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OPTIMISATION OF THE CONDUCTIVE MATERIALS DEVELOPMENT FOR SENSORS AND EM SHIELDING

RALUCA MARIA AILENI, ADRIAN CORNEL MARIN, ION RĂZVAN RĂDULESCU, CEZAR LUPESCU

The National Research and Development Institute for Textiles and Leather (INCDTP), 16 Lucretiu Patrascanu St., 030508, Bucharest, Romania, raluca.aileni@incdtp.ro

The paper presents aspects of optimising textile materials for flexible electronics (actuators and sensors) and electromagnetic screens. The optimisation of electroconductive materials for sensors, actuators or materials for electromagnetic shielding has a common denominator: electrical resistance. This electrical resistance must be minimal to increase electrical conductivity for the textile materials used as electroconductive materials for sensors and actuators, respectively, as a screen for the attenuation of electromagnetic radiation. In order to allow the optimal selection of electroconductive fabrics for actuators, sensors or flexible electromagnetic screens for a specific application, certain performance characteristics such as flexibility, low mass, air permeability and low cost are required. For the analysed cases (resistive sensors, actuators depending on the electrical resistance fluctuation such as shape memory alloy, materials for electromagnetic shielding), the optimisation is based on a function to minimise the electric resistance variable to increase the conductivity and effectiveness of the electromagnetic shielding. To select and classify suitable electroconductive fabrics for sensors, actuators, and electromagnetic shields, we used the receiver operating characteristic (ROC) curve to represent the performance of the binary classification model. We also calculated the area under the curve (AUC) for the Rs training set, representing the ROC's integral. The higher AUC values for training (0.8333 and 0.9545) indicated excellent performance of the classifier. We were able to optimize the influential parameters for electromagnetic shielding (SE) to target a value of 50 dB for a fabric with a thickness of 0.46 mm, mass of 87.8795 g/m^2, air permeability of 9090 l/m^2/s, and electrical resistance of 20 Ω.

Keywords: optimisation, conductive, textile.

INTRODUCTION

Researchers meticulously select the most suitable materials and techniques used in electronic textiles to create fabric sensors. The sensing functionality can be ingeniously tailored through intrinsic and extrinsic modifications to textile substrates, depending on the degree of integration into the fabric platform. These sensors accurately measure force, pressure, chemicals, humidity, and temperature variations (Castano & Flatau, 2014).

Manufacturing textile-based sensors involves using a silicone-textile composite resistive strain sensor, which relies on a conductive textile encapsulated into a dual silicone rubber layer. This innovative sensor design allows recording chest wall expansion during respiratory activity and precisely capturing elbow flexion/extension movements (Di Tocco *et al*., 2022). Moreover, the incorporation of organic conductive polymers such as polypyrrole (PPy) for coating textile materials in order to achieve significant strain sensing capabilities is founded on the creation of a conductive textile exhibiting exceptional sensing performance, including low electrical resistance, high strain sensitivity, and environmental sustainability (Raman & Ravi Sankar, 2022).

The optimisation of electroconductive materials for various applications, such as sensors, actuators, and materials for electromagnetic shielding, is crucial for improving their performance. One of the critical factors in this optimisation process is the electrical resistance

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of these materials. It is essential to minimise the electrical resistance to increase the electrical conductivity of textile materials used in sensors, actuators, and electromagnetic shielding applications. This enhanced conductivity improves performance in these devices, making them more effective in their respective roles. In order to select the optimal materials for specific applications, it is essential to consider various performance characteristics such as flexibility, low mass, air permeability, and cost-effectiveness. These attributes are significant in determining the suitability of materials for use in sensors, actuators, and electromagnetic shielding applications. For instance, resistive sensors and actuators that rely on the fluctuation of electrical resistance, such as shape memory alloys, require careful optimisation to ensure optimal performance. Similarly, materials used for electromagnetic shielding must be optimised to minimise electrical resistance and enhance their effectiveness in attenuating electromagnetic radiation.

In electrical material engineering, optimization involves the intricate and detailed process of carefully adjusting the electrical resistance of materials. This adjustment is essential to ensure the materials demonstrate the specific conductivity or semiconductor characteristics required for their intended applications (sensors, actuators or electromagnetic (EM) shields). These properties are crucial for the efficient functioning of electrodes in a wide range of sensors and actuators. Optimization involves fine-tuning the electrical properties of the materials to achieve an optimal balance between resistance and conductivity. This balance is essential for ensuring the reliable and effective performance of the sensors, EM shields and actuators across various real-world applications and scenarios.

