sector. Therefore, it is necessary to take targeted steps to reduce emissions, which is possible by popularizing and encouraging environmentally friendly means of transport.

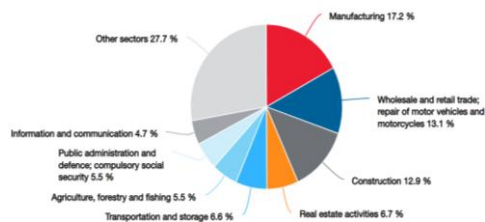
In Georgia, greenhouse gas emissions in the transport sector have increased due to the growth of the vehicle fleet, which mainly consists of used cars. The emissions of these gases depend on the type of fuel, combustion technology, user conditions, control technology, maintenance of equipment, and its age. Since Georgia is a transit country, the number of fuel-consuming transit trucks purchased on the territory of Georgia is also increasing along with the growth of the local transport fleet. The annual growth of local and transit transport leads not only to an increase in carbon dioxide and other greenhouse gases but also to an increase in local pollutants. It should also be noted that transit pipelines of energy carriers pass through Georgia, for the operation of which natural gas and diesel fuel are consumed at substations. The greenhouse gas inventory in the Georgian transport sector includes road transport, railway transport, civil aviation, inland navigation, and pipelines.

Table 2. Emissions from the transport sector and their share in national emissions

| Year | National GHG, Gg CO <sub>2</sub> eq. | Transport                 |       |
|------|--------------------------------------|---------------------------|-------|
|      |                                      | SG, Gg CO <sub>2</sub> eq | Share |
| 1990 | 45,814                               | 3,901                     | 8.5%  |
| 1995 | 12,696                               | 863                       | 6.8%  |
| 2000 | 10,923                               | 965                       | 8.8%  |
| 2005 | 11,168                               | 1,571                     | 14.1% |
| 2010 | 13,688                               | 2,630                     | 19.2% |
| 2015 | 18,214                               | 4,208                     | 23.1% |
| 2016 | 18,534                               | 4,500                     | 24.3% |
| 2017 | 17,766                               | 4,472                     | 25.2% |

In recent years, the share of transportation in national greenhouse gas emissions has been characterized by a constant increase. From 2000 to 2017, this increase amounted to 186%, which is truly worrying, which emphasizes the need to implement a sustainable transport policy. Main motive for improving national logistics is to stimulate competitiveness and achieve additional and continuous economic growth.

According to the National Statistics Office of Georgia, the rate of transport and storage in 2024 was 6.6% in the sectoral structure of Georgia's GDP, increasing by 8% compared to the previous year.



Sectoral structure of gross domestic product 2024\* %, Source: [14].

Within the framework of the study, 71.6 % of respondents believe that transport-logistical services have a negative impact on the environment, and 28.4 % think that it has a very negative impact. 53% of respondents fully agree with the notion that transport and logistics play an important role in creating jobs, and 46.4% largely agree with this opinion; i.e., in total, 100% of respondents are positive, and only 0.6% have no answer.

Respondents are of the view that transport and logistics enhance trade and increase economic indicators; he answers are as follows: 69.7% fully agree with the opinion, 29.1% of the opinion is positive, and 1.2% have no answer.

According to respondents, the economic benefits that the country will have with the development of transport and logistics networks are as follows: More foreign investments in infrastructure development (58.4%), increased trade (26.4%), and (15.1%) make up jobs.

More than 84% of respondents suffer from air pollution caused by shipping, and up to 16% suffer from noise.

According to respondents, environmental impacts can be reduced by performing specific actions, namely, effective waste management (20.5%), using ecological fuel (19.5%), tightening regulations (10.7%), investing in green technologies (30.2%), and effectively planning routes (19.1%).

The development of transport and logistical networks in turn has a multiplier effect on employment, trade, investment, education, etc. Our country needs attention in this direction and the necessary actions.

According to the World Bank report, according to the Logistics Index (LPI), Georgia ranks 79th in 2023. According to the National

Strategy of Transport and Logistics Action Plan of 2023-2030 of Georgia (2023-2024), this figure is planned by and the target is  $\leq 69$ .

### 3. Conclusion

Transport and logistics are important sectors of the national economy, which not only ensure the movement of products but also create new jobs, contribute to the integration of regions, and are a stimulus for economic development.

From an economic perspective, improving logistics systems directly affects the efficiency of goods delivery, reducing costs and increasing export potential.

From a social perspective, the development of transport and logistics ensures improved mobility of the population, regional equality, and access to public services.

Green logistics balances economic benefits and environmental and social requirements with a focus on sustainability and reducing the environmental impact. It focuses on reducing greenhouse gas emissions, energy consumption, and waste generation in logistics operations. Environmentally friendly practices, such as optimizing transport routes and using energy-efficient vehicles, reduce the environmental impact of logistics processes and contribute to its protection.

Green logistics aims to reduce emissions through various means, including promoting alternative fuels, optimizing vehicle loads, and using multimodal transportation strategies. Moreover, the introduction of environmental standards in logistics processes lays the foundation for long-term, balanced and sustainable economic growth.

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# Utilization of Software-Based Methods for Calculating Vehicle Speed in Traffic Accident Reconstruction: A Case Study

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**Abstract:** The use of video surveillance systems (Closed-Circuit Television - CCTV) has become widespread across various modern applications. In the context of forensic documentation submitted for expert analysis, digital video recordings of traffic collisions are increasingly common. These recordings often capture not only the moment of impact but also crucial pre- and post-collision events. Such footage provides valuable data for understanding the dynamics of an incident and conducting detailed kinematic analyses. Accident reconstruction software, such as AnalyzerPro and PC Crash, includes specialized video analysis modules. When certain conditions are met, these modules can be used to extract quantitative information about the position and velocity of involved vehicles or individuals at specific moments in time. This paper provides an overview of the operational principles of these modules, the prerequisites for their effective use, and the precision with which they estimate kinematic parameters, as demonstrated in a case study.

