

ACOUSTICAL CHARACTERIZATION AND STRUCTURAL OPTIMIZATION OF POROUS MATERIALS AND THEIR MIXTURES

Prof. Branko Radičević, Ph.D.
 radicevic.b@mfkv.kg.ac.rs



Faculty of Mechanical and Civil Engineering in Kraljevo
 University of Kragujevac



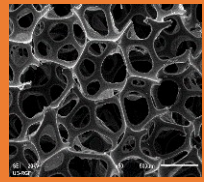
CONTENT

01



Introduction – Noise as a global problem

02



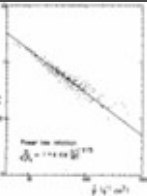
Acoustic properties of porous materials

03



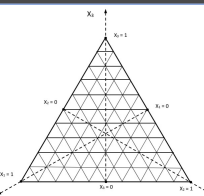
Methods for determining sound absorptions

04



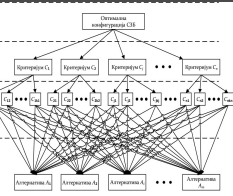
Models for predicting sound absorption

05



Determining absorption properties of mixtures

06



Multi-criteria optimization on the example of selecting sound-absorbing materials

World Health Organization (WHO) classifies noise as the
SECOND LARGEST ENVIRONMENTAL POLLUTANT
 — right after air pollution.

ASPECTS OF NOISE AS A GLOBAL PROBLEM



IMPACT ON HUMAN HEALTH

(Cardiovascular · Sleep Disturbance · Auditory Effects)



URBAN ACOUSTICS & INFRASTRUCTURE

(Traffic as Primary Source · Sound Insulation)



ECOLOGICAL IMPACT ON BIODIVERSITY

(Masking Communication · Habitat Abandonment)



MASKING
COMMUNICATION

HABITAT
ABANDONMENT

2
NOISE

WHO

1
AIR
POLLUTION



ECONOMIC COSTS



Drop in Property Values
in Noisy Areas

Healthcare Costs
for Stress & Noise-Related
Illnesses

Loss of Productivity
due to Reduced Concentration
& Fatigue



Noise pollution is a **GLOBAL CHALLENGE** affecting **HEALTH, NATURE, CITIES, and ECONOMIES** —
 demanding urgent action worldwide.

COMBATING NOISE REQUIRES A MULTIDISCIPLINARY APPROACH

1

Engineering Aspect

Noise control at the source,
Acoustical design, urban planning & architecture...
use of new porous materials &
absorption panels

3

Medical and Biological Aspect

Doctors and biologists study how noise
affects the human body and its systemic
health, ecological & social aspects

2

DEVELOPMENT AND IMPLEMENTATION OF ACOUSTIC KNOWLEDGE

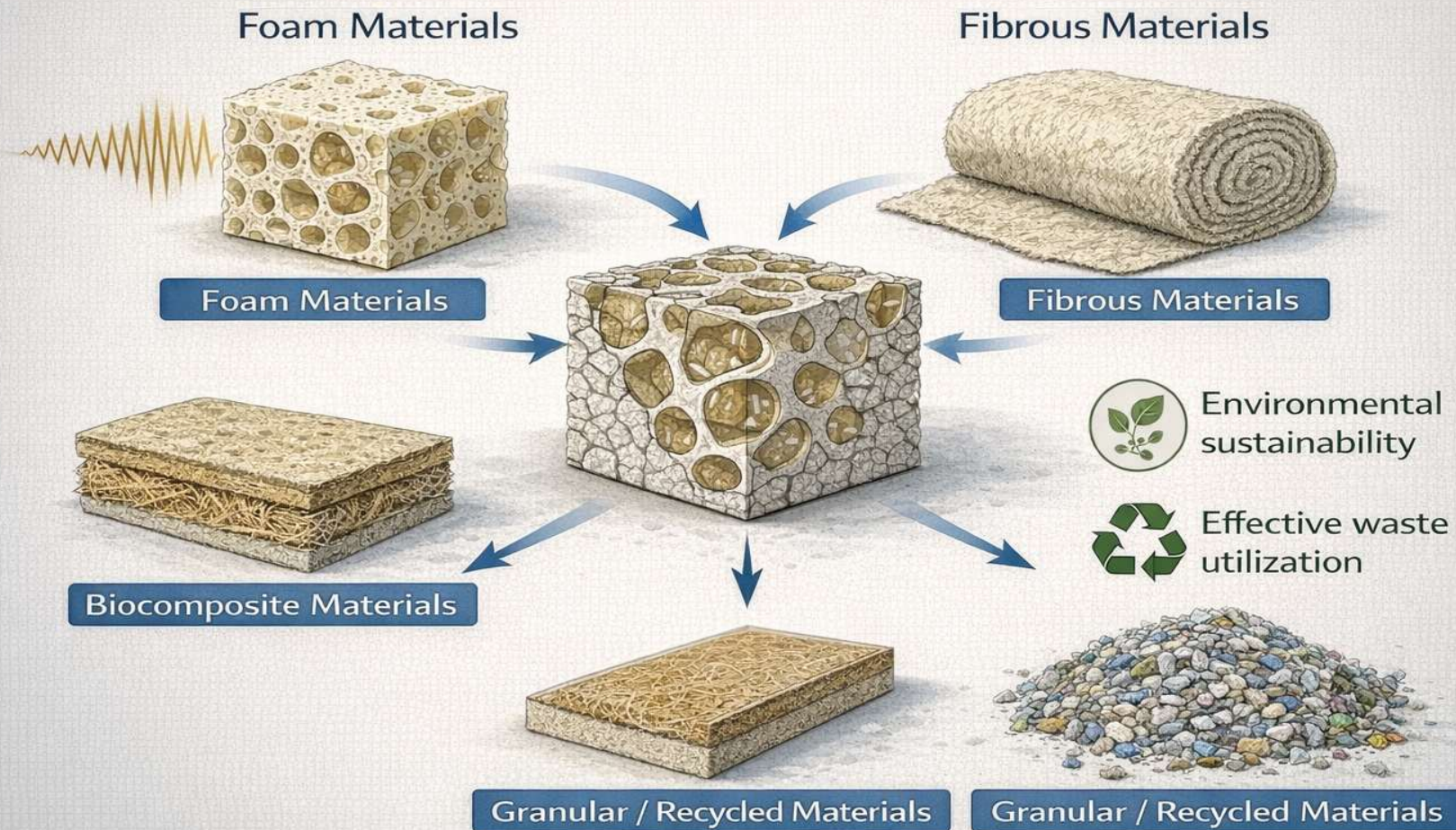
New methods, new models, inverse acoustic
characterization, multi-criteria optimization, application
of artificial intelligence, development of active noise control