EXPERIMENTAL PART

The conductive fabrics analysed were obtained by electroplating polyamide yarns using electrolyte solutions based on silver, copper and aluminium. Considering the electroconductive textiles obtained, we have to make an optimal selection of the materials to be used for sensors, actuators, or electromagnetic shields.

The proposed approach started from the premise that we have to minimize the value of electrical resistance to increase the conductivity of the materials used for sensor electrodes. At the same time, for materials capable of absorbing or reflecting electromagnetic radiation, we have to increase the shielding effectiveness (SE) and as an indirect consequence, the electrical resistance should be reduced and conductivity must have high values.

In the research part, we emphasise the critical importance of minimizing electrical resistance to enhance the materials' conductivity in sensor electrode development. This involves a comprehensive analysis of the material properties (mass (M), air permeability (Pa), thickness (δ), resistance (Rs)) and structure to identify avenues for optimization by reducing the electrical resistance. Additionally, for materials capable of absorbing or reflecting electromagnetic radiation, our focus is directed towards optimizing the shielding effectiveness (SE) through a detailed investigation of the material's electromagnetic properties and the design of the shielding structure. As a result, our approach requires a thorough understanding of both electrical and electromagnetic characteristics to ensure that the electrical resistance is minimized while achieving high conductivity and the shielding effectiveness is maximized. Using data from conductive and semiconductive materials developed and having Pa in the range 38 - 9090 $l/m^2/s$, M in the range 86 - 559 g/m^2, δ in the range of 0.4 - 1.6 mm, Rs between 20 - 8.5×10^9, respective SE in the range 0.2 - 47 dB, was developed data analysis, optimization and regression equations creation for Rs and SE. The regression equations for Rs are provided for two distinct cases: electrically conductive materials (1) and dissipative materials (2). The regression equation for SE is presented as (3).

$$y = -2294 + 2868\ x_1 + 0.3963\ x_3 + 4.591\ x_2 + 3.118\ x_4 - 879.2\ x_1^2 - 0.000020\ x_3^2 + 0.001305\ x_2^2 - 0.3010\ x_4^2 - 0.2837\ x_1{*}x_3 - 1.744\ x_1{*}x_2 - 3.550\ x_1{*}x_4 - 0.000258\ x_3{*}x_2 + 0.001985\ x_3{*}x_4 \tag{1}$$

$$y = 8507585 + 2868\ x_1 + 0.3963\ x_3 + 4.591\ x_2 + 3.118\ x_4 - 879.2\ x_1^2 - 0.000020\ x_3^2 + 0.001305\ x_2^2 - 0.3010\ x_4^2 - 0.2837\ x_1{*}x_3 - 1.744\ x_1{*}x_2 - 3.550\ x_1{*}x_4 - 0.000258\ x_3{*}x_2 + 0.001985\ x_3{*}x_4 \tag{2}$$

where Electrical resistance is y; Thickness is x_1; Mass is x_2; Air permeability is x_3

$$y = -844 - 85\ x_1 + 0.1892\ x_3 + 4.93\ x_2 + 0.000017\ x_4 - 1050\ x_1^2 - 0.000011\ x_3^2 - 0.01594\ x_2^2 + 0.1107\ x_1{*}x_3 + 6.60\ x_1{*}x_2 - 0.000880\ x_3{*}x_2 \tag{3}$$

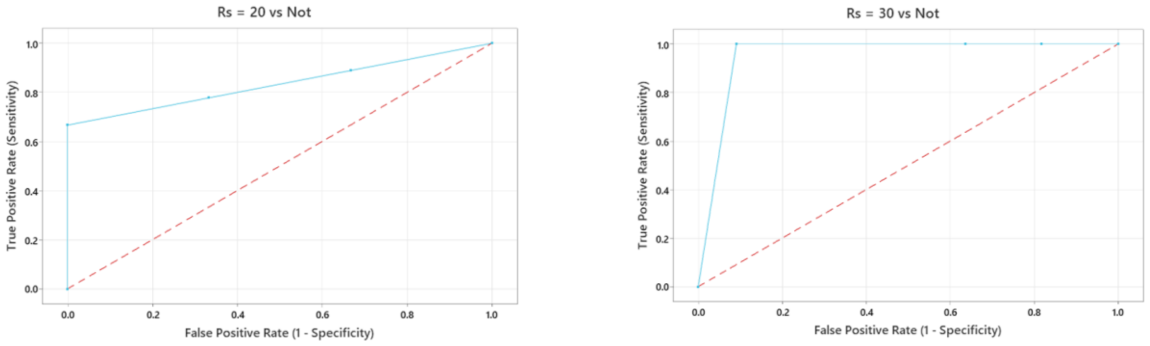
where SE is y; Thickness is x_1; Mass is x_2; Air permeability is x_3; Rs is x_4.