**Keywords:** SPEED, VIDEO TRACK, ANALYZERPRO, PC CRASH

## 1. Introduction

In today's world, security has become one of the most important aspects of both, public and private life. Technological advancements have enabled the development of sophisticated surveillance systems, with Closed-Circuit Television (CCTV) occupying a prominent position among them. The use of such systems has become standard in many areas, ranging from traffic monitoring to property protection.

In most cases, video recordings of traffic accidents are analyzed primarily to determine how the accident occurred. However, these recordings can also serve as a valuable source of information for identifying kinematic parameters essential for a high-quality and reliable time-distance analysis of the accident's progression. One of the fundamental parameters for such analysis is the speed of the vehicles involved [1].

The quality and specifications of video record can vary significantly from one recording to another. When determining the speed of the participants involved in an accident, the key parameters extracted from the footage are time (s) and distance (m) [2].

Data about the elapsed time during the analyzed video sequence can be obtained by dividing the video into time segments (frames). This can be done using professional or online video conversion tools to extract frames—usually by converting video files (e.g., AVI, MP4, or other codecs) into JPEG format. The frame rate, or frequency, is expressed in frames per second (fps). The most common standard is 25 fps, which is sufficient for the human eye to perceive a smooth and continuous image. At this frame rate, the time interval between two consecutive frames is approximately 0.04 seconds. Before analyzing the time intervals between frames, it is important to check whether the frames were captured at consistent intervals within each second or if there are variations. Regardless of the recording frequency, the primary indicator of the elapsed time between frames should be the detection of motion between two consecutive images. Another parameter necessary for speed calculation is the distance traveled. To determine this, the video must show the characteristic positions of moving objects—those being analyzed—in relation to stationary objects or markings on the road surface that can be subsequently identified. These may include road markings, the position and dimensions of objects, the pavement grid pattern, etc. [3]

The software packages AnalyzerPro and PC Crash, designed for the simulation and reconstruction of traffic accidents, include modules that, under certain conditions, can be used to determine the position and speed of the vehicle being analyzed.

The basis of these modules is the transformation of the camera image into a planar orthogonal plane, on which the traveled path of the analyzed object can be determined over time, as well as the detection of the movement of the object under analysis using machine learning (ML), i.e., artificial intelligence (AI).

In this paper, using a case study of a real traffic accident, an analysis of video analysis tools contained within the software packages AnalyzerPro and PC Crash was performed.

## 2. Modules for video analysis in the programs AnalyzerPro and PC Crash

During the last decades, several software packages designed for the simulation and reconstruction of traffic accidents have been developed, enabling dynamic and kinematic analysis of such events. Although most of these programs are based on similar principles, they are continuously improved, primarily by expanding the vehicle databases, as well as through the development and implementation of additional tools and specialized modules applied in traffic accident analysis.

In the latest versions of the AnalyzerPro and PC Crash programs, video analysis tools for traffic accidents are now available. These tools allow for detailed kinematic analysis to determine the exact moment of the accident, the positions of the vehicles at and immediately before the collision, as well as their speeds at the time of impact.

A comparative study of the video analysis modules in AnalyzerPro and PC Crash was conducted under controlled conditions. The camera position during recording was precisely known, and the vehicle's speed was regulated by the driver and concurrently measured via GPS. The recording was performed from a fixed vantage point on a bridge overlooking the roadway. The comparison focuses on data obtained at a vehicle speed of 30 km/h.

### 2.1. Video Analysis Module in the AnalyzerPro

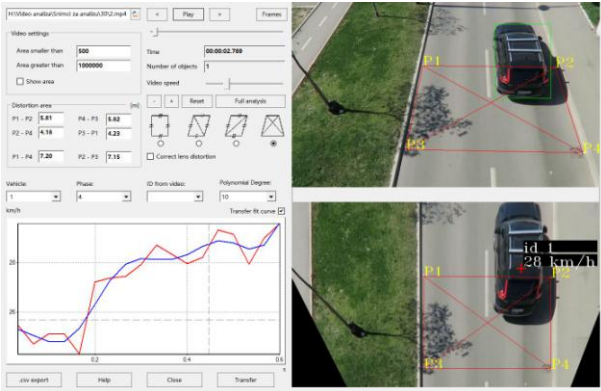
The video analysis module within the AnalyzerPro program includes specialized tools that, under certain conditions, enable the determination of vehicle speed from the recorded video record of the analyzed event.

After importing the video, based on the position of at least 4 characteristic points arranged in an orthogonal or other form, where the mutual distance between them is known, it is possible to establish an orthogonal view of the section that is the subject of analysis within the video analysis tool included in this software package.



**Fig. 1** Layout of the road section on which the analysis was performed with characteristic points and their mutual distances

Then, depending on the position and characteristics of the video camera, the parameters of which are mostly unknown, the optimization of the orthogonal image is carried out using an algorithm based on the recognition of rectangular or collinear shapes, which also calibrates the image, in order to reduce as much as possible their distortion caused by the position of the camera and the lack of knowledge of its parameters. In this way, an orthogonal projection of the location where the analysis is carried out is established, which also defines the path traveled by the vehicle over time when moving through the observed section, which is the basis for determining its speed.



**Fig. 2** Rectified view of the section where the recording was made with the speed of the identified vehicle

The detection of objects in motion is performed using algorithms based on ML, so the calculation of the speed of the vehicle represents the relationship between the marked section covered by the video and the time during which the analyzed vehicle passed through that section.

**2.2. Video Analysis Module in the PC Crash**

In the PC CRASH 15.0 software package, the video analysis module enables the determination of vehicle position and speed frame by frame, depending on the frame rate of the video. The analysis is based on establishing a correspondence between the video frames and an ortho-photo image of the actual location. This spatial alignment allows for accurate tracking of vehicle movement across time intervals, forming the basis for kinematic analysis.

In this sense, it is first necessary to define the base on which the analysis is carried out, by downloading it from some of the geoportals, as a Google Maps, by entering GPS coordinates or by importing, with the establishment of an appropriate scale, which would achieve a realistic relationship between the dimensions of the vehicles that are the subject of the analysis and the roads on which they move.