4

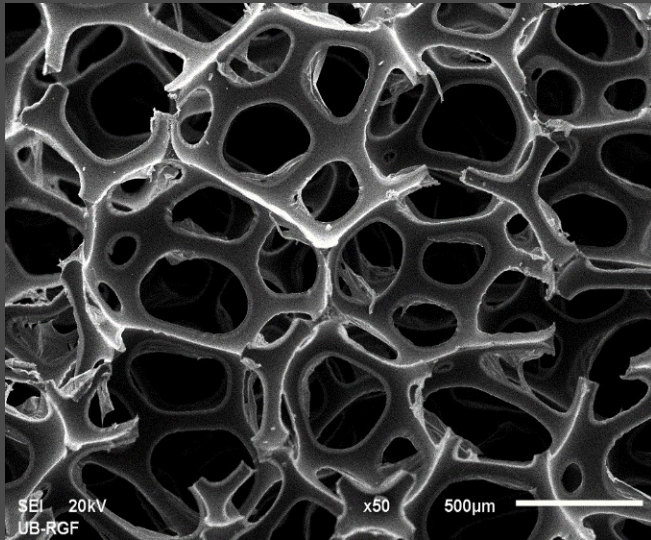
LEGAL REGULATION

Legislation, Strategic noise maps,
Inspection oversight

Types of Porous Materials

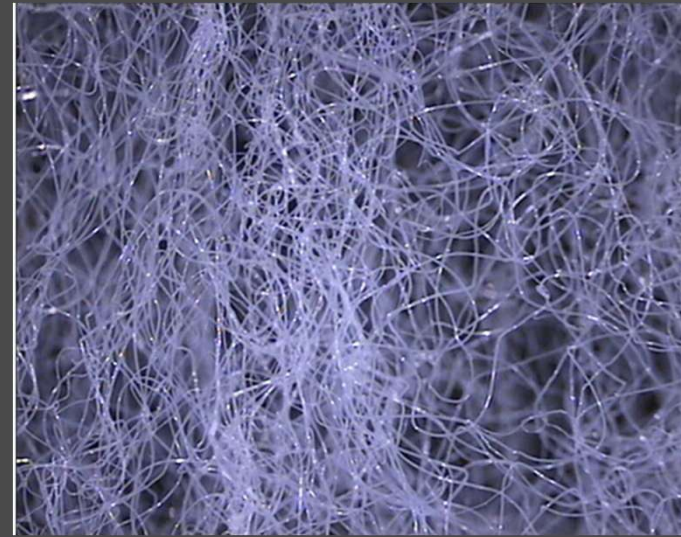


Foam materials



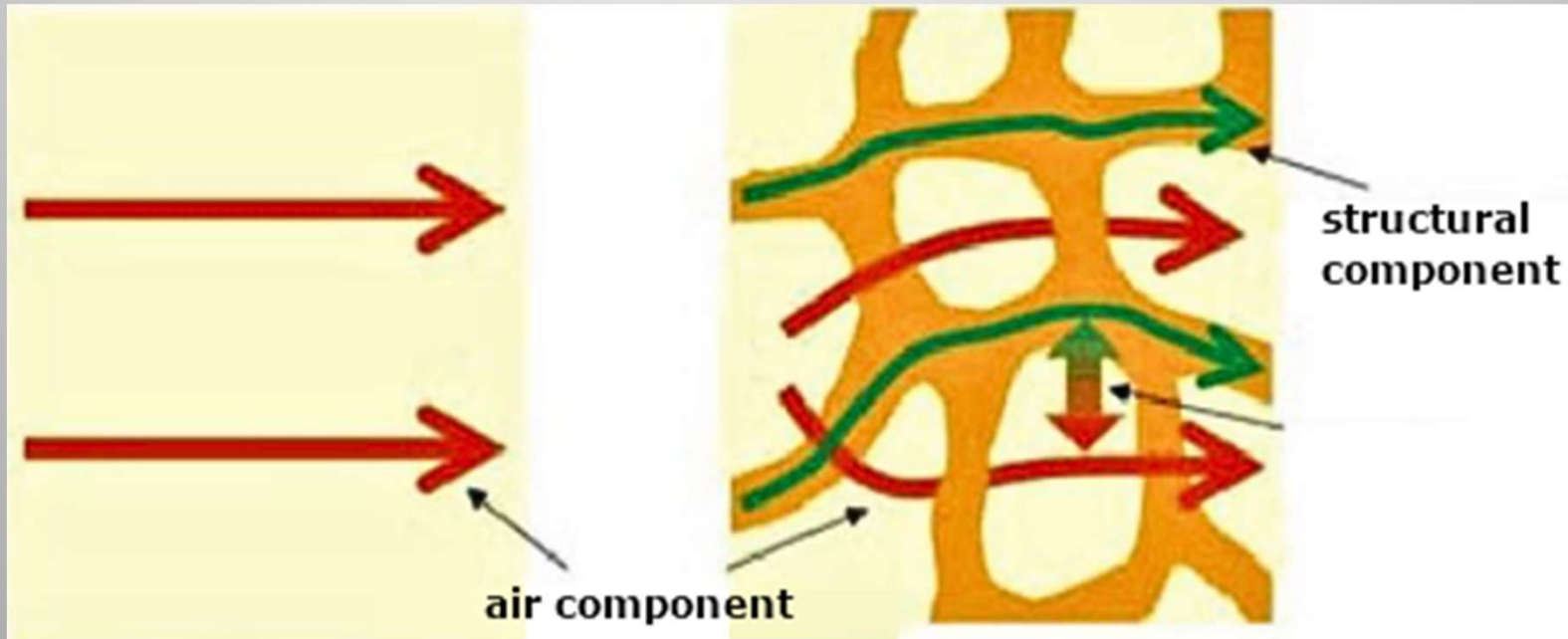
Biocomposite materials

Fibrous materials

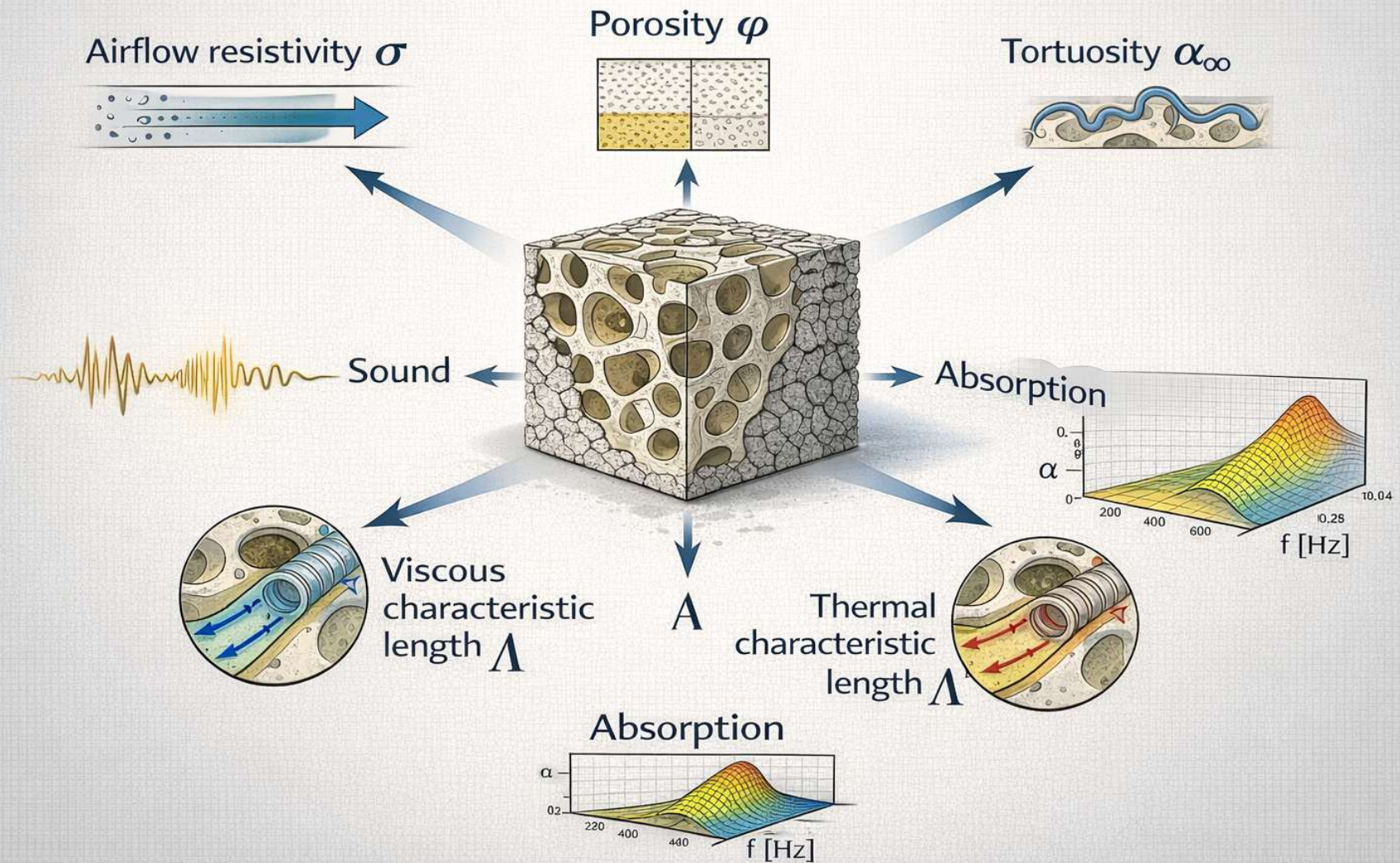


Granular/Recycled materials

- Porous materials are those materials in which the **solid mass is permeated with canals**, i.e. pores, interconnected in a continuous network.
- The sound penetrates deep into the pores of these materials, where, due to high friction, the **acoustic energy is converted into heat**.

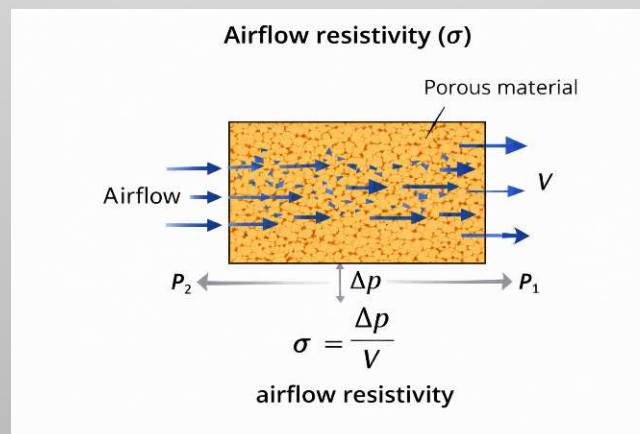


Key acoustic parameters of porous materials








1. Airflow Resistance

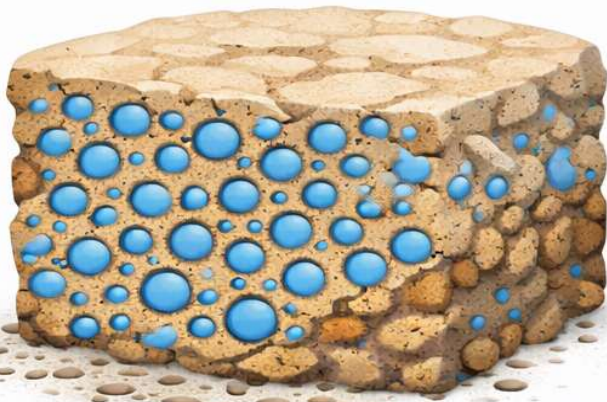
- If the material is not porous enough, sound bounces off the surface (high reflectivity)
- If the material is too porous, sound passes through it without significant attenuation (high transmission)
- Optimal porosity allows for maximum interaction of the sound wave with the inner surface of the material, which is crucial for high absorption coefficients ($\alpha \approx 1$)



Rapid Engineering Classification

Airflow Resistivity

Material	Airflow Resistivity	Character
	2 – 10 kPa·s/m ²	Low resistance
	5 – 20 kPa·s/m ²	Moderate resistance
	10 – 50 kPa·s/m ²	Variable resistance
	20 – 100 kPa·s/m ²	High resistance
	Granular / Recycled Materials	High resistance



Small Pores


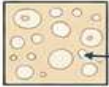



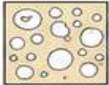








Large Pores

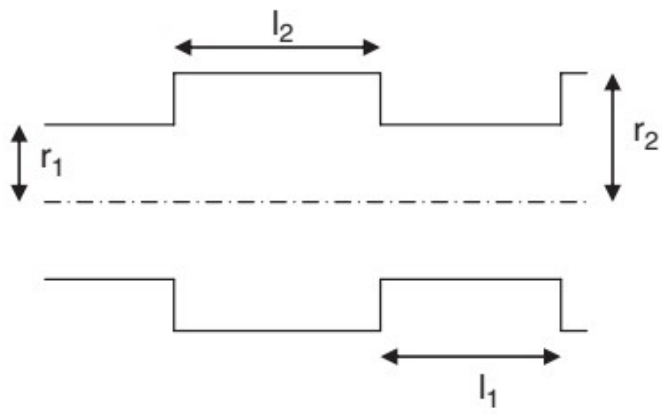
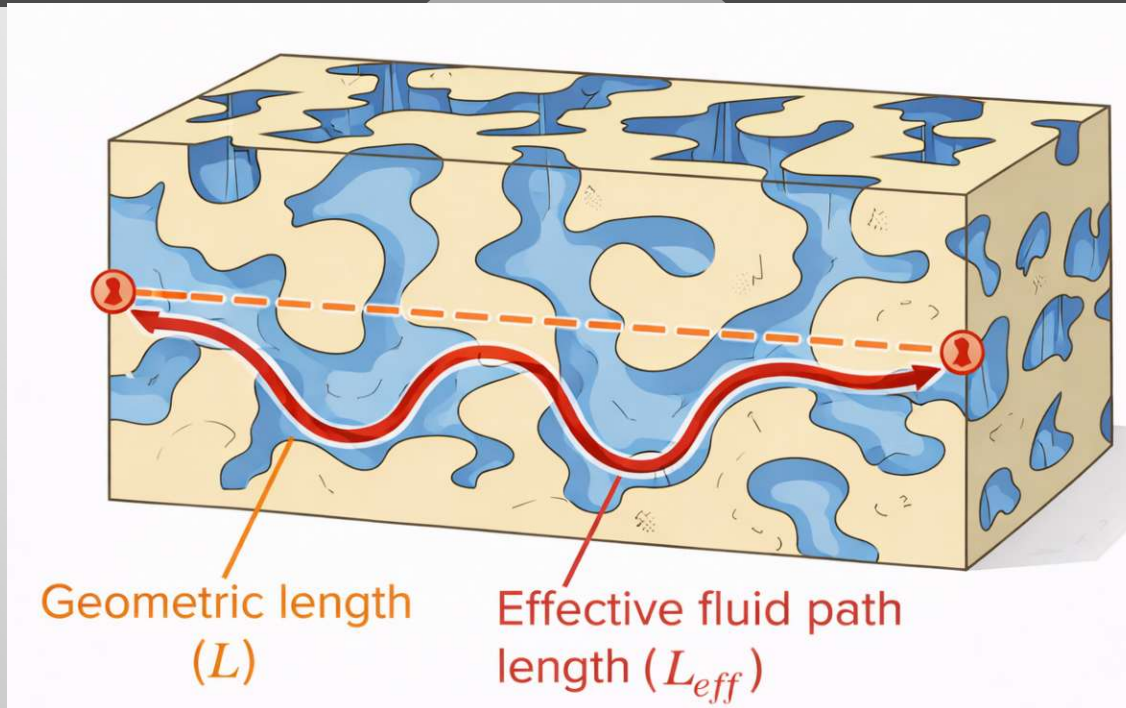
$$\text{Porosity } (\phi) = \frac{V_{\text{void}}}{V_{\text{total}}} \times 100\% \quad \text{or} \quad \phi = \frac{V_{\text{void}}}{V_{\text{void}} + V_{\text{solid}}} \times 100\%$$

Rapid Engineering Classification

Porosity (ϕ) – Air Void Content

Material	Porosity ϕ	Character
 	80–98 % (0.80 – 0.98)	Ultra-high porosity almost all voids
 	70–95 % (0.70 – 0.95)	Very high porosity fibrous networks
 	50–80 % (0.50 – 0.80)	High porosity bio-based composites
 	35–55 % (0.35 – 0.55)	Medium porosity granular packs / recyclates
 	20–35 % (0.20 – 0.35)	Moderate porosity dense granular
 	5–20 % (0.05 – 0.20)	Low porosity compacted / solid-like

ϕ = Porosity (air void fraction). Values are typical ranges for engineering materials.



$$\alpha_{\infty} = \frac{(l_1 S_2 + l_2 S_1)(l_1 S_1 + l_2 S_2)}{(l_1 + l_2)^2 S_1 S_2}$$

Tortuosity α_∞ of Porous Materials

BOUNDS FROM LITERATURE

Material		Tortuosity α_∞ (-)	Character
		1.0 – 1.3 (typ. 1.0–1.2)	Almost straight paths
		1.1 – 2.0 (typ. 1.2–1.6)	Moderately tortuous
		1.0 – 1.2 (typ. 1.0–1.1)	Slightly irregular
		1.5 – 4.0 (typ. 2.0–3.0)	Highly tortuous

Reference (literature)

- *Bonfiglio & Pompoli, 2013*
- *Jute Felt Study, 2021*
- *Allard & Atalla, 2009*

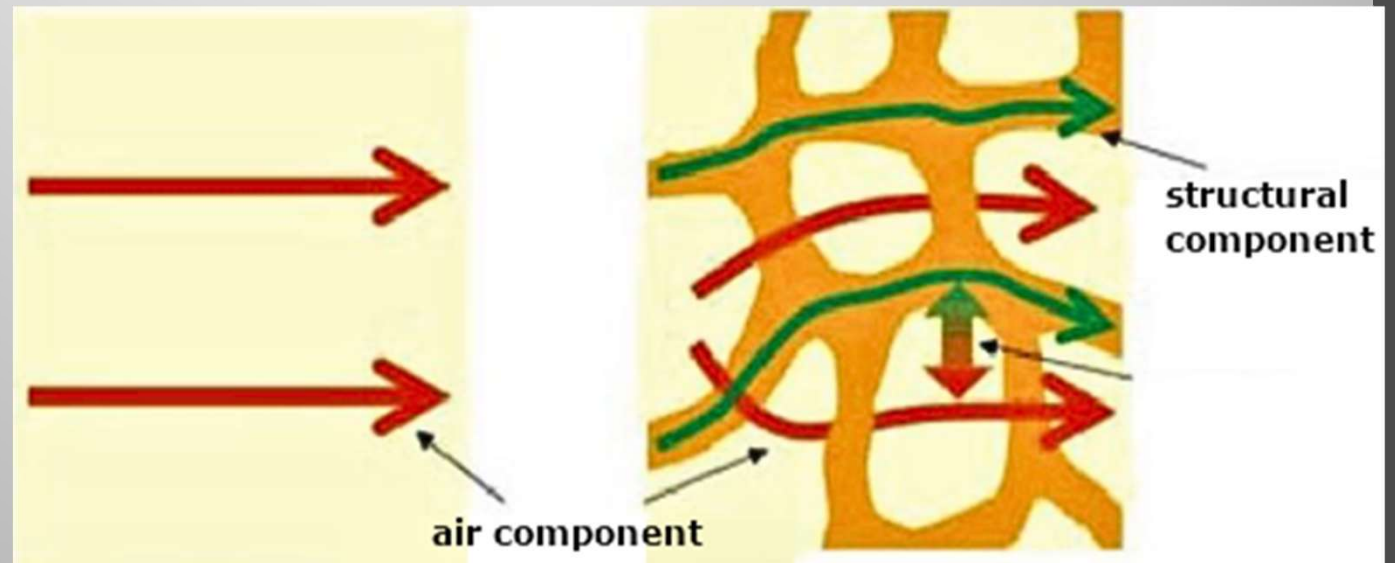
Mechanism of sound energy dissipation in porous materials:

- Viscous losses

$$\frac{2}{\Lambda} = \frac{\int_A v_i^2(\mathbf{r}_w) dA}{\int_V v_i^2(\mathbf{r}) dV}$$

- Thermal losses

$$\frac{2}{\Lambda'} = \frac{\int_A dA}{\int_V dV} = \frac{A}{S}$$



Characteristic Lengths and Boundary Layers

Characteristic Lengths

Viscous: $\Lambda \approx \text{geometry}$

Λ = effective viscous pore size

Thermal: $\Lambda' \approx \text{geometry}$

Λ' = effective thermal pore size

Characteristic Lengths

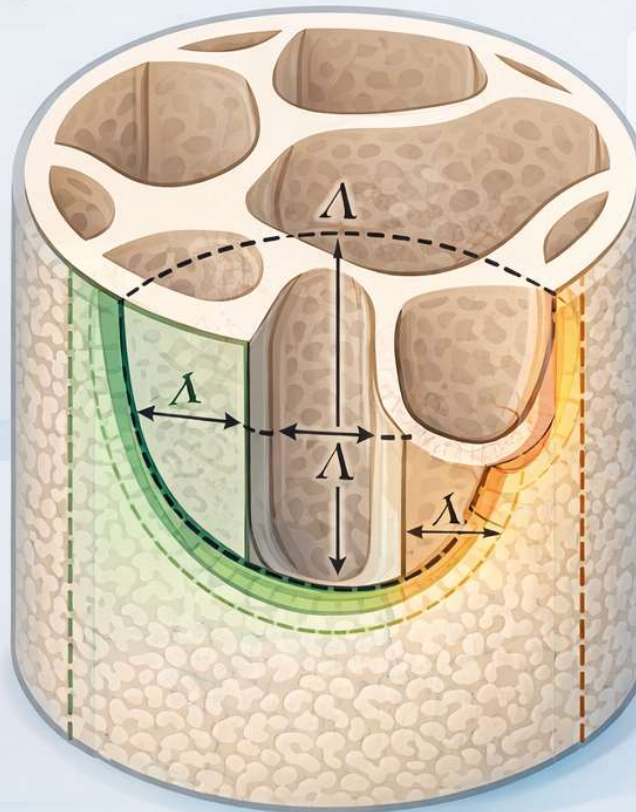
Viscous: $\Lambda \approx \text{geometry}$

Λ = effective viscous pore size

Thermal: $\Lambda' \approx \text{geometry}$

Λ' = effective thermal pore size

Pores Diagram



Boundary Layers

Viscous penetration depth

$$\delta_v = \frac{\sqrt{2\eta}}{\rho_0\omega}$$


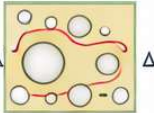



Thermal penetration depth

$$\delta_t = \frac{\sqrt{2\kappa}}{\rho_0 c_p \omega}$$

- Viscous Boundary Layer, δ_v
- Thermal Boundary Layer, δ_t
- Viscous Characteristic Length
- Thermal Characteristic Length

Rapid Engineering Classification


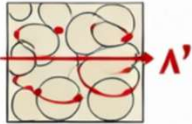




Viscous Characteristic Length Λ

Material	Viscous Characteristic Length Λ (μm)	Character
	 45 – 100 μm Small	Fine / thin pores
	60 – 150 μm Small / Medium	Increasingly narrow pores
	100 – 300 μm Medium / Large	Variable / irregular pores
	200 – 800 μm Large	Variable pores
	200 – 800 μm Large	Coarse / wide pores

Λ = Viscous Characteristic Length (μm). Values are typical ranges for engineering materials.