Table 1 presents the analysis of variance for electrical resistance for sensors.

Table 1. Analysis of Variance for Rs depending on Pa, M, SE, δ and categorical variable conductivity (C)

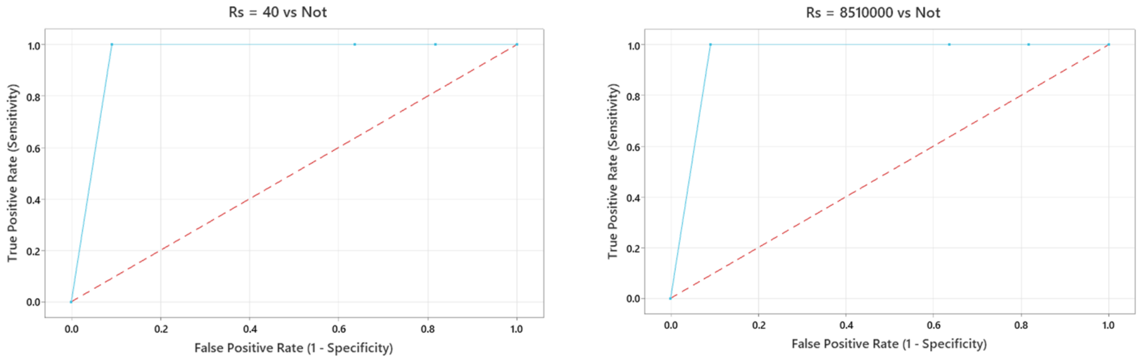
Source	DF	Adj SS	Adj MS
Model	14	1.32769E+14	9.48353E+12
Linear	5	5.66527E+12	1.13305E+12
Thickness	1	257	257
Pa	1	197	197
Mass	1	151	151
SE	1	76	76
Conductivity	1	2.61020E+11	2.61020E+11
Square	4	489	122
Thickness*Thickness	1	202	202
Pa*Pa	1	197	197
Mass*Mass	1	4	4
SE*SE	1	330	330
2-Way Interaction	5	590	118
Thickness*Pa	1	282	282
Thickness*Mass	1	149	149
Thickness*SE	1	9	9
Pa*Mass	1	69	69
Pa*SE	1	79	79
Error	9	0	0
Total	23	1.32769E+14	

The model's relationship between y and x variables is statistically significant because $p < 0.10$. The regression model explains the 99.59% variation well. The Rs model fits the data well and can be used to predict Rs for specific variables x or find the appropriate x values to obtain a specific value for Rs. Figure 1 presents the ROC (receive operating characteristic) curve, respective in Figure 2 presents the 3D representation of the electrical resistance depending on mass (M), air permeability (Pa), thickness (δ) and shielding effectiveness (SE). The ROC (Receiver Operating Characteristic) curve graphically represents the performance of the binary classification model at various threshold settings. It illustrates the trade-off between true and false positive rates across different threshold values, providing valuable insights into the model's predictive accuracy. The area under the curve (AUC) for the Rs training set is the numerical value indicating the performance of the model and represents the integral of the ROC (Tsang, 2007) and represents the ability of the model ability to classify (Choi *et al.*, 2024) classes. In our cases, the higher AUC values (AUC for training 0.8333 (a), respective 0.9545 (b, c, d)) indicate an excellent performance of the classifier.



a. Area under the curve: Training = 0.8333

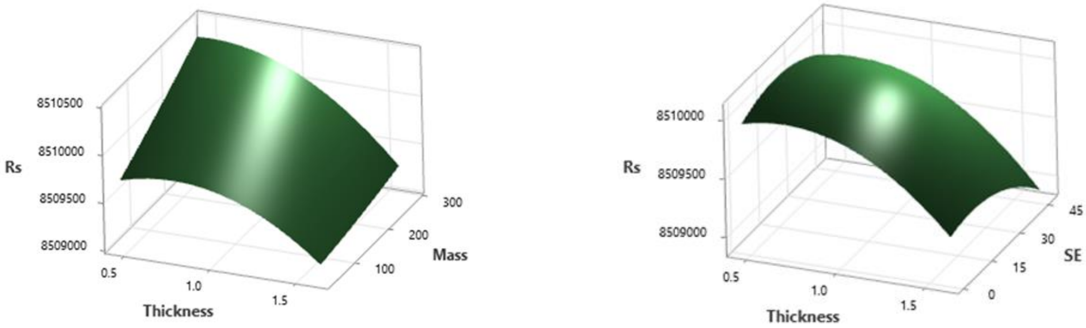
b. Area under the curve: Training = 0.9545