The next step is to enter the appropriate vehicle on the ortho-photo base, along with defining the kinematic parameters related to its direction and direction of movement.



**Fig. 3** Orthophoto image of the road section where the video recording was made

Within the PC Crash 15.0 program, there are several tools intended for video analysis, i.e. determining the speed of movement and the positions of the participants in the accident [4]. One of them is the video cutter, which can be used to extract from the video only that part that is important for the event itself, which separates the important facts from the irrelevant ones and shortens the analysis time. In addition to shortening the video, with this tool the video itself, that is, its part, which is the subject of analysis, is developed into frames.

PC Crash 15.0 includes several tools dedicated to video analysis, specifically for determining vehicle speeds and positions of accident participants [4]. One such tool is the Video Cutter, which enables users to extract only the relevant segment of the video that pertains directly to the incident. This functionality helps isolate critical data, eliminate irrelevant content, and significantly reduce analysis time. In addition to trimming the video, this tool also decomposes the selected segment into individual frames, allowing for frame by frame analysis essential for precise motion tracking and timing measurements.

To maximize coverage, most security cameras employ wide-angle lenses, which typically do not provide sufficient metadata for accurate calibration [2]. Additionally, the exact spatial position and orientation of the recording camera are often unknown. For video analysis to produce valid results, especially when determining vehicle positions and velocities at specific time points, it is essential to compensate for lens distortion by characterizing the lens curvature and accurately defining the camera's spatial location and orientation. These parameters are crucial for correcting perspective distortion and ensuring the spatial fidelity of the analysis.

To begin calibration, it is necessary to identify a line in the video that is realistically straight in the real world. Examples include curbs, horizontal lane markings, pedestrian crossings, or vertical objects such as streetlight poles and building edges. Unless the video footage is recorded orthogonally, the drawn line in the image will typically deviate from its true straight form due to distortion.

To correct these distortions, five calibration parameters are adjusted:

- Radial distortion parameters (K1, K2, K3):  
K1 - corrects distortion affecting the entire image;  
K2 - addresses distortion near the image edges;  
K3 - compensates for distortion at the outermost edges.
- Tangential distortion parameters (P1, P2) correct image tilt caused by lens misalignment or camera orientation.

The next step involves determining the camera's position during recording. This is done by aligning the approximate camera location with an ortho-photo of the area. Initially, the camera is roughly placed on a two-dimensional ortho-photo base near its actual position during the video capture.

Then, by overlaying a three-dimensional representation of the analyzed section with the two-dimensional ortho-photo—allowing

adjustment of transparency—the virtual camera is positioned so that at least five characteristic points or mutually parallel lines, visible in both the video and ortho-photo, overlap precisely.

Using the program's optimization tools, the camera position and distortion parameters are iteratively refined to achieve the best fit between the video and ortho-photo. A combination of parallel lines and characteristic points typically yields the most accurate calibration results.



**Fig. 4, 5** Comparative display of the recorded section during research with the position of the virtual camera after its position has been optimized

Object identification in motion is also achieved using machine learning (ML), which aims to develop statistical algorithms capable of “learning from experience.” These algorithms predict future behavior based on observed past patterns [5], [6].



**Fig. 6, 7** Identification of the vehicle that was the subject of the investigation, with a speed diagram

### 3. Application of the tools for video reconstruction of traffic accidents: a case study

In the analyzed traffic accident, a car ran into a pedestrian, who was crossing the road along the edge of the pedestrian crossing, closer to the oncoming vehicle, from the right to the left side, viewed in the direction of the vehicle's movement. As part of the submitted documentation, a video recording was also available, from which it was possible to see the course of the accident itself. Based on the video analysis, it was determined that the pedestrian, after starting to cross the road, turned from right to the left towards the oncoming vehicle with the front side of his body, and that the contact occurred in the area of the left edge of the pedestrian crossing, viewed in the direction of his movement.

The basis for analyzing a video of a traffic accident lies in identifying orthogonal forms visible in the video recording whose dimensions are known, or in locating characteristic points or parallel lines that are visible both in the video and on the ortho-photo base of the specific microlocation where the analysis is conducted.

In this particular case, consideration was given to the fact that the marking of horizontal traffic marks follows standards specifying that the width of each white field is 0.5 meters, and the gaps between the fields are also 0.5 meters. An analysis of the ortho-photo of the accident scene confirmed that the pedestrian crossing where the traffic accident occurred adheres to the standard width of 4.0 meters.

By dividing the video of the traffic accident into individual frames, it was determined that the recording was made at a frame rate of 15 frames per second (fps).

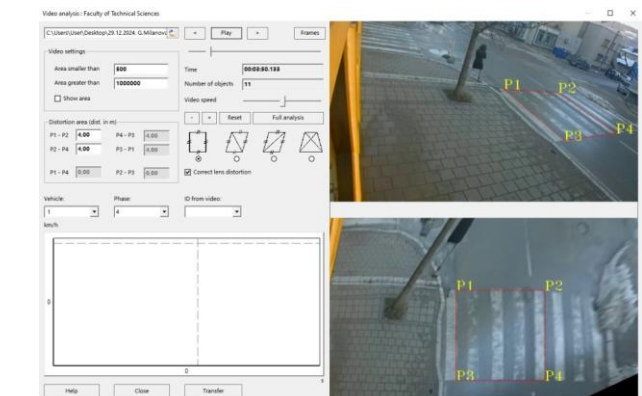


**Fig. 8, 9** Positions of vehicles and pedestrian in relation to the edges of the marked pedestrian crossing

By analyzing the video frame by frame, it was determined that the vehicle under analysis crossed the pedestrian crossing within 9 frames, equivalent to 0.6 seconds. Based on this, the vehicle's speed at the moment of impact with the pedestrian was calculated to be 24 km/h.