Rapid Engineering Classification

Thermal Characteristic Length Λ'

Material	Thermal Characteristic Length Λ' (μm)	Character
	 150 – 200 μm Small	Very restricted thermal pores
	200 – 300 μm Small / Medium	Narrow thermal pores
	400 – 600 μm Medium / Large	Variable thermal pores
	500 – 1000 μm Large	Open thermal pores
	500 – 1000 μm Large	Thermalxarnal pores

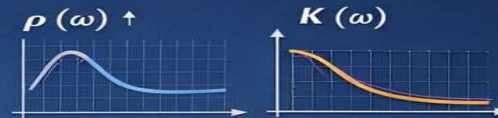
Λ' = Thermal Characteristic Length (μm). Values are typical ranges for engineering materials.

INVERSE ACOUSTIC CHARACTERIZATION OF POROUS MATERIALS – BOUNDS FROM LITERATURE



General Bounds

σ : $1 \times 10^3 - 1.5 \times 10^5 \text{ Ns/m}^4$
 ϕ : 0.1 – 1.0
 α_ω : 1 – 40
 Λ : 10 – 500 μm
 Λ° : 10 – 500 μm



PU FOAM

σ : 3k – 30k Ns/m^4
 ϕ : 0.90 – 0.99
 α_ω : 1.0 – 1.3
 Λ : 100 – 500 μm



FIBROUS MATERIALS

σ : 5k – 100k Ns/m^4
 ϕ : 0.70 – 0.98
 α_ω : 1.0 – 2.0
 Λ : 10 – 150 μm
 Λ° : 20 – 300 μm



BIOCOMPOSITES

σ : 20k – 50k Ns/m^4
 ϕ : 0.80 – 0.95
 α_ω : 1.0 – 1.2
 Λ : 20 – 300 μm
 Λ° : 100 – 200 μm



GRANULAR / RECYCLED MATERIALS

σ : 10k – 100k Ns/m^4
 ϕ : 0.30 – 0.80
 α_ω : 1.5 – 4.0
 Λ : 200 – 800 μm
 Λ° : 400 – 1000 μm

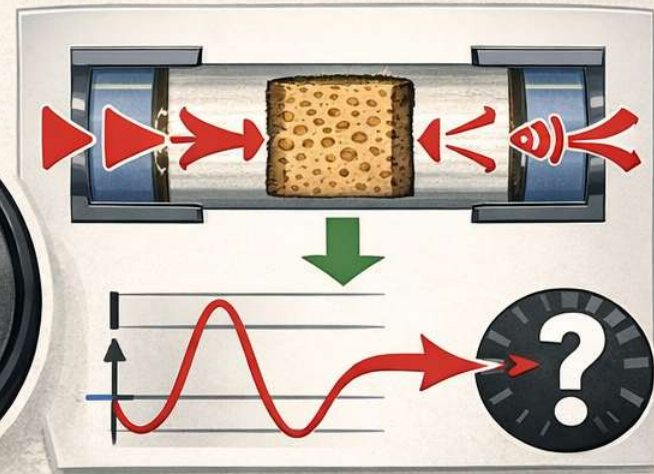
- Bonfiglio & Pompoli, 2013
- Jute Felt Study, 2021
- Allard & Atalla, 2009

METHODS FOR MEASURING ACOUSTIC
CHARACTERISTICS OF POROUS MATERIALS

DIRECT MEASUREMENTS

Sound Absorption (α)Airflow Resistivity (σ)

INVERSE ACOUSTIC CHARACTERIZATION

Porosity (ϕ)

Derived Parameters (Inverse Method):

- Tortuosity (α_∞)
- Viscous characteristic length Λ
- Thermal characteristic length Λ'
- Bulk modulus (K)
- $T \cdot K = \Lambda, \Lambda', \Lambda'; \alpha_\infty$

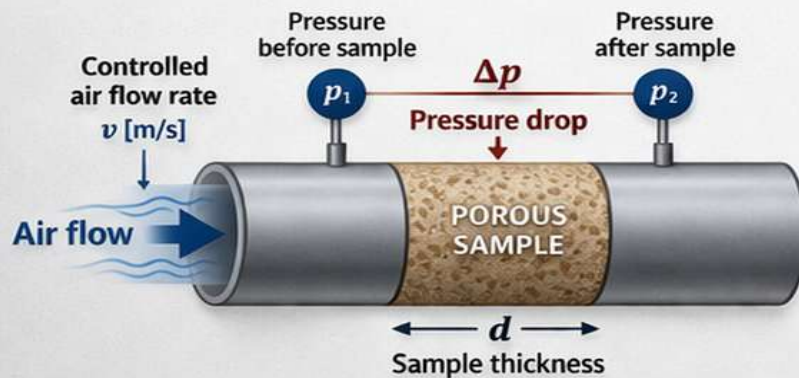
AIRFLOW RESISTIVITY (σ) MEASUREMENT PRINCIPLE


1 WHAT IS IT?

$$\sigma = \frac{\Delta p}{(v \cdot d)}$$

Δp = Pressure drop [Pa]
 v = Air velocity [m/s]
 d = Sample thickness [m]

2 MEASUREMENT SETUP



 **Low σ** → Air passes easily

 **High σ** → Greater resistance
 → More energy dissipation

3 PHYSICAL INTERPRETATION



Airflow resistivity (σ) quantifies **how hard it is for air to pass through** a porous material.

→ Key parameter in **DB** and **JCA** models

4 STANDARDS



ISO 9053

Acoustics — Determination of airflow resistivity of porous materials



ISO 9053-1:2018

Part 1: Steady airflow method



ISO 9053-2:2020

Part 2: Alternating airflow method

5 METHODS

✓ Steady Airflow

- Constant air flow
- Most common method

⚡ Alternating Airflow

- Oscillating flow
- Suitable for thin samples

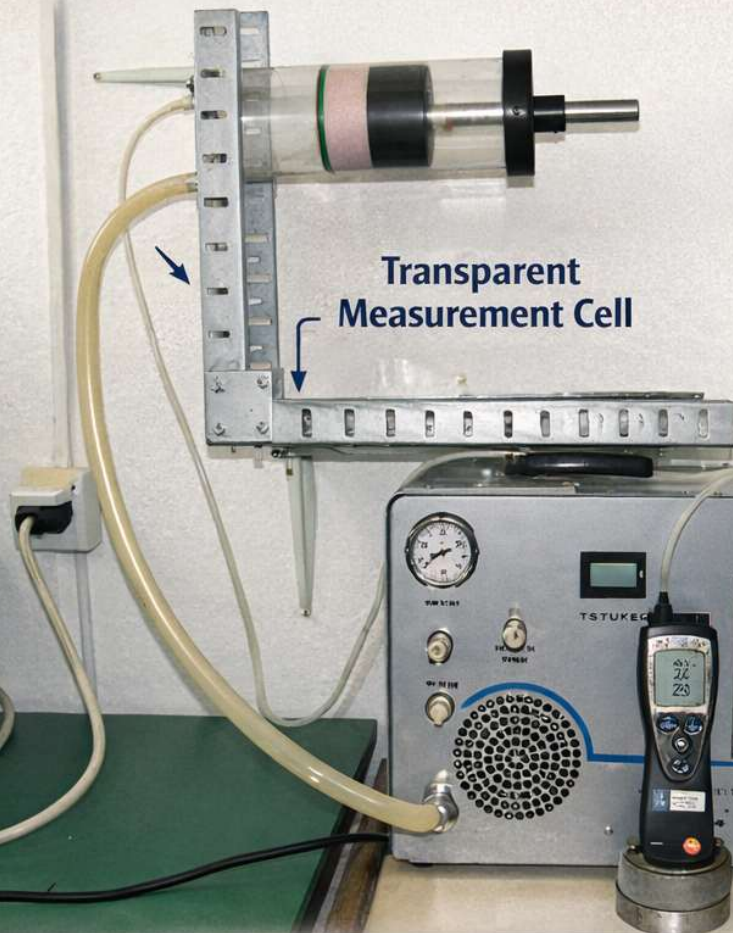


COMMON SOURCES OF ERROR

- ✗ Poor sample sealing
- ✗ Turbulent flow (must be laminar!)
- ✗ Incorrect air velocity

AIRFLOW RESISTIVITY (σ) is the key input for both **DB** and **JCA** acoustic models.

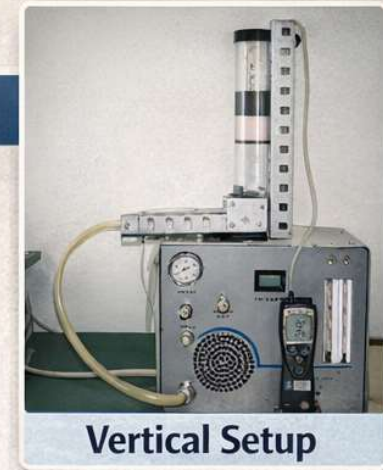
Custom Measurement System for Airflow Resistivity (ISO 9053-Based)



Transparent
Measurement Cell

Key Features

- ✓ Developed according to ISO 9053
- ✓ Modular design (horizontal & vertical setup)
- ✓ Transparent measurement cell (visual sealing control)
- ✓ Compatible sample diameter with impedance tube testing
- ✓ Experimental validation performed
- ✓ To the best of our knowledge, this is the first system for airflow resistivity measurement developed in Serbia.



Vertical Setup

Enables reliable determination of airflow resistivity for inverse acoustic characterization.

POROSITY (ϕ) MEASUREMENT METHODS

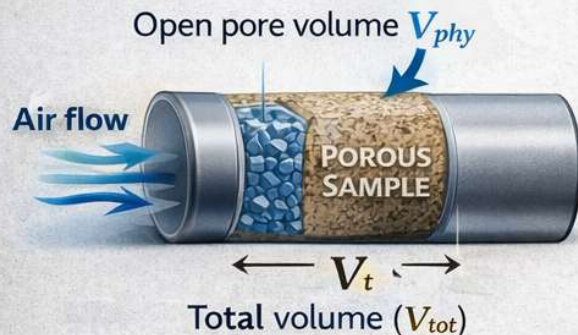
1 WHAT IS IT?

$$\phi = \frac{V_{phy}}{V_{tot}}$$

V_{phy} = Volume of open pores

V_{tot} = Total volume of material

2 MEASUREMENT SETUPS



Low σ - Air passes easily



High σ → Greater resistance

→ More energy dissipation

→ Key methods for determining porosity (ϕ) ←

1 AIR-DISPLACEMENT PYCNOMETRY



- ✓ **Air-Displacement Pycnometry**
Measures porosity by displacing a known amount of gas

2 MERCURY INTRUSION POROSIMETRY



- Uses high pressure to force mercury into the pores

3 MERCURY INTRUSION POROSIMETRY



- Uses high pressure to force mercury into the pores

3 OPTICAL METHODS

- Analyze images of the material to calculate pore area

3 INTERPRETATION

- **High ϕ** → More air in pores
- **Higher sound absorption**
- **Low ϕ** → Lower absorption



IMPORTANT NOTES

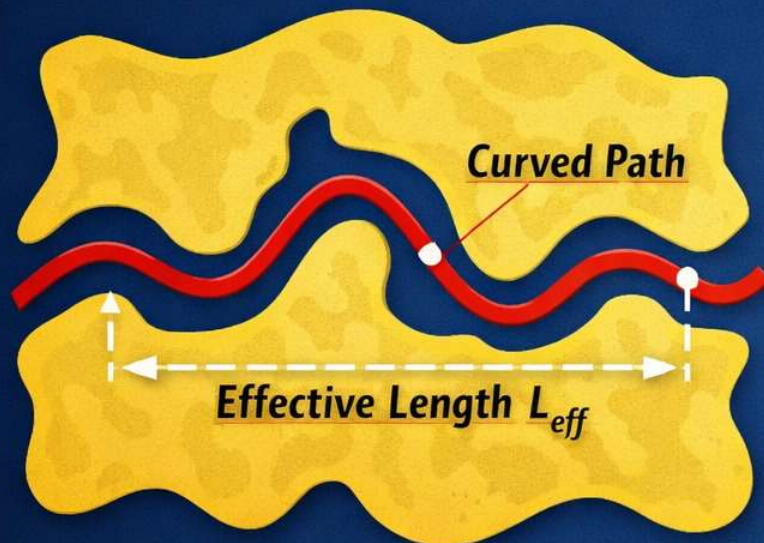
- ✗ Presence of closed pores
- ✓ Sample preparation

more material than is closed in these chambers

Porosity (ϕ) is the ratio of open pore volume to the total volume of porous material: $\phi = \frac{V_{phy}}{V_{tot}}$