c. Area under the curve: Training = 0.9545

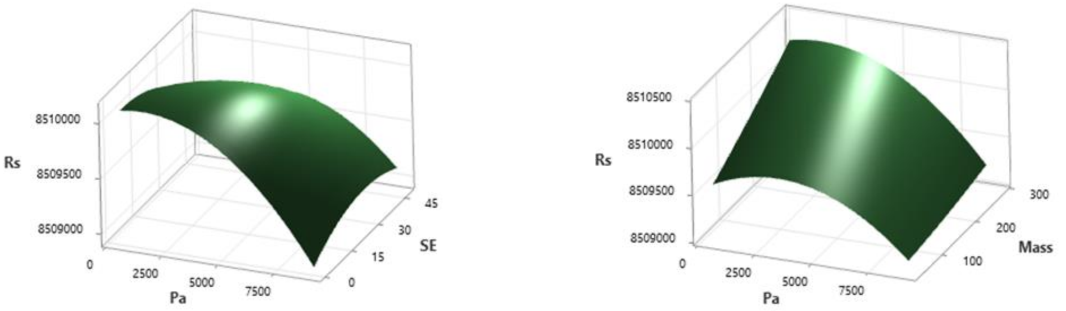
d. Area under the curve: Training = 0.9545

Figure 1. Receiver operating characteristic



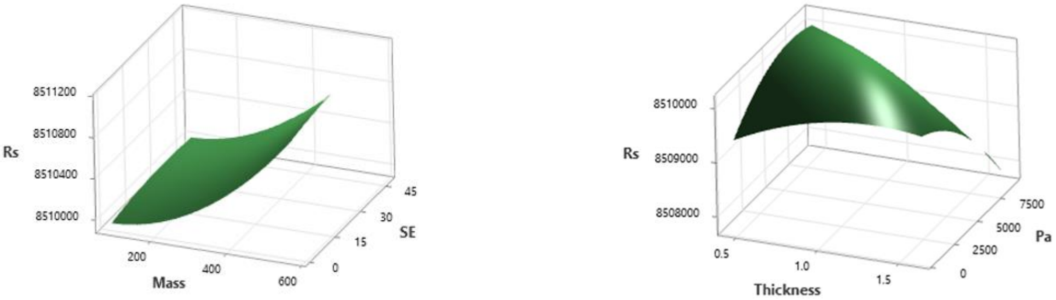
a. Rs = f(δ, M)

b. Rs = f(δ, SE)



c. Rs = f(Pa, SE)

d. Rs = f(Pa, M)



e. Rs = f(M, SE) f. Rs = f(δ, Pa)

Figure 2. Surface resistance depending on thickness (δ) and mass (a), thickness and SE (b), air permeability (Pa) and SE (c), mass (M) and air permeability (d), mass and SE (e), respective thickness and Pa (f)

Figure 3 presents the optimal tree for electrical resistance starting with root node Rs=20 Ω al following levels defined by splitting experiments with conditions related to air permeability (Pa) and electromagnetic attenuation effectiveness ((SE). The information within the terminal nodes presents a valuable opportunity to systematically rank all distinct subsets based on their respective class probabilities. This ranking process enables a nuanced understanding of the distribution of probabilities among the various subsets. The method class probability and optimal tree within 1 standard error used for node splitting to minimize misclassification costs. For validation was used the 10-fold cross-validation method (Nagaraj *et al*., 2021).