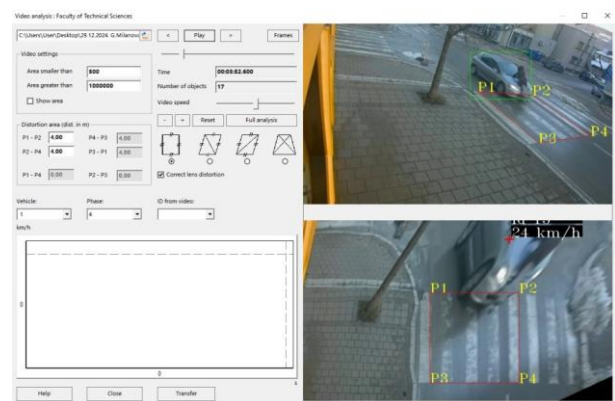
#### 3.1. Application of the Video Analysis Module in the AnalyzerPro Software: A Case Study

The first step in analyzing the traffic accident using the AnalyzerPro software is to identify orthogonal forms visible in the video, whose relative dimensions can be determined either directly or indirectly. In this case, the width of the pedestrian crossing, measured at 4 meters, was obtained from the ortho-photo view of the accident scene. Using the standard dimensions of pedestrian crossing markings on the roadway, an orthogonal projection of the accident scene was created, based on a 4.0 by 4.0 meter reference area.



**Fig. 10** Basic and rectified views of the accident scene at the moment the pedestrian enters the roadway, displayed within the AnalyzerPro software environment

By activating the "play" command, the procedure for determining vehicle speeds based on the rectified video is initiated. The display then shows the speeds of the vehicles present in the video, each identified by a unique serial number (ID).



**Fig. 11** Relationship between the video frame and its rectified output with the recorded vehicle speed

As part of the analysis of this accident, in the AnalyzerPro program, the pedestrian was not detected as a moving object, so his speed could not be determined.

3.2. Application of the Video Analysis Module in the PC-Crash Software: A Case Study

After setting up the ortho-photo of the accident scene, the camera parameters used to capture the video were optimized as part of the video analysis. Since the video was not recorded from an orthogonal perspective but rather from a three-dimensional viewpoint, determining the exact position and parameters of the camera is a highly complex task. Consequently, only an approximate match can be achieved, allowing for the estimation, rather than the precise determination of the vehicle’s speed at the moment under analysis.



Fig. 12, 13 Comparison of the pedestrian’s position based on video frames and the reconstructed position in the PC-Crash software

In this specific event, two moving objects were identified: a vehicle, assigned the identification number ID9, and a pedestrian, assigned ID7.

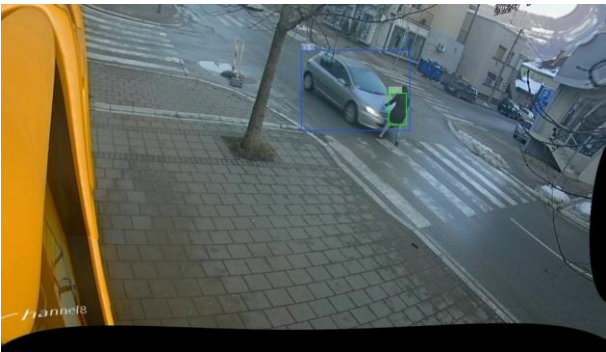


Fig. 14 Moment and location of contact with identification numbers of accident participants (PC-Crash 15.0)

The analysis determined that the vehicle’s impact speed at the moment of collision was between 18 and 20 km/h.



Fig. 15 Vehicle speed diagram determined by video analysis in PC-Crash software

In the video analysis conducted using the PC-Crash software, the pedestrian was detected as a moving object, with a crossing speed of approximately 5 km/h. This speed aligns with normal

walking mode, which was consistent with the conditions of the analyzed traffic accident.

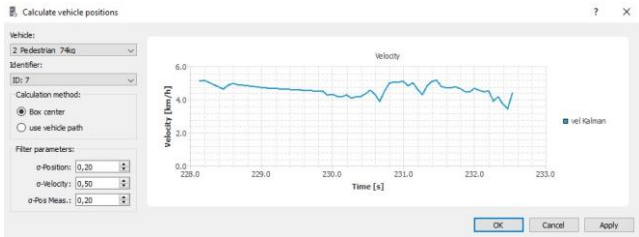


Fig. 16 Pedestrian speed diagram determined by video analysis in the PC Crash software

3. Conclusion

The use of CCTV (Closed-Circuit Television) recordings in traffic accident analysis is becoming increasingly common due to the numerous advantages they offer in accurately and efficiently reconstructing events. Unlike witness statements, which can be subjective, video recordings provide a credible and unbiased account of the accident.

Camera recordings provide clear insight into the sequence of events before, during, and immediately after an accident. Advances in AI and ML have made it possible to recognize moving objects in videos, allowing for the analysis of factors such as vehicle speed, signaling, and driver and pedestrian behavior.

Newer versions of software packages for traffic accident reconstruction and simulation, such as AnalyzerPro and PC-Crash, include video analysis modules. These modules can be used to determine the kinematic parameters of accident participants, primarily focusing on their speeds.

The video analysis module in the AnalyzerPro software package detects moving objects using AI, based on photogrammetry principles. This involves creating a rectified orthogonal representation of the surface captured in the video, using clearly identifiable reference points with known distances between them.

Within the PC-Crash, the video analysis module also relies on ML and moving object recognition. However, it is based on establishing the correspondence between the camera’s position during the video recording and its position on the ortho-photo base of the accident scene, sourced from geoportals.

In research conducted under controlled conditions, where the camera parameters were known, the deviations between the actual and measured vehicle speeds on the virtual surface were minimal when using both software packages.

In the case study of a real traffic accident, the vehicle’s speed was initially analyzed using clear CCTV record by dividing the video into frames and relating their duration to the length of a characteristic section the vehicle crossed, in this case, a pedestrian crossing.

The vehicle speed determined by the AnalyzerPro software closely matched the speed obtained through analytical video analysis.