Tortuosity Measurement

Porous Material



Sound Wave



Sound Wave Out

Tortuosity is determined indirectly



Acoustic Response
Analysis



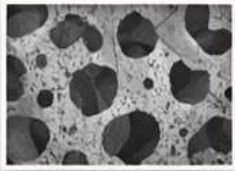
Inverse Estimation

Identified from Acoustic Data

Λ & Λ' Measurement

Λ – Viscous Characteristic Length

- Microstructure-Based Estimation



- Inverse Acoustic Characterization



Λ' – Thermal Characteristic Length

- Microscopic Image Analysis



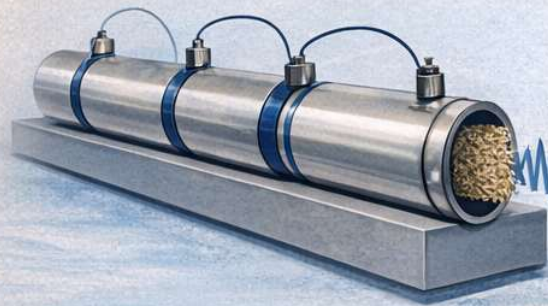
- Porous Media Modeling



Indirect Determination from Microstructure & Acoustic Response

Integration of Measurement Methods for Reliable Acoustic Characterization

Impedance Tube System (B&K)

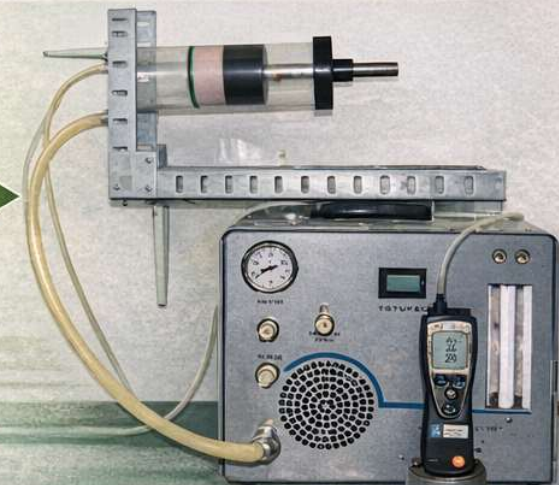


$\alpha(f)$ Measurement

- ISO 10534-2

University of Niš - International Project

Custom Airflow Resistivity System



- ISO 9053

University of Kragujevac

$$\alpha(f) + \sigma$$

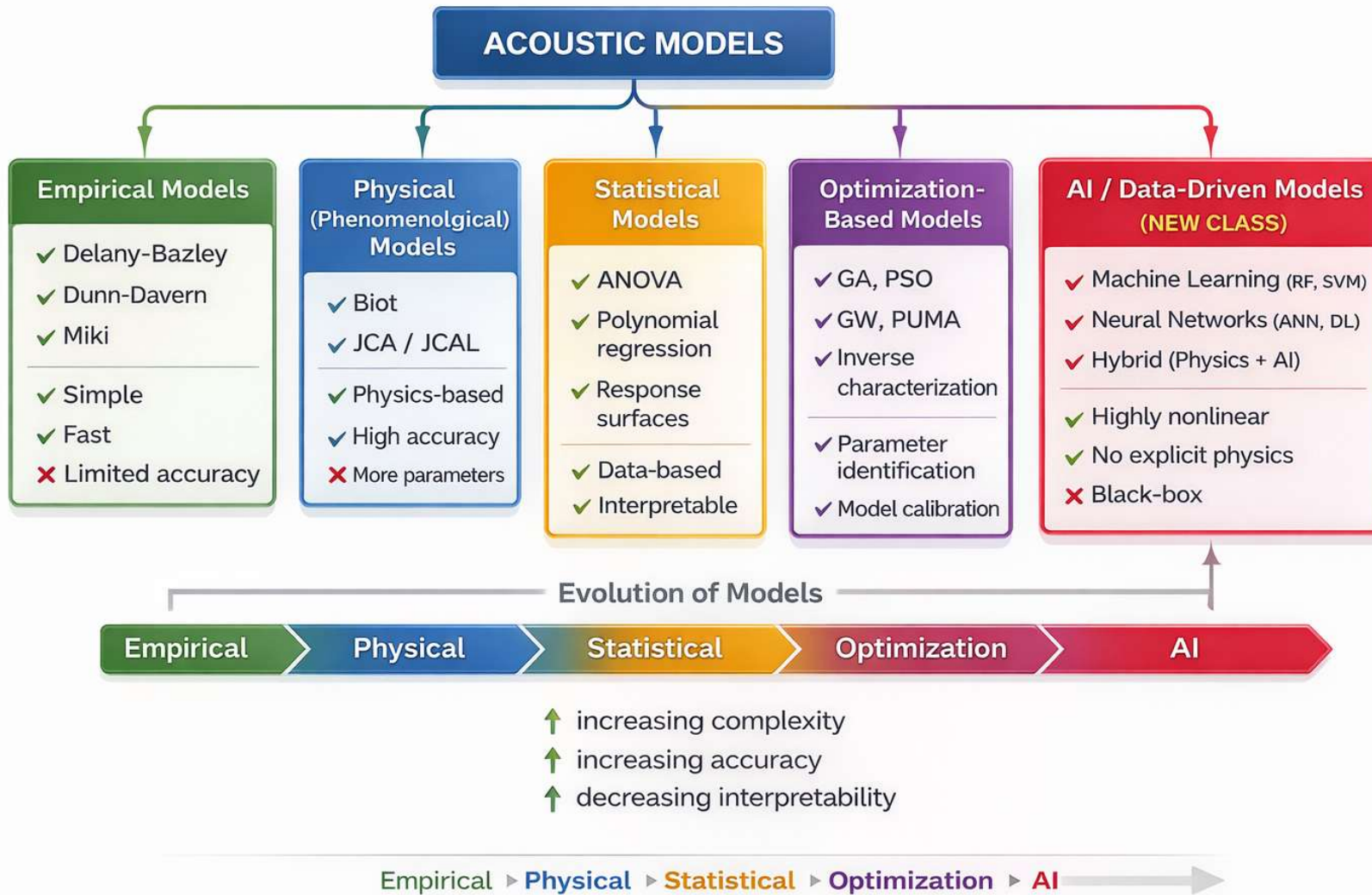
Reliable Acoustic Modeling

- ✓ **Outcomes:**
- ✓ Validation of **airflow resistivity** measurement method
- ✓ Validation of **empirical models** (DB-type)
- ✓ Reduced parameter space in **inverse** characterization
- ✓ Improved **optimization** accuracy

*Integration of experimental methods enables **more reliable and physically consistent** acoustic characterization.*

*Contribution to advancement of acoustic engineering in **Serbia***

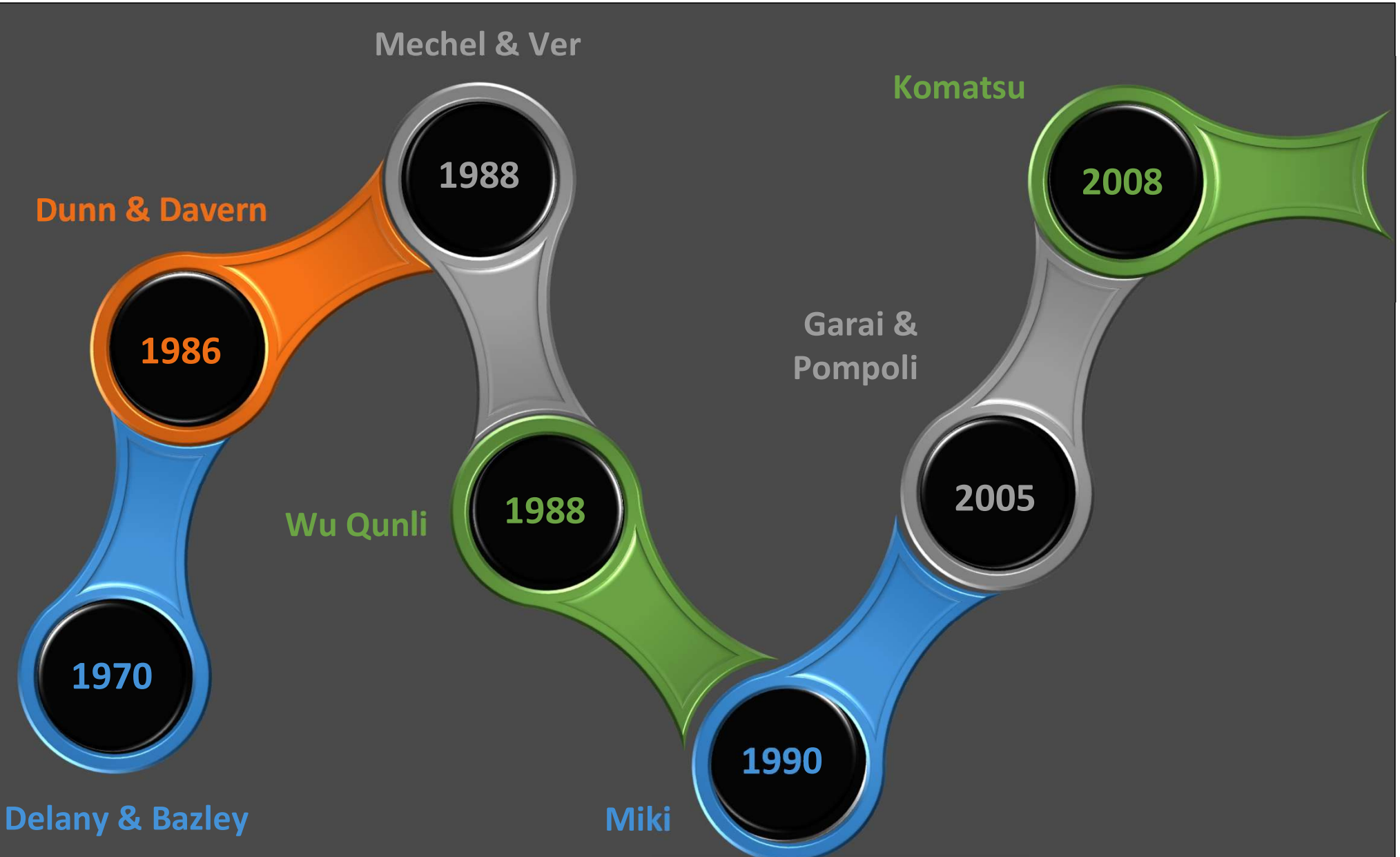
Classification of Acoustic Models for Porous Materials