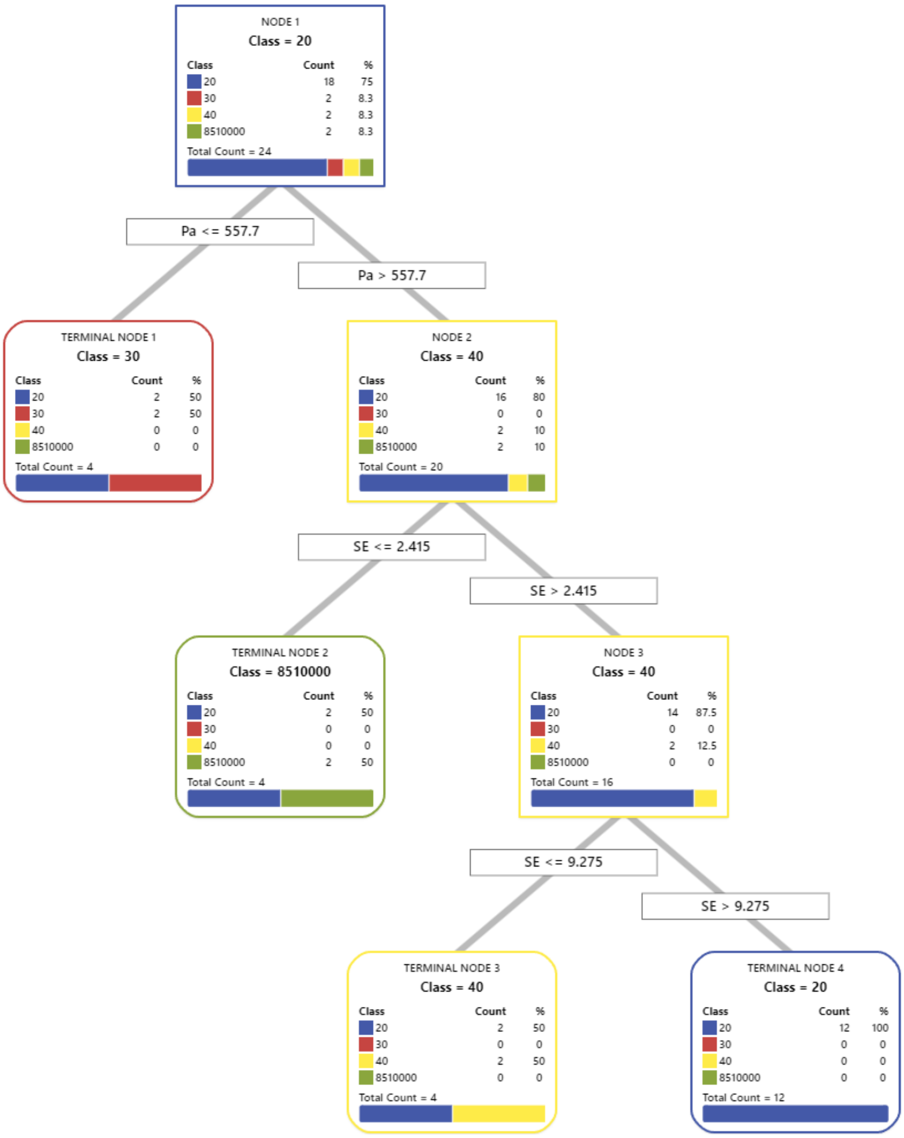


Figure 3. Optimal tree diagram

ANALYSIS AND DISCUSSIONS

The importance of the variables for model improvement is presented in Figure 4 when splits are made on a predictor. We can observe that the importance of SE is 100% and air permeability (Pa) is 86.8%.

Figure 5 presents the optimization of the SE value, targeting 50 dB for shielding effectiveness. It can be observed that this can be achieved if conductive coated materials have estimative values for thickness 0.46 mm, M 87,8795 g/m^2, Pa 9090 l/m^2/s and Rs 20 Ω.

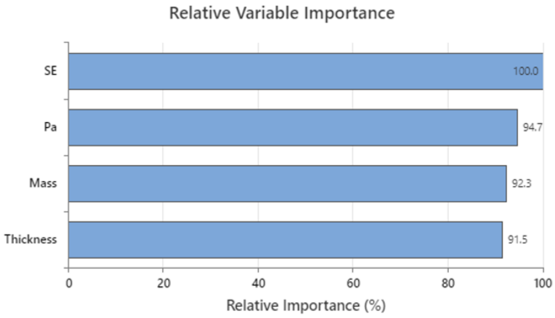


Figure 4. Variable importance measuring model optimization

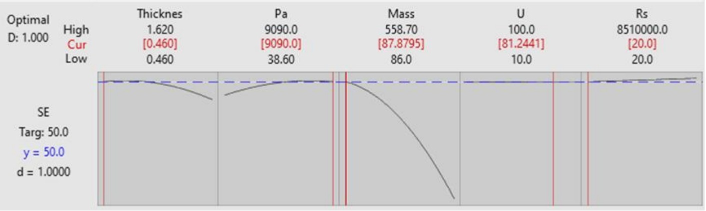


Figure 5. Shielding effectiveness optimization

CONCLUSIONS

Based on the premise that minimizing electrical resistance increases the conductivity of materials used for sensor electrodes, it can be concluded that the optimization of electrical resistance indirectly optimizes the conductivity of materials used in sensors and actuators. This process involves a comprehensive analysis of material properties such as mass (M), air permeability (Pa), thickness (δ), and resistance (Rs), as well as the structure of the materials. By identifying the appropriate path for optimization, which includes reducing the electrical resistance, it is possible to achieve maximum shielding effectiveness and conductivity values. This comprehensive approach ensures that the materials used for sensor electrodes are refined to provide the highest level of performance in terms of electrical conductivity and resistance.

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