Defining the position of the camera from which the video was recorded is fundamental for establishing correspondence between the ortho-photo—sourced from geoportals—and the traffic accident video within the PC-Crash software. In controlled research conditions, where the camera’s position and parameters were known, the vehicle speed determined by this software closely matched the actual measured values. However, in the analysis of a real traffic accident, accurately establishing the camera’s position relative to the ortho-photo base proved very challenging. This difficulty primarily stems from the ortho-photo’s resolution, which

hinders the identification of characteristic points necessary to align the images. Consequently, a reliable determination of the vehicle's speed using video analysis in PC-Crash was not possible in this case. Nonetheless, future versions of video analysis tools for traffic accidents are expected to offer improved reliability and precision.

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# Energy and exergy analyses of gas turbine set and its components

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**Abstract:** This paper presents energy and exergy analysis results of whole gas turbine set and all its components. From the energy viewpoint, combustion chamber has the lowest energy loss (21.31 MW) and the highest energy efficiency (97.20%) of all gas turbine set components. Exergy analysis shows totally opposite trend in comparison to the energy analysis. From the exergy viewpoint, turbocompressor and turbine have low exergy destruction (both around 12 MW) and very high exergy efficiencies (92.43% for turbocompressor and 96.12% for turbine) at the base ambient state. Simultaneously, at the base ambient state combustion chamber has an exergy destruction of 159 MW and low exergy efficiency of 73.29% only. The combustion chamber is the most sensitive to the ambient temperature change of all components from the gas turbine set – the ambient temperature change of 10 °C will result with combustion chamber exergy efficiency change of approximately 0.67%. Whole gas turbine set (plant) has an energy efficiency of 34.40% and exergy efficiency of 33.08%.

**KEYWORDS:** ENERGY ANALYSIS, EXERGY ANALYSIS, GAS TURBINE SET, COMPONENTS, THE AMBIENT TEMPERATURE CHANGE

## 1. Introduction

Gas turbine sets are nowadays widely used in various aspects of human life. They can be used as mechanical power producers in many power plants [1, 2], they have application in marine power systems [3, 4] and they are the dominant propulsors of various passenger airplanes [5]. Internal combustion engines today dominantly uses turbocharging processes and in that process turbochargers are actually special variant of a gas turbine set [6, 7].

Gas turbine set can be an open cycle and closed cycle [8]. In open cycle gas turbine set, turbocompressor and turbine have a direct connection to the environment (air is taken from the environment and combustion gas is released to the environment) [9]. In closed cycle gas turbine set, there is no any connection to the environment (inside closed cycle gas turbine set circulate always the same gas which did not have any connection to the environment) [10].

Base gas turbine set consists of one turbocompressor, combustion chambers and one gas turbine. However, in practical exploitation can be found various complex gas turbine sets with many improvements and modifications [11, 12].

In this paper is analyzed industrial base gas turbine set (and all its components) from the energy and exergy viewpoint. It was interesting to observe which differences in the dominant conclusions offer both types of the analyses, because applied energy and exergy analyses consider a different kind of losses. Exergy analysis of all gas turbine set components is performed at the base ambient state and during the ambient temperature change, so it is investigated and presented which component is the most sensitive to the ambient temperature change.

## 2. Description of the analyzed gas turbine set

General and simplified scheme of the analyzed gas turbine set along with operating points required for the energy and exergy analyses is presented in Fig. 1. Gas turbine set presented in Fig. 1 is a constituent component of the combined cycle power plant [13]. In this paper, gas turbine set will be observed independently of all other components and systems from the combined cycle power plant.

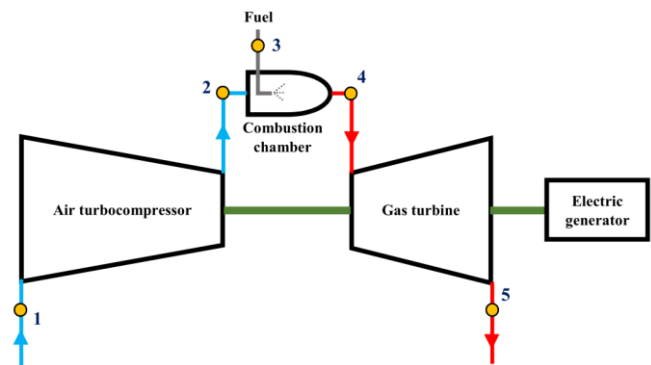
Observed gas turbine set consists of three components: air turbocompressor, combustion chamber and gas turbine.

Air turbocompressor takes air from the environment (operating point 1, Fig. 1), increases its pressure (and simultaneously increases its temperature) and delivers compressed air to the combustion chamber (operating point 2, Fig. 1). In the combustion chamber air from the turbocompressor is mixed with fuel (used fuel is natural gas, operating point 3, Fig. 1), fuel and air mixture burns and combustion gas obtained at the combustion chamber outlet is delivered to the gas turbine (operating point 4, Fig. 1). It should be highlighted that analyzed gas turbine set has several combustion chambers – in Fig. 1 is presented only one due to simplicity, while the operating parameters related to the combustion chambers and used in the calculations are taken for all combustion chambers because each combustion chamber operates with the same mass

flow rates, pressures and temperatures. Produced combustion gas in the combustion chamber is delivered to the gas turbine through which it expands. After expansion in the turbine, remaining combustion gas is delivered to the environment through turbine exhaust (operating point 5, Fig. 1).

The first function of the gas turbine in any gas turbine set is to produce sufficient mechanical power and deliver it through the shaft for the turbocompressor drive, while remaining mechanical power produced in the gas turbine (useful mechanical power) which is not used for the turbocompressor drive, is used for the drive of any other mechanical power consumer [14]. In the analyzed gas turbine set, useful mechanical power is applied for the electric generator drive.

Gas turbine set analyzed in this paper is very similar to many other industrial gas turbine sets [15].



**Fig. 1.** General scheme of the analyzed gas turbine set along with marked operating points required for the energy and exergy analyses

Observing all components from the analyzed gas turbine set (gas turbine set is considered as the entire plant), it should be explained how the energy and exergy analyses are performed.