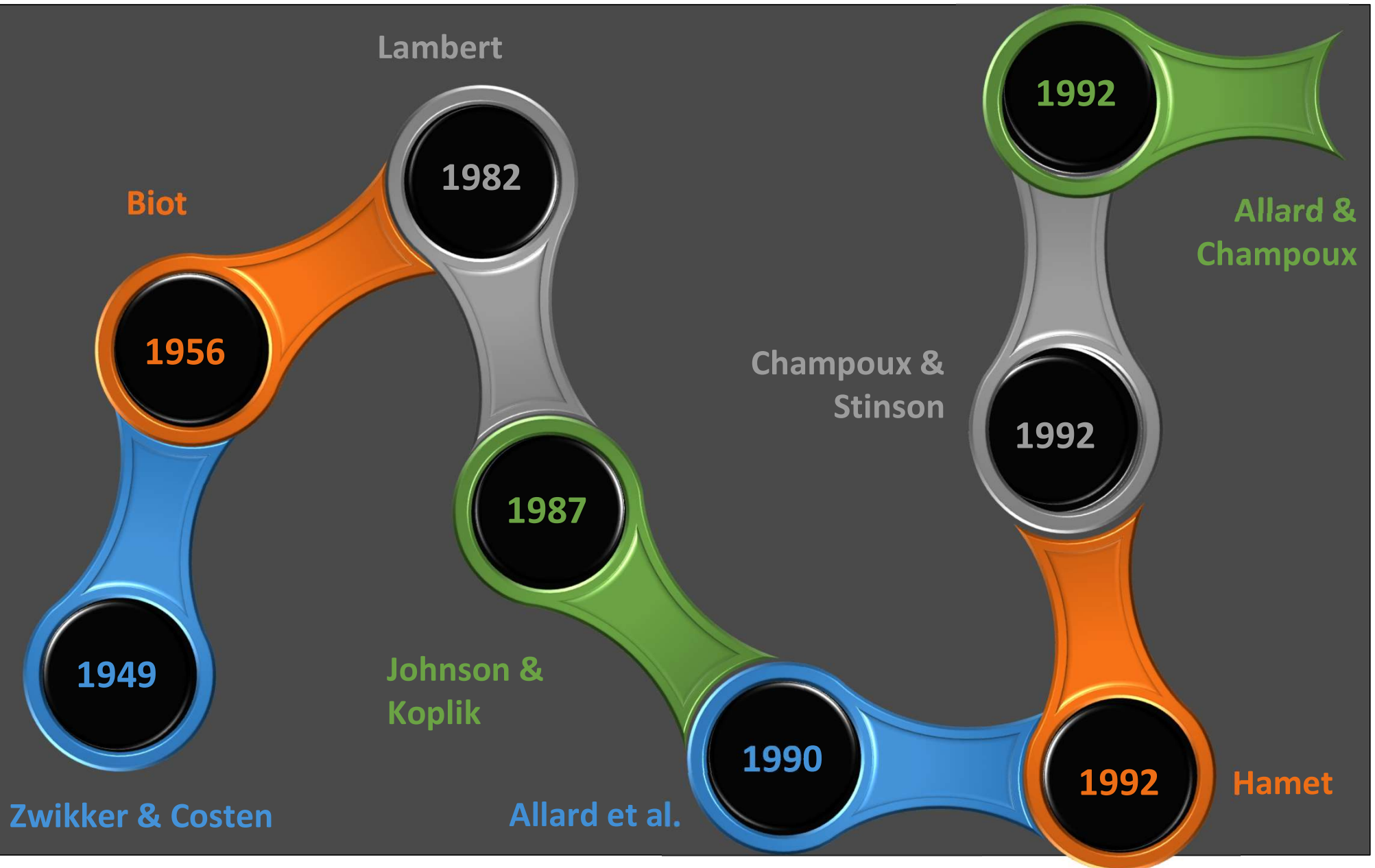
04

MODELS FOR PREDICTING THE ACOUSTIC PROPERTIES OF POROUS MATERIALS

Empirical models

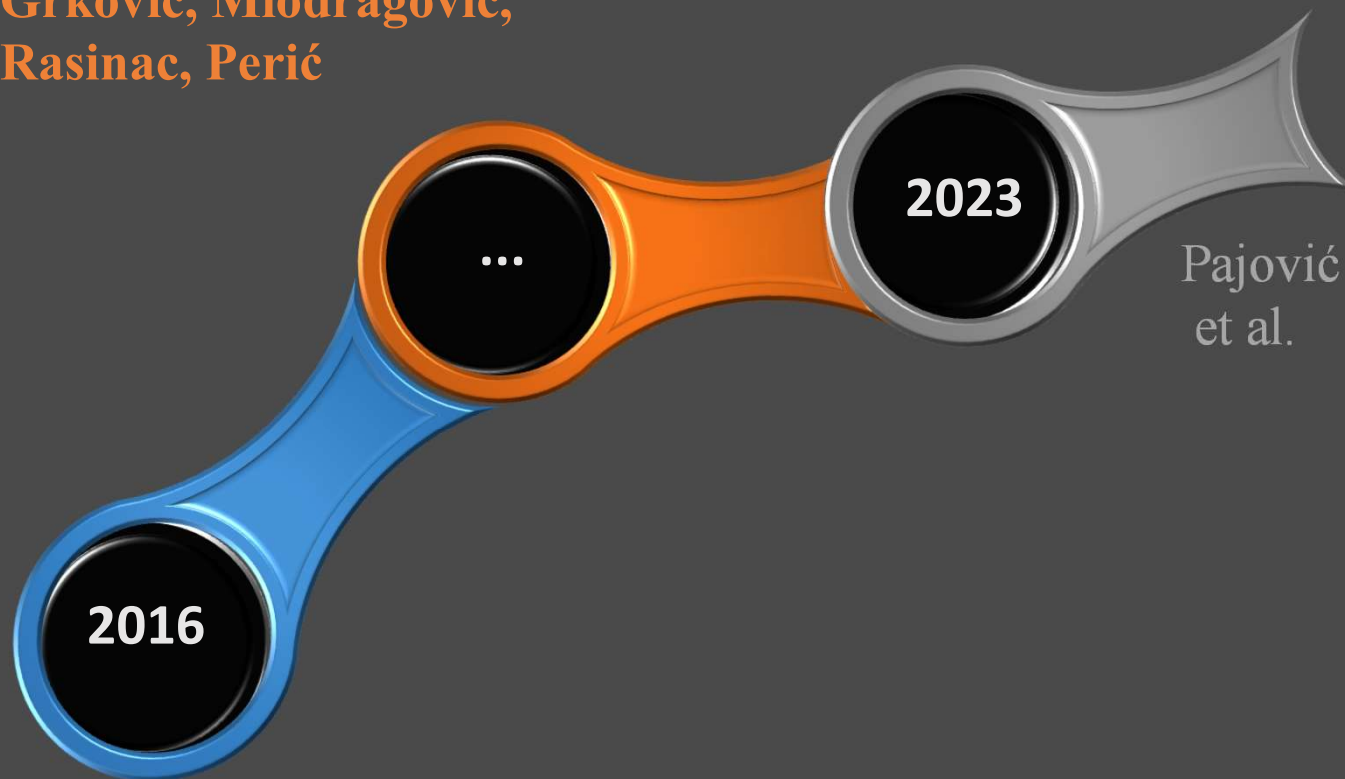


Physical models

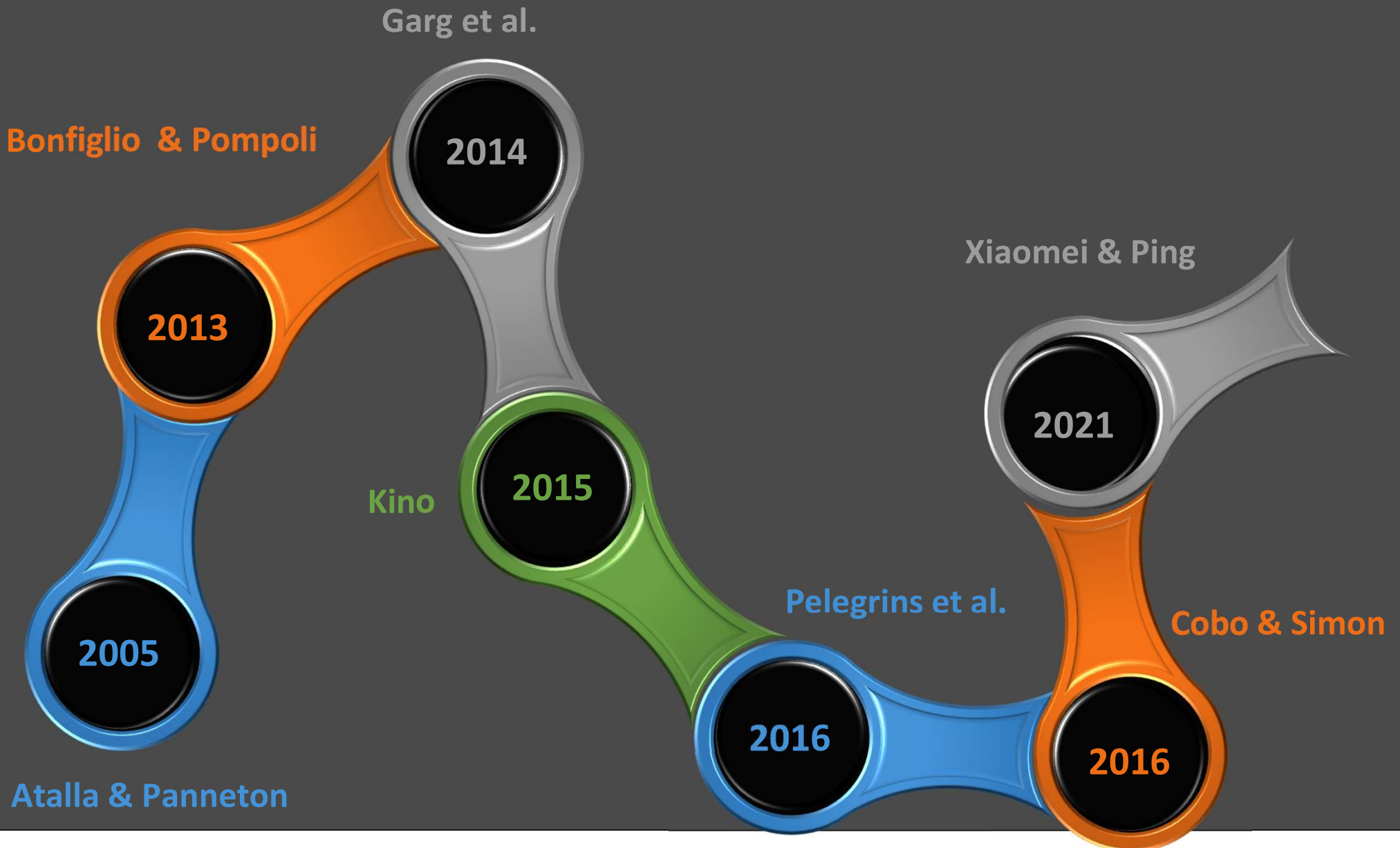


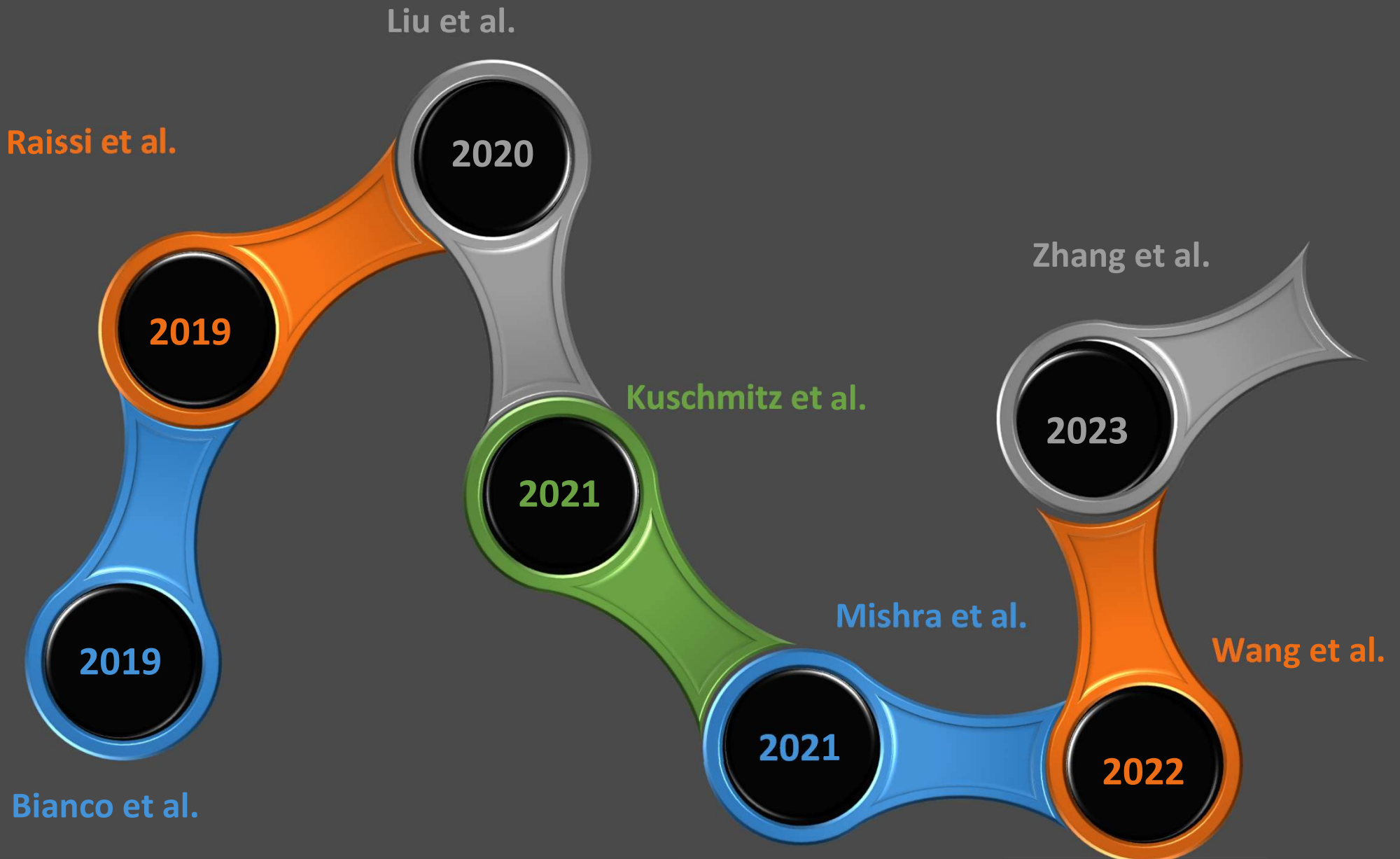
Radićević, Kolarević, Bjelić,
Grković, Miodragović,
Rasinac, Perić

Acoustic properties of highly elastic polyurethane
foam VAPEN HR 3744



Radićević B., Development of a decision-making model for the selection of the optimal mixture of sound absorbing materials, Faculty of Mechanical and Civil Engineering in Kraljevo, University of Kragujevac, Doctoral Dissertation, 2016





In 1970, Delany & Bazley presented a model for determining the characteristic impedance and the propagation coefficient depending on the resistance to air flow.

$$Z_0 = R + jX$$

$$\gamma = \alpha + j\beta$$






$$Z_c = \rho_0 c \left[1 + 0.0571 \left(\frac{\rho_0 f}{\sigma} \right)^{-0.574} - j0.087 \left(\frac{\rho_0 f}{\sigma} \right)^{-0.732} \right]$$

$$\gamma = \frac{\omega}{c} \left[1 + 0.0978 \left(\frac{\rho_0 f}{\sigma} \right)^{-0.7} - j0.189 \left(\frac{\rho_0 f}{\sigma} \right)^{-0.595} \right]$$