Exergy analysis of each component (turbocompressor, combustion chamber and turbine) is performed by using operating parameters from real exploitation process which are found in the literature [13]. Therefore, in the exergy analysis are considered real (polytropic) air compression process in the turbocompressor and real (polytropic) combustion gas expansion process in the turbine. Actually, exergy analysis of the whole gas turbine set and each its component consider fluid operating parameters from the real exploitation conditions only.

Energy analysis of each component from the observed gas turbine set is performed by using some simplifications. For the combustion chamber, energy analysis is performed in the standard way (combustion chamber is considered as mixing heat exchanger).

For the turbocompressor and turbine, isentropic analysis is considered as energy analysis. For both turbocompressor and turbine energy (isentropic) analysis is performed by comparison of

the real (polytropic) and ideal (isentropic) air compression and combustion gas expansion processes, Fig. 2.

Real (polytropic) air pressure increase process in turbocompressor (process between operating points 1 and 2, Fig. 2 (a)) is characterized by the increase in air specific entropy. Increase in the air specific entropy represents losses which occur in the turbocompressor stages. Ideal (isentropic) air pressure increase process in turbocompressor (process between operating points 1 and 2s, Fig. 2 (a)) did not consider any losses in turbocompressor, so air specific entropy remains the same during the ideal pressure increase process. In both turbocompressor processes (ideal and real) inlet and outlet air pressures are the same. Turbocompressor is mechanical power consumer, so in the ideal (isentropic) air pressure increase process, turbocompressor will consume the lowest possible mechanical power, while in the real (polytropic) air pressure increase process turbocompressor will consume higher mechanical power in comparison to the ideal process (due to losses consideration).

Real (polytropic) combustion gas expansion process in turbine (process between operating points 4 and 5, Fig. 2 (b)) is characterized by the increase in combustion gas specific entropy. Increase in the combustion gas specific entropy represents losses which occur in the turbine stages. Ideal (isentropic) combustion gas expansion process (process between operating points 4 and 5s, Fig. 2 (b)) did not consider any losses in the turbine, so combustion gas specific entropy remains the same during the ideal expansion process. In both turbine processes (ideal and real) inlet and outlet combustion gas pressures are the same. Turbine is a mechanical power producer, so in the ideal (isentropic) expansion process, turbine will produce the highest possible mechanical power, while in the real (polytropic) expansion process turbine will produce lower mechanical power in comparison to the ideal process (due to losses).

Operating points of the turbocompressor and turbine presented in both Fig. 2 parts are consistent with operating points from Fig. 1.

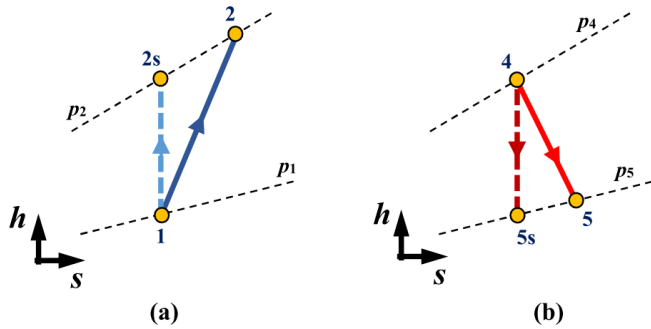


Fig. 2. Ideal (isentropic) and real (polytropic) compression processes of air turbocompressor (a) and expansion process of gas turbine (b) required for the energy analysis

### 3. Energy and exergy analyses equations

The main difference between energy (isentropic) and exergy analyses is that energy (isentropic) analysis did not consider the parameters of the ambient (ambient pressure and temperature) inside which observed component or system operates [16], while exergy analysis considers that ambient parameters [17]. This means that variation of the ambient parameters (especially variation of the ambient temperature) can have a notable influence on the exergy analysis results of any system or component [18].

Both energy (isentropic) and exergy analyses are “black box” methods because they did not consider the inner structure of neither one observed component [19]. Energy (isentropic) and exergy analyses equations of the components and whole gas turbine set are defined according to the literature [10, 14] and by using operating points presented in Fig. 1 and Fig. 2.

#### 3.1. Energy analysis equations of the components and whole gas turbine set

**Turbocompressor** energy loss and energy efficiency:

$$En_{Loss,TC} = P_{re,TC} - P_{id,TC} = \dot{m}_1 \cdot (h_2 - h_1) - \dot{m}_1 \cdot (h_{2s} - h_1), \quad (1)$$

$$\eta_{En,TC} = \frac{P_{id,TC}}{P_{re,TC}}, \quad (2)$$

where  $P$  is mechanical power, re is an index of real (polytropic) process, id is an index of ideal (isentropic) process,  $\dot{m}$  is fluid mass flow rate,  $h$  is fluid specific enthalpy,  $\eta$  is efficiency, En is marking for the energy analysis and TC is an abbreviation of turbocompressor. These markings remain the same also in other equations which follow below.

**Combustion chamber** energy loss and energy efficiency:

$$En_{Loss,CC} = \dot{m}_2 \cdot h_2 + \dot{m}_3 \cdot LHV - \dot{m}_4 \cdot h_4, \quad (3)$$

$$\eta_{En,CC} = \frac{\dot{m}_4 \cdot h_4}{\dot{m}_2 \cdot h_2 + \dot{m}_3 \cdot LHV}, \quad (4)$$

where LHV is used fuel (natural gas) Lower Heating Value and CC is an abbreviation of combustion chamber.

**Turbine** energy loss and energy efficiency:

$$En_{Loss,TUR} = P_{d,TUR} - P_{re,TUR} = \dot{m}_4 \cdot (h_4 - h_{5s}) - \dot{m}_4 \cdot (h_4 - h_5), \quad (5)$$

$$\eta_{En,TUR} = \frac{P_{re,TUR}}{P_{d,TUR}}, \quad (6)$$

where TUR is an abbreviation of turbine. Whole gas turbine set (plant) energy efficiency is:

$$\eta_{En,Plant} = \frac{P_{re,TUR} - P_{re,TC}}{\dot{m}_3 \cdot LHV}. \quad (7)$$

#### 3.2. Exergy analysis equations of the components and whole gas turbine set

**Turbocompressor** exergy destruction and exergy efficiency:

$$Ex_{Des,TC} = \dot{m}_1 \cdot \varepsilon_1 + P_{re,TC} - \dot{m}_2 \cdot \varepsilon_2, \quad (8)$$

$$\eta_{Ex,TC} = \frac{\dot{m}_2 \cdot \varepsilon_2 - \dot{m}_1 \cdot \varepsilon_1}{P_{re,TC}}, \quad (9)$$

where  $\varepsilon$  is fluid specific exergy and Ex is marking for the exergy analysis. These markings remain the same also in other equations which follow below.