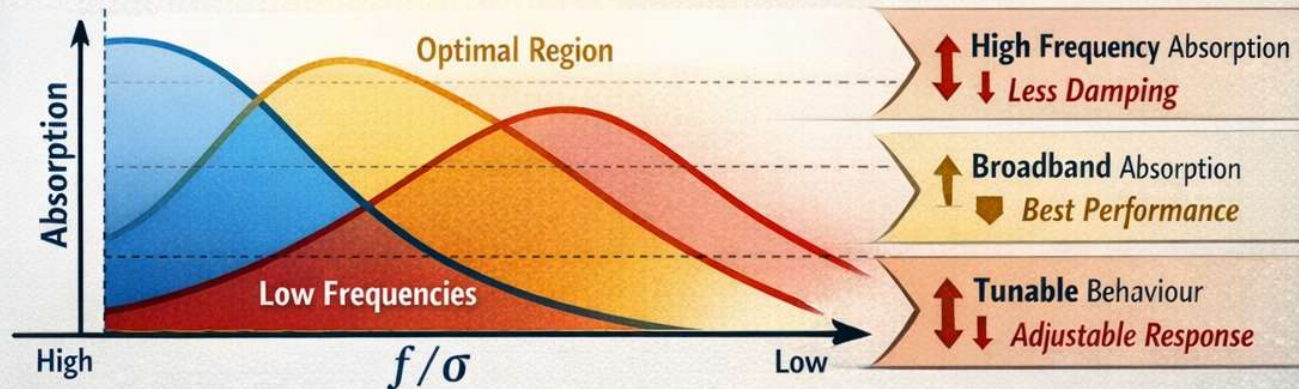
$$10 \leq f/\sigma \leq 1000$$

MODELS FOR PREDICTING THE ACOUSTIC PROPERTIES OF POROUS MATERIALS

Airflow Resistivity σ – Influence on Delany–Bazley Model

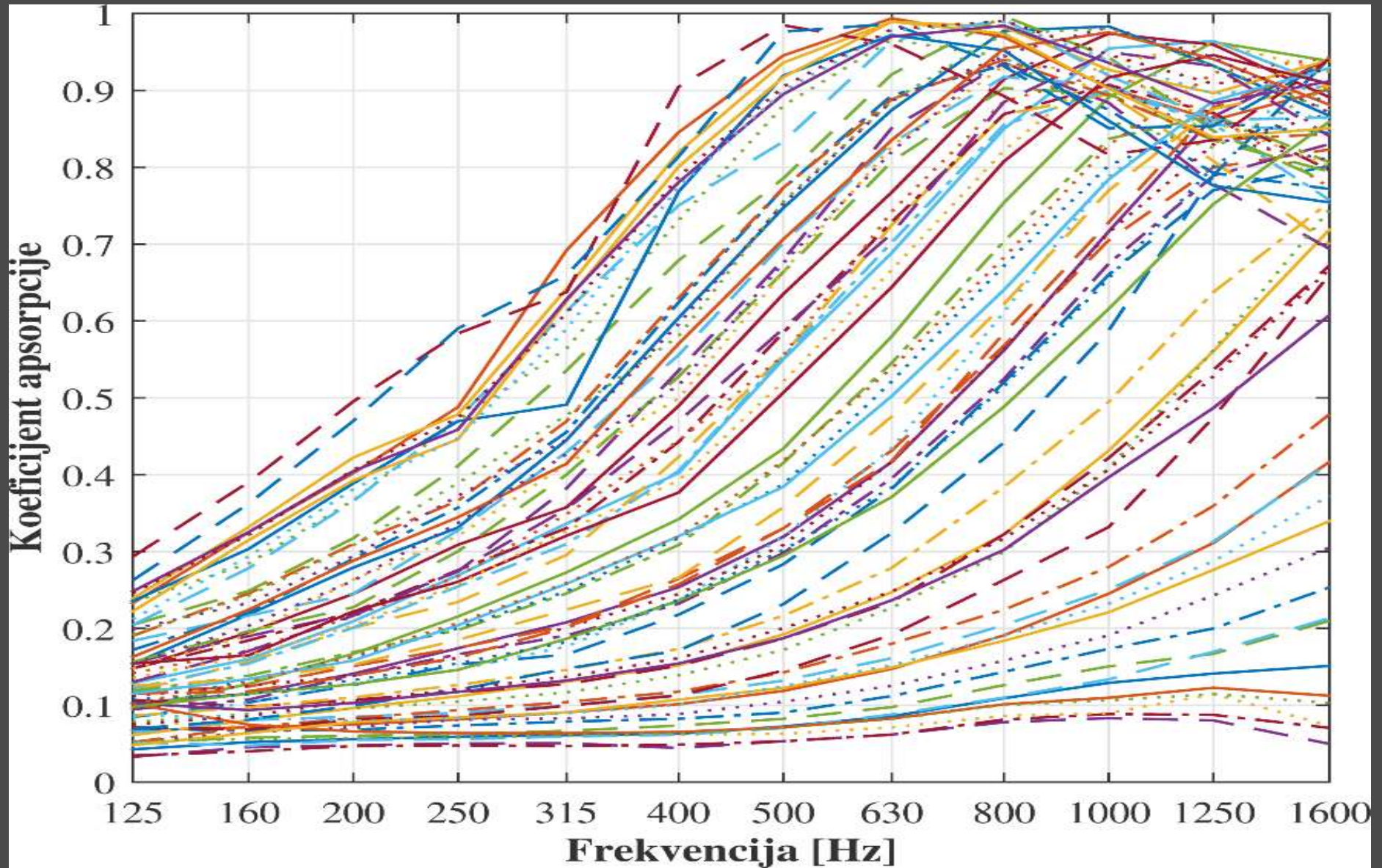
PU Foam	Fibrous	Biocomposites	Granular	
σ 3k – 30k	σ 5k – 100k Ns/m ⁴	σ 20k – 50k Ns/m ⁴	σ 10k – 100k Ns/m ⁴	σ 10k – 100k Ns/m ⁴
				

↑ High Frequencies



$$Z_c = 1 + C_1 X^{-C_2} - j C_3 X^{-C_4}$$

$$k = \frac{\omega}{c_0} (1 + C_5 X^{-C_6} - j C_7 X^{-8})$$



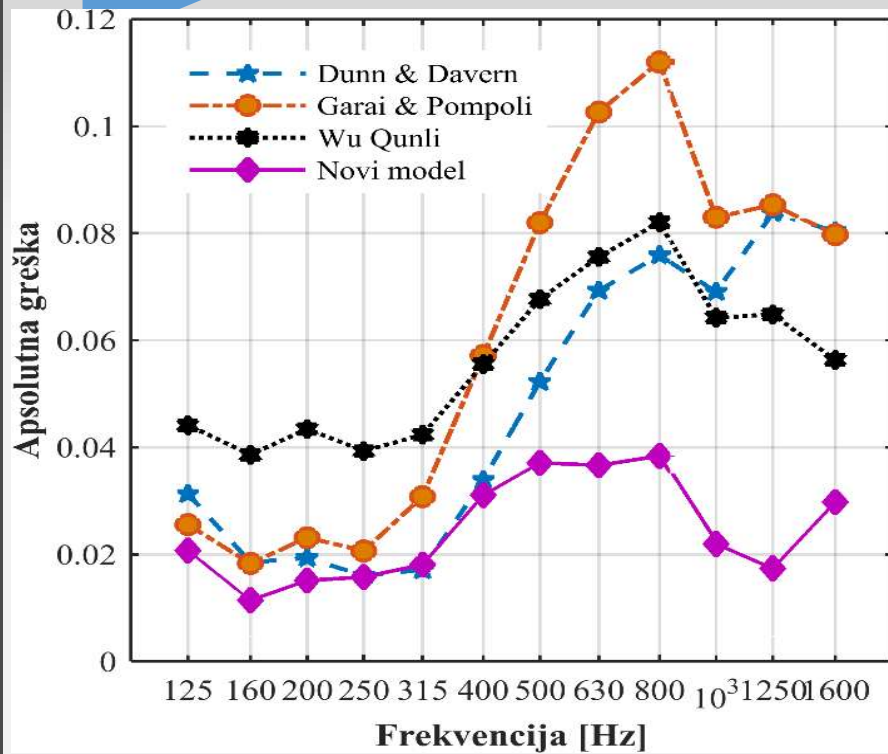
04

MODELS FOR PREDICTING THE ACOUSTIC PROPERTIES OF POROUS MATERIALS

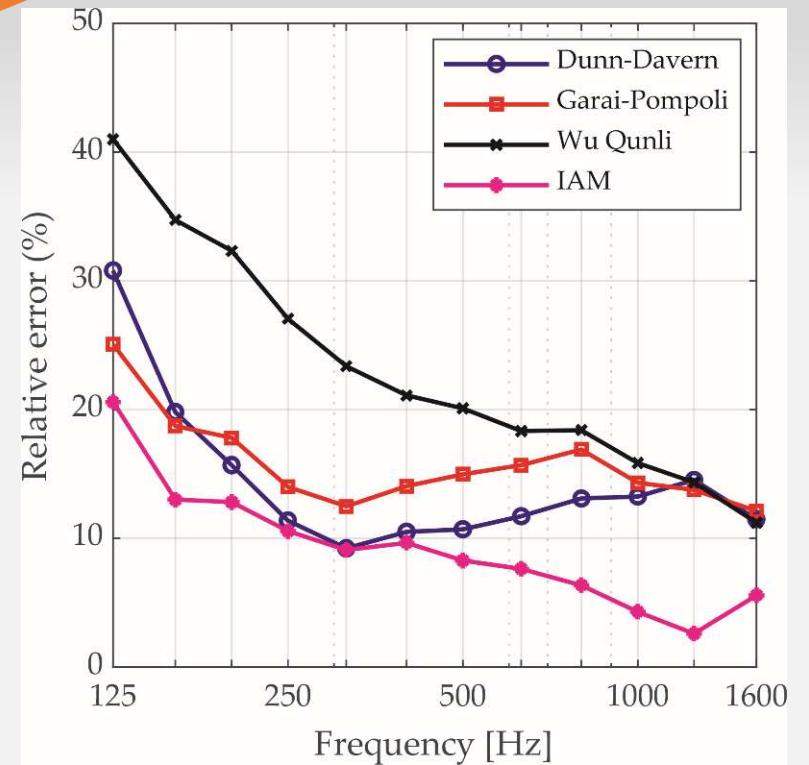
1. An example of an empirical model Radičević B.

A model for predicting the sound absorption of open-cell polyurethane foams

01



02



It contains five physical parameters: porosity (ϕ); air flow resistance (σ); tortuosity (α); viscous characteristic length (Λ); thermal characteristic length (Λ')

According to the JCA model, the effective density $\rho_e(\omega)$ and bulk modulus $K(\omega)$ of porous materials can be calculated using the following expressions:

$$\rho_e(\omega) = \alpha_\infty \rho_0 \left[1 - j \frac{\sigma \phi}{\alpha_\infty \rho_0 \omega} \sqrt{1 + j \frac{4\alpha_\infty^2 \eta \rho_0 \omega}{\sigma^2 \Lambda^2 \phi^2}} \right]$$

$$K_e(\omega) = \gamma P_0 \left[\gamma \frac{\gamma - 1}{1 - j \frac{8\eta}{\rho_0 \omega N_{pr} \Lambda'^2} \left(1 + \sqrt{1 + j \frac{\rho_0 \omega N_{pr} \Lambda'^2}{16\eta}} \right)^{\frac{1}{2}}} \right]^{\frac{1}{2}}$$

Characteristic impedance $Z_c(\omega)$ and the complex expansion constant $k(\omega)$ of porous materials can be deduced from Eqs

$$Z_c(\omega) = \sqrt{K_e(\omega) \rho_e(\omega)}$$

$$k_e(\omega) = \omega \sqrt{\frac{\rho_e(\omega)}{K_e(\omega)}}$$

Considering that the porous material of thickness d is covered by a rigid boundary, the sound absorption coefficient (SAC) α of the porous material can be denoted by the following equations:

$$Z_s(\omega) = -j \frac{Z_c(\omega)}{\phi} \cot(k_e(\omega)d)$$

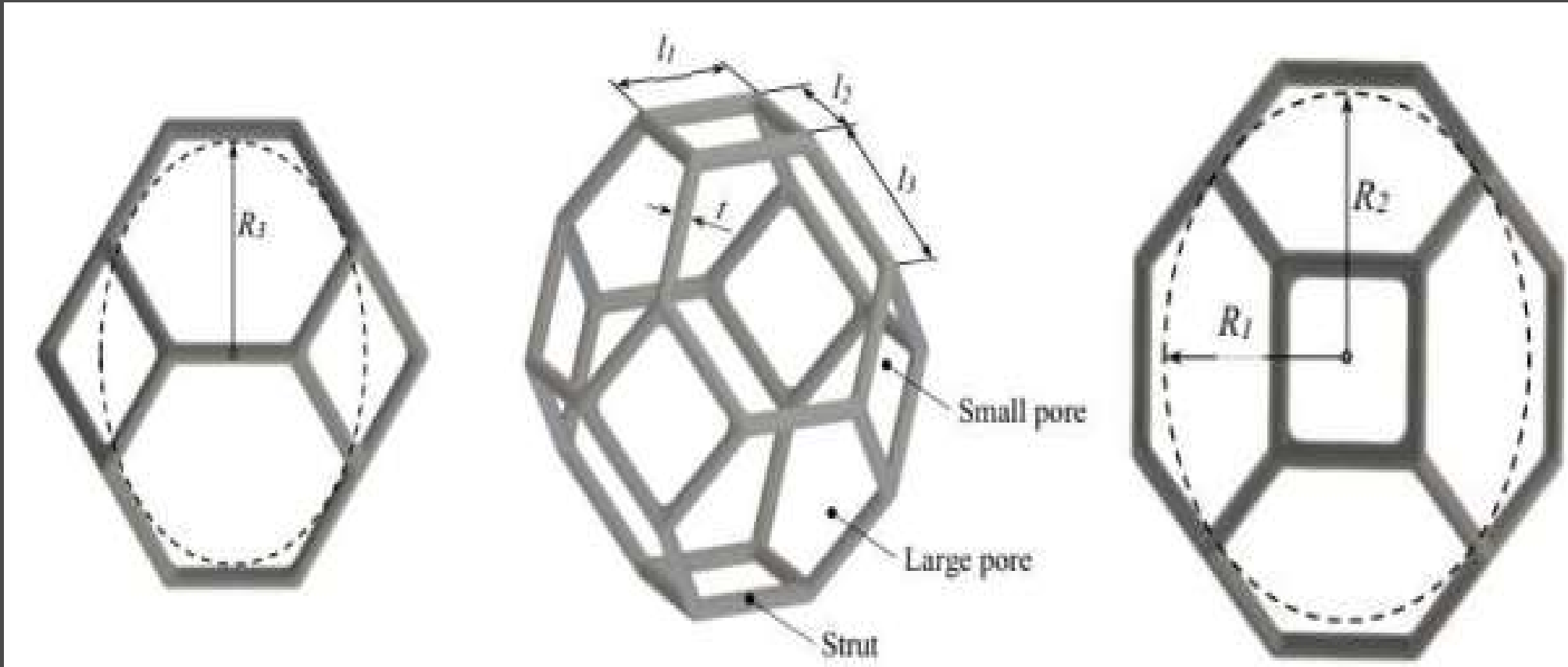
$$R = \frac{Z_s(\omega) - Z_o}{Z_s(\omega) + Z_o}$$

$$\alpha = 1 - R^2$$

where $Z_s(\omega)$ is the surface characteristic impedance, Z_o is the air characteristic impedance and is equal to $\rho_0 c_0$ where c_0 is the sound speed and R is the sound reflection coefficient.

$$Z_l = Z_c \coth(jk_c d)$$

Where d is the sample thickness.



$$(\Phi, \alpha_\infty, \Lambda, \Lambda') = f(t, l)$$

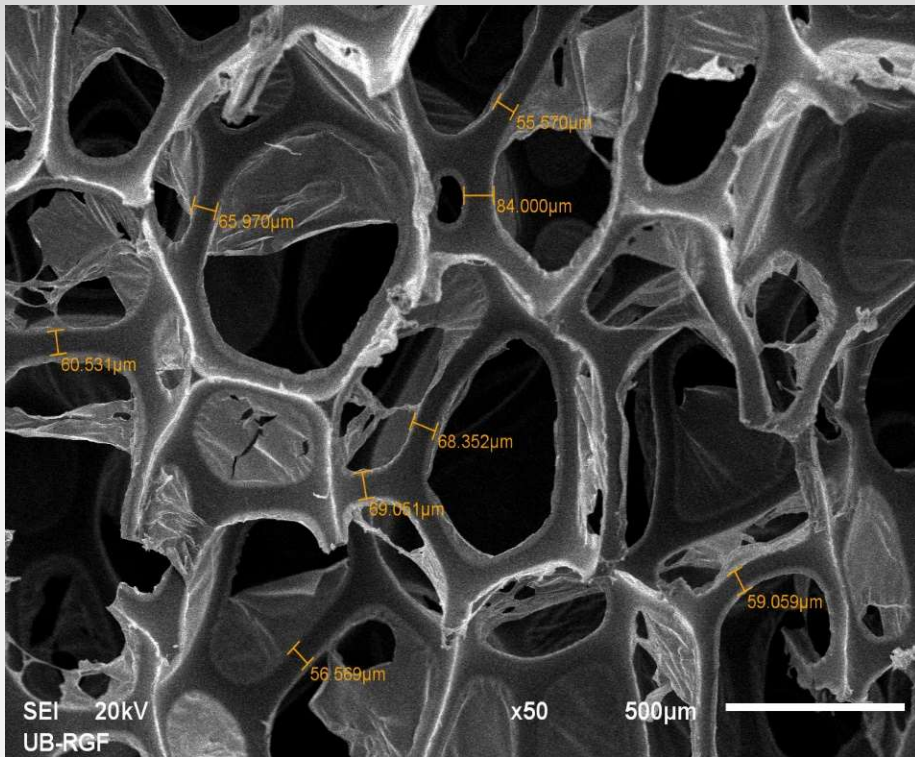
04

MODELS FOR PREDICTING THE ACOUSTIC PROPERTIES OF POROUS MATERIALS

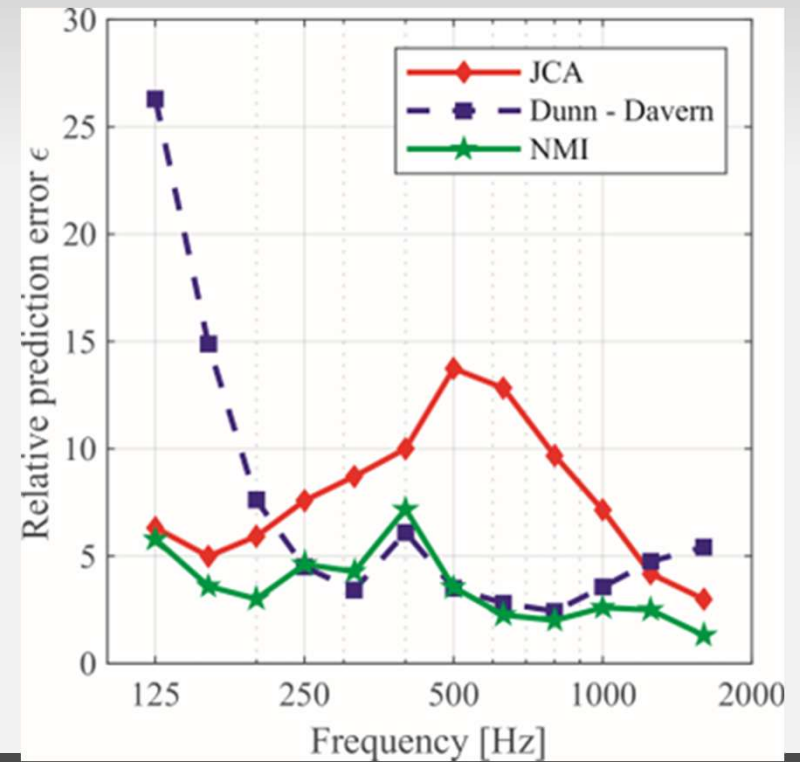
2. An example of an theoretical model Radičević B.

Sound absorption prediction methods and their accuracy in partially open cell polyurethane foams

01



02



WHEN TO USE DB AND WHEN JCA?

WHEN TO USE DB OR JCA?

DELANY – BAZLEY (DB)

Empirical Model

- ✓ Quick estimation
- ✓ Single parameter (σ)
- ✓ Used for ~50 years
- ✓ Simple and reliable



BASIC PREDICTOINS

When to use DB:

- ✓ For quick estimation
- ✓ When microstructure is not available
- ✓ Mid-frequency range

VS

JOHNSON – CHAMPOUX – ALLARD (JCA)

Physical Model

- ✗ Complex simulation
- ✗ 5 parameters ($\phi, \Lambda, \Lambda', k_0, \sigma_{\pm}$)
- ✗ Since 1991, for advanced materials
- ✗ Detailed & powerful



PRECISE MODELS

When to use JCA:

- ✓ For precise simulations
- ✓ When microstructure is known or being designed
- ✓ Extreme cases (low and high frequencies)

BASIC PREDICTIONS

PRECISE MODELS

TYPICAL MISTAKES IN ACOUSTIC MODELING



COMMON MISTAKES

- ✗ **Ignoring frequency range**
(wrong model or wrong range)
- ✗ **Assuming different materials are similar**
(one-size-fits-all approach)
- ✗ **Using empirical models outside of valid range**
(DB is limited to mid frequencies)
- ✗ **Overfitting or underfitting parameters**
(optimizing does not guarantee validity)
- ✗ **Misinterpreting complex parameters**
(invalid microstructural assumptions)

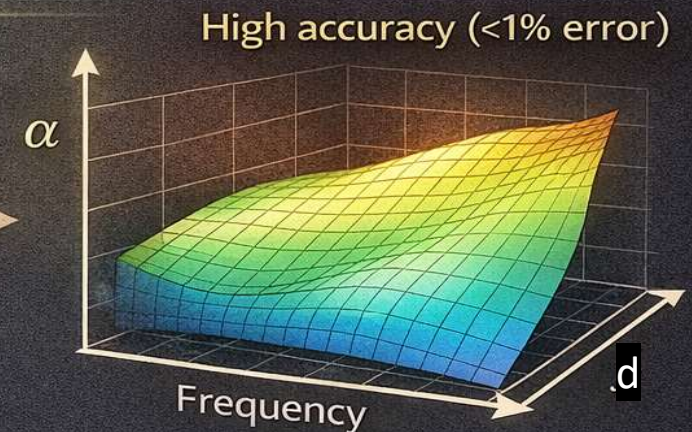
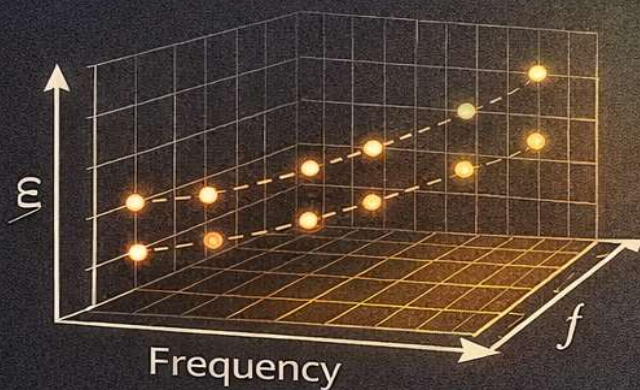
Best practice: Know the model's limitations!

Statistical (Stochastic) Models – ANOVA-based

ANOVA-based polynomial model

$$\alpha(f, d) = \alpha_0 + \alpha_1 f + \alpha_2 d + \alpha_3 f^2 + \alpha_4 d^2 + \alpha_5 f d + \dots$$

$$\alpha = \sum_{l=1} \alpha_{ij} f^i d^j$$



- ✓ Polynomial dependence: $\alpha = f$ (frequency, thickness)
- ✓ Very high accuracy (<1%)
- ✓ Based on experimental design (ANOVA)

⚠ Valid only within experimental domain

Developed in this research

The software package Design Expert v.9.0.6.2 was used to create and analyze Statistical models. The choice of the regression model depends, first of all, on the available number of experimental points.

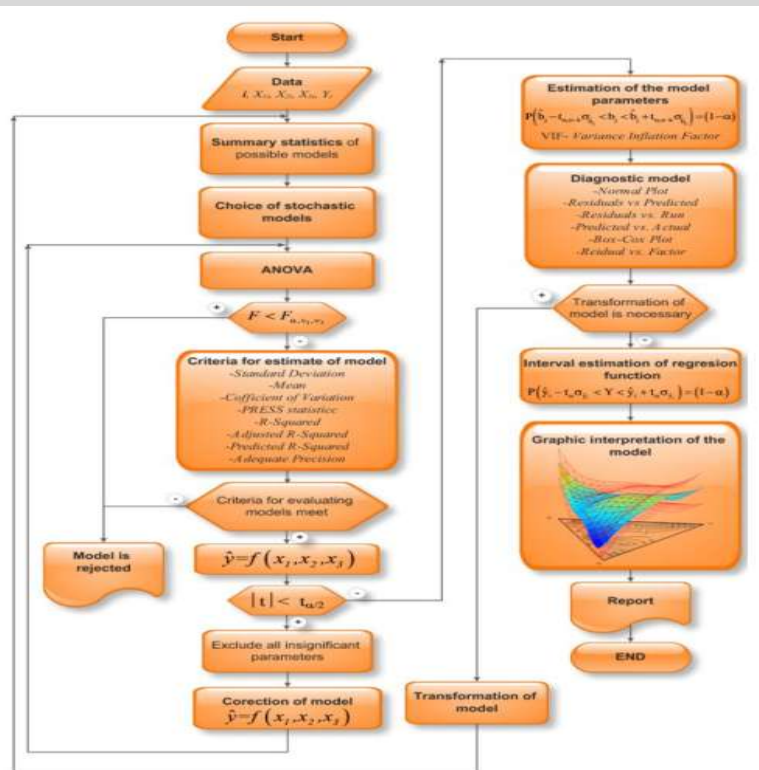
The sound absorption coefficient can be expressed by a polynomial function, as given in the expression for open and partially open cell polyurethane foams:

$$\begin{aligned} \ln(\alpha) = & -2.15980 - 51.64481 * d - 3.46202E - 003 * f + \\ & + 0.28361 * d * f + 1164.37919 * d ^ 2 + 3.54443E - 006 * f ^ 2 - \\ & - 2.87696 * d ^ 2 * f - 1.56509E - 004 * d * f ^ 2 - 6589.93271 * d ^ 3 - \\ & - 1.19549E - 009 * f ^ 3 + 3.58649E - 004 * d ^ 2 * f ^ 2 + 11.80043 * \\ & * d ^ 3 * f + 3.97690E - 008 * d * f ^ 3 \end{aligned}$$

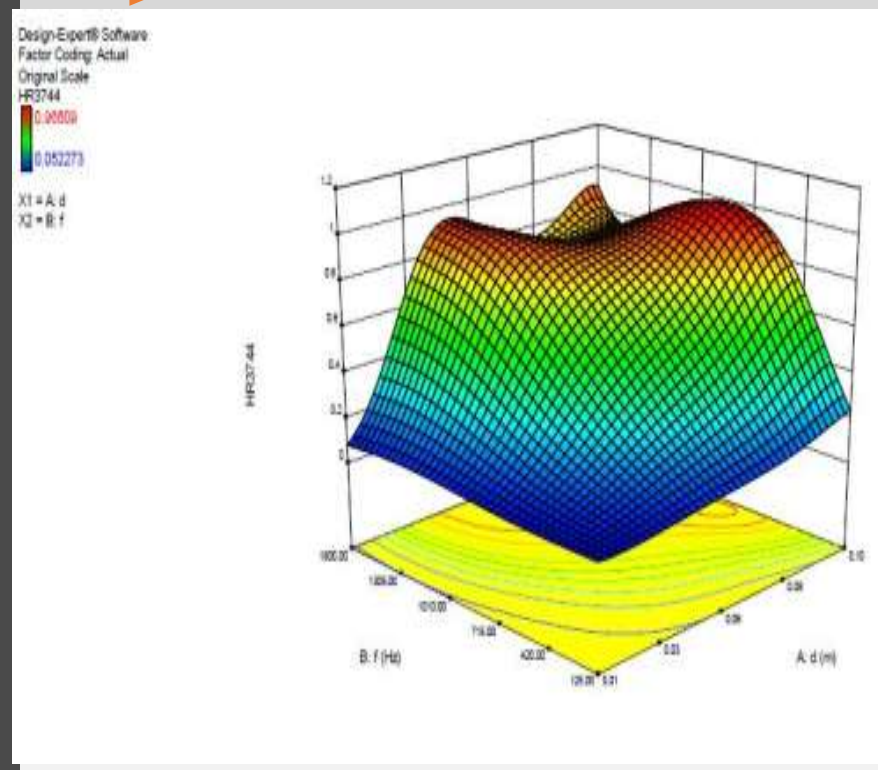
where d is the thickness of the material in m, and f is the frequency in Hz.