**Combustion chamber** exergy destruction and exergy efficiency:

$$Ex_{Des,CC} = \dot{m}_2 \cdot \varepsilon_2 + \dot{m}_3 \cdot LHV \cdot EC - \dot{m}_4 \cdot \varepsilon_4, \quad (10)$$

$$\eta_{Ex,CC} = \frac{\dot{m}_4 \cdot \varepsilon_4}{\dot{m}_2 \cdot \varepsilon_2 + \dot{m}_3 \cdot LHV \cdot EC}, \quad (11)$$

where EC is an exergy coefficient, which is equal to 1.04 for natural gas [20] based on the lower heating value.

**Turbine** exergy destruction and exergy efficiency:

$$Ex_{Des,TUR} = \dot{m}_4 \cdot \varepsilon_4 - \dot{m}_5 \cdot \varepsilon_5 - P_{re,TUR}, \quad (12)$$

$$\eta_{Ex,TUR} = \frac{P_{re,TUR}}{\dot{m}_4 \cdot \varepsilon_4 - \dot{m}_5 \cdot \varepsilon_5}. \quad (13)$$

Whole gas turbine set (plant) exergy efficiency is:

$$\eta_{Ex,Plant} = \frac{P_{re,TUR} - P_{re,TC}}{\dot{m}_3 \cdot LHV \cdot EC}. \quad (14)$$

### 4. Air and combustion gas operating parameters required in the energy (isentropic) and exergy analyses

Operating parameters of air and combustion gas for the real (polytropic) process are found in [13] and presented in Table 1. These operating parameters are fluid temperature, pressure and mass flow rate. Other fluid operating parameters presented in Table 1 are calculated by using NIST-REFPROP 9.0 software [21].

Combustion chamber of the analyzed gas turbine set uses natural gas as a fuel (natural gas LHV is presented in Table 1).

Ideal (isentropic) compression and expansion processes assume always the same fluid specific entropy, while retaining the same pressures and mass flow rates as in the real (polytropic) processes. Isentropic specific enthalpies for ideal compression and expansion processes are presented in Table 2.

Exergy analysis of any system or component requires definition of the base ambient state [22]. In this paper, the base ambient state is defined by the ambient temperature of 25 °C and ambient pressure of 1 bar.

**Table 1.** Air and combustion gas operating parameters for the real (polytropic) process

| O. P.* | Temp. (°C) | Pressure (bar) | Mass flow rate (kg/s) | Specific enthalpy (kJ/kg) | Specific entropy (kJ/kg·K) |
|--------|------------|----------------|-----------------------|---------------------------|----------------------------|
| 1      | 25.0       | 1.01           | 402.4                 | 424.44                    | 3.8826                     |
| 2      | 402.6      | 13.25          | 402.4                 | 813.83                    | 3.9815                     |
| 3      | -          | -              | 9.1                   | 47574.00**                | -                          |
| 4      | 1254.0     | 12.59          | 411.5                 | 1796.10                   | 4.9289                     |
| 5      | 621.5      | 1.01           | 411.5                 | 1053.40                   | 5.0295                     |

\* O. P. = Operating Point (in accordance to Fig. 1 and Fig. 2)

\*\* Fuel LHV (Lower Heating Value)

**Table 2.** Air and combustion gas operating parameters for the ideal (isentropic) process

| O. P.* | Pressure (bar) | Mass flow rate (kg/s) | Specific entropy (kJ/kg·K) | Isentropic specific enthalpy (kJ/kg) |
|--------|----------------|-----------------------|----------------------------|--------------------------------------|
| 1      | 1.01           | 402.4                 | 3.8826                     | 424.44                               |
| 2      | 13.25          | 402.4                 | 3.8826                     | 750.01                               |
| 3      | -              | 9.1                   | -                          | -                                    |
| 4      | 12.59          | 411.5                 | 4.9289                     | 1796.10                              |
| 5      | 1.01           | 411.5                 | 4.9289                     | 967.31                               |

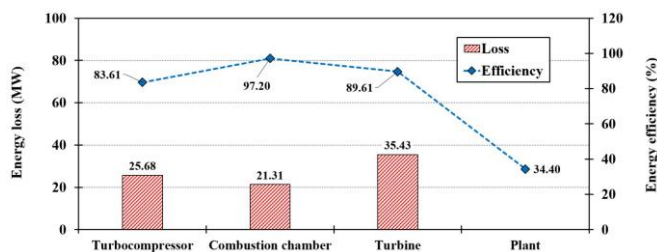
\* O. P. = Operating Point (in accordance to Fig. 1 and Fig. 2)

## 5. Results and discussion

The results of energy (isentropic) analysis of all components and whole gas turbine set (plant) are presented in Fig. 3.

From the energy viewpoint, combustion chamber has the lowest energy loss of all components (21.31 MW), lower than turbocompressor and turbine, while the turbine has the highest energy loss (35.43 MW). Observing energy efficiency, the highest one is obtained for the combustion chamber (97.20%) of all components, what led to conclusion that the combustion chamber is almost ideal from the energy viewpoint. Turbine has higher energy efficiency in comparison to turbocompressor (89.61% in comparison to 83.61%), regardless of the higher energy loss. Finally, observing all the components in the gas turbine set, it can be concluded that all of them are highly efficient, while the combustion chamber is close to the ideal from the energy viewpoint.

Whole gas turbine set (plant) has an energy efficiency of 34.40%, what is in the range of similar comparable gas turbine sets from the available literature [23]. In addition, useful mechanical power produced by the gas turbine set, which is used for the electric generator drive is equal to 148.93 MW.

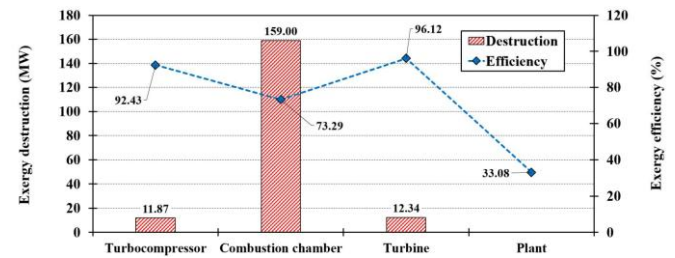


**Fig. 3.** Energy (isentropic) analysis results of all components and gas turbine set (plant)

Exergy analysis results of all components and whole gas turbine set (plant) at the base ambient state show some notably different conclusions and trends in comparison to the energy analysis results, Fig. 4.

From the exergy viewpoint, turbocompressor and turbine have low exergy destruction (both around 12 MW) and very high exergy efficiencies (turbocompressor exergy efficiency is 92.43% and turbine exergy efficiency is 96.12%). Simultaneously, combustion chamber is the component which shows the worst performance from the exergy viewpoint of all gas turbine set components. Combustion chamber has an exergy destruction of 159 MW what is notably higher in comparison to both turbocompressor and turbine as well as notably lower exergy efficiency than turbocompressor and turbine (combustion chamber exergy efficiency is 73.29% only), Fig. 4. The same conclusions obtained in this analysis can be found in the literature – from the exergy viewpoint, combustion chamber is the holder of the highest exergy destruction and the lowest exergy efficiency in the entire gas turbine set [23]. Therefore, regardless of extraordinary energy performance, combustion chamber shows the worst performance in the entire gas turbine set when the parameters of the ambient are taken in the consideration.

Whole gas turbine set (plant) has exergy efficiency of 33.08% at the base ambient state, what is also in range of other comparable gas turbine sets from the literature [23]. Moreover, it can be clearly seen through a comparison of Fig. 3 and Fig. 4 that due to the additional losses, exergy efficiency of the whole gas turbine set (plant) is lower in comparison to plant energy efficiency.

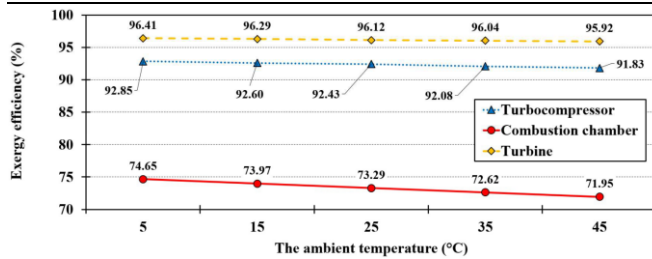


**Fig. 4.** Exergy analysis results of all components and gas turbine set (plant) at the base ambient state

This analysis also involves observation of the gas turbine set components during the ambient temperature change. Components are observed in the ambient temperature range from 5 °C up to 45 °C in steps of 10 °C, Fig. 5, while the ambient pressure remains the same as at the base state at any ambient temperature. In real gas turbine set exploitation, the ambient pressure change is small and it did not have a notable influence on any component exergy parameters.

It should be highlighted that the ambient temperature increase simultaneously increases exergy destruction and decreases exergy efficiency of all components from the analyzed gas turbine set. From the ambient temperature viewpoint, for all gas turbine set components will be the most beneficial to operate at the lowest possible ambient temperature.

Observing exergy efficiencies of all gas turbine set components, Fig. 5, it can be concluded that the combustion chamber is the most sensitive to the ambient temperature change – ambient temperature change of 10 °C will result with combustion chamber exergy efficiency change of approximately 0.67%. Simultaneously, turbine is the component from the observed gas turbine set which exergy efficiency is the lowest influenced by the ambient temperature change – ambient temperature change of 10 °C will result with turbine exergy efficiency change of approximately 0.12%.



**Fig. 5.** Exergy analysis results of gas turbine set components during the ambient temperature change

Further research related to the gas turbine set and all its components will be based on the usage of various artificial intelligence methods and processes which have many interesting applications in the energy sector [24-26].

## 6. Conclusions

This paper presents energy and exergy analyses of gas turbine set and all its components. Exergy analysis is performed at the base ambient state and during the ambient temperature variation. As energy and exergy analyses consider a different kind of losses, in each analysis are obtained different conclusions about the observed components. The most important highlights of the performed research are:

- From the energy viewpoint, combustion chamber has the lowest energy loss (21.31 MW) and the highest energy efficiency (97.20%) of all gas turbine set components.
- Observing all the components in the gas turbine set, it can be concluded that all of them are highly efficient, while the combustion chamber is close to the ideal from the energy viewpoint.
- From the exergy viewpoint, turbocompressor and turbine have low exergy destruction (both around 12 MW) and very high exergy efficiencies (turbocompressor exergy efficiency is 92.43% and turbine exergy efficiency is 96.12%) at the base ambient state.
- Combustion chamber has an exergy destruction of 159 MW as well as notably lower exergy efficiency than turbocompressor and turbine (combustion chamber exergy efficiency is 73.29% only) at the base ambient state. From the exergy viewpoint, combustion chamber is the holder of the highest exergy destruction and the lowest exergy efficiency in the entire gas turbine set.
- The combustion chamber is the most sensitive to the ambient temperature change of all components from the gas turbine set – the ambient temperature change of 10 °C will result with combustion chamber exergy efficiency change of approximately 0.67%. Simultaneously, turbine is the component from the observed gas turbine set which exergy efficiency is the lowest influenced by the ambient temperature change – ambient temperature change of 10 °C will result with turbine exergy efficiency change of approximately 0.12%.
- Whole gas turbine set (plant) has an energy efficiency of 34.40% and exergy efficiency of 33.08%, what is in the range of similar comparable gas turbine sets from the literature.

## 7. Acknowledgment

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