Acoustic properties of highly elastic polyurethane foam Vapen HR 3744

01



02







Acoustic properties of porous materials

01

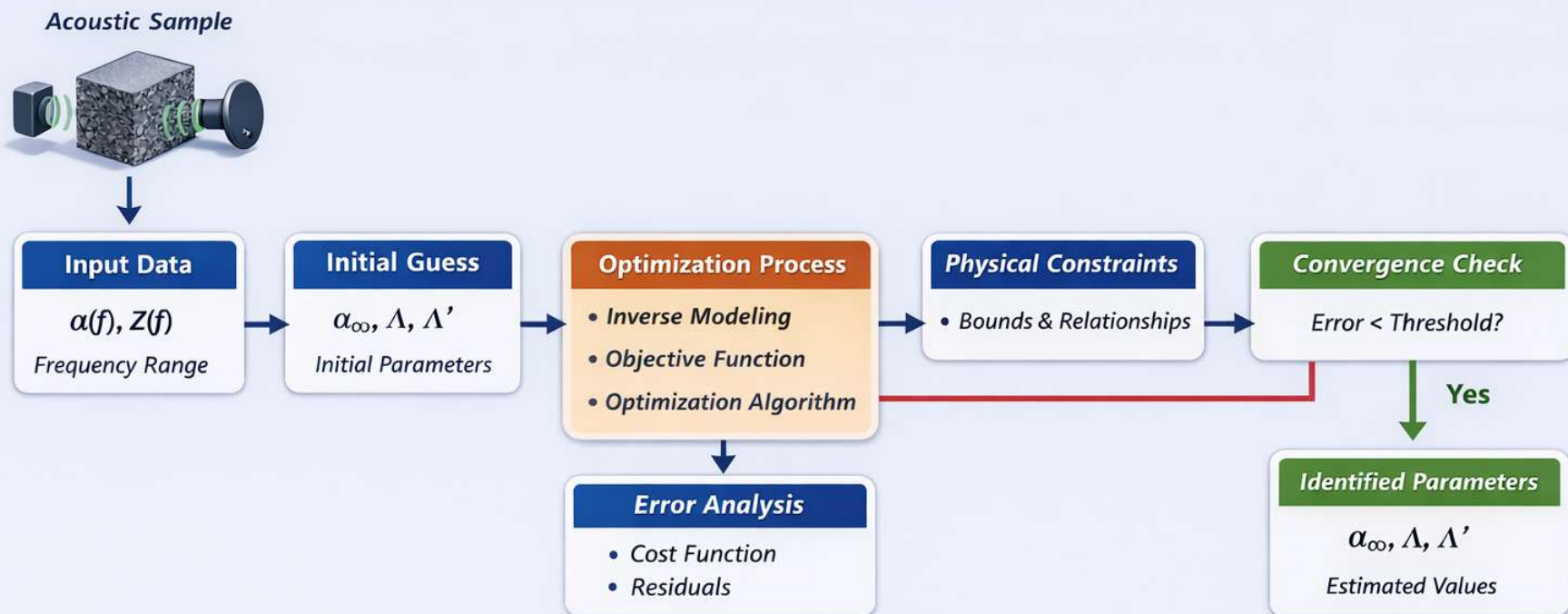
Elaborates:

1. Acoustic properties of polyurethane foams
2. Acoustic properties of granular recycled materials
3. Acoustic properties of multilayer granular recycled materials
4. Acoustic properties of fibrous materials

02

 FAKULTET ZA MAŠINSTVO I GRAĐEVINARSTVO U KRALJEVO	 UNIVERSITY OF KRAGUJEVAC  FACULTY OF MECHANICAL AND CIVIL ENGINEERING IN KRALJEVO
Факултет за машинство и грађевинарство у Краљеву Универзитета у Краљевцу, Број: 267/1 Датум: 04.03. 2016. год. Краљево, Доситејева 19.	PROJEKAT 37020 Elaborat 4/2016 AKUSTIČKA SVOJSTVA VLAKNASTIH MATERIJALA
Elaborat uradili: 1. Prof. dr Milan Kolarević 2. Mr Branko Radičević 3. Mr Mišo Bjelić 4. Vladan Grković	Overio: Dekan  Prof. dr Mile Savković
Kraljevo, mart 2016. god.	

Inverse Characterization Workflow



1. **Input Data:** Start with experimental acoustic data, representing absorption coefficient $\alpha(f)$ and impedance $Z(f)$ over a frequency range.
2. **Initial Guess:** Propose starting values for acoustic parameters $\alpha_{\infty}, \Lambda, \Lambda'$.
3. **Optimization Process:** Use inverse modeling and define an objective function to fit experimental data.
4. **Error Analysis:** Calculate error using a cost function that compares modeled vs. experimental data.
5. **Physical Constraints:** Apply parameter bounds/relationships to ensure realistic solutions.

In the JCA model, there are five non-acoustic parameters to be identified: porosity, airflow resistance, tortuosity, viscous characteristic length, and thermal characteristic length. Often this problem boils down to finding four unknown parameters, as porosity can be determined with high accuracy from measured density. In this way, the dimension of the vector $\mathbf{x} = [\sigma, \alpha_\infty, c, c']$ is reduced by one.

Non-acoustic parameter identification is essentially a constrained multidimensional parameter optimization problem.

$$\min f_{obj}(f_i, \mathbf{x}) = \sum_{i=1}^T [\alpha_{EXP}(f_i) - \alpha_{JCA}(f_i, \mathbf{x})]^2$$

$$s. t. \begin{cases} 1000 \leq \sigma \leq 20000 \\ 1 \leq \alpha_\infty \leq 4 \\ 0.3 \leq (c, c') \leq 3.3 \\ c \geq c' \end{cases}$$

where T is the number of sampling frequency points in the test frequency range, f_i is the i th frequency point sampled in the experiment, α_{EXP} denotes the sound absorption coefficient measured at the frequency f_i and α_{JCA} denotes the sound absorption coefficient predicted by the JCA model at the same frequency.

04

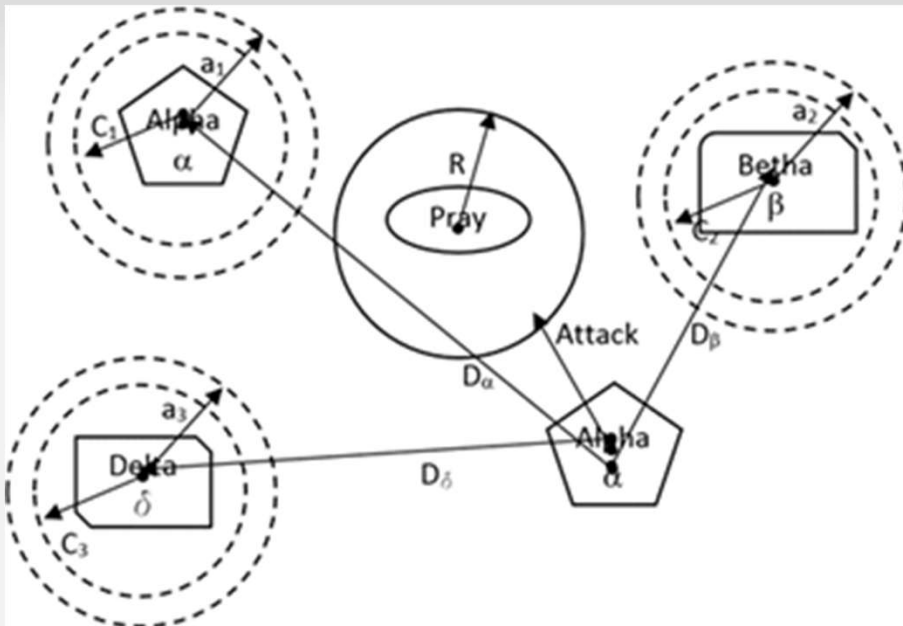
MODELS FOR PREDICTING THE ACOUSTIC PROPERTIES OF POROUS MATERIALS

5. An example of an optimization model Dulović T. & Radičević B.

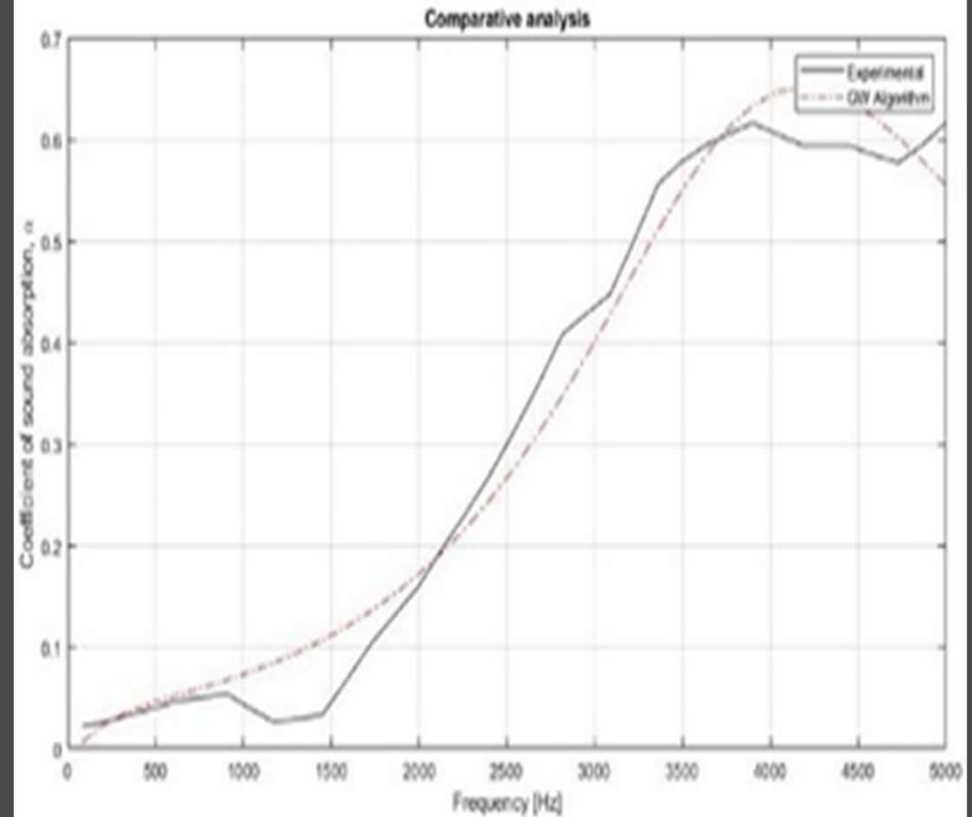
Optimization of non-acoustic parameters of fibrous materials using biologically inspired algorithms

01

Illustration of updating search agent positions in the GWO algorithm



02



AI models learn the relationship between material properties and acoustic response directly from data, without explicit physical equations.

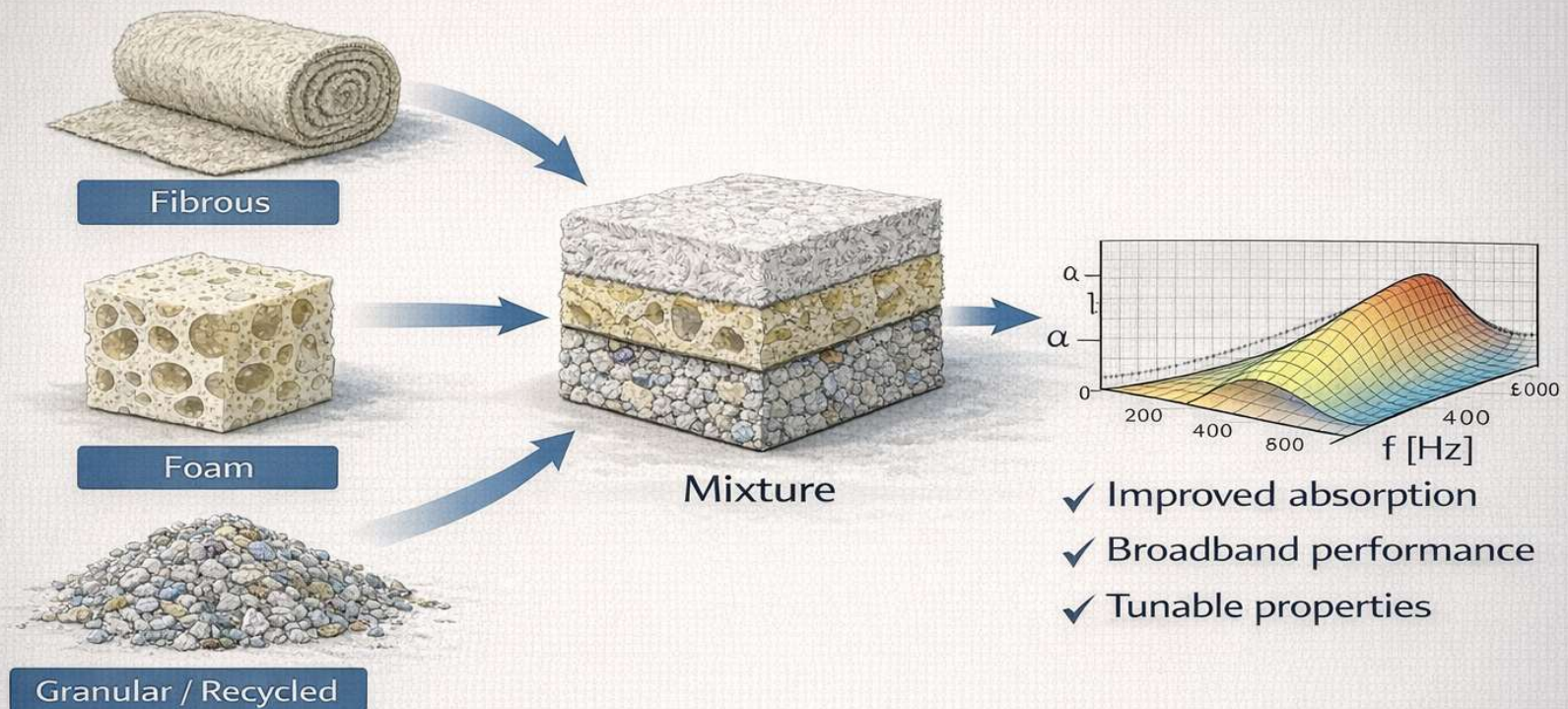
$$y = \mathcal{F}(x; \theta)$$
$$\alpha(f) = \mathcal{F}(f, \sigma, \phi, \alpha_{\infty}, \Lambda, \Lambda'; \theta)$$

$$\theta^* = \arg \min_{\theta} \sum_{i=1}^N [\alpha_i^{exp} - \mathcal{F}(x_i; \theta)]^2$$

where: x — input parameters (frequency, airflow resistivity, porosity, microstructure)
 y — acoustic response (e.g., $\alpha(f)$)
 θ — model parameters learned from data

Valid only within the domain of the training dataset.

Mixtures of Materials



Combination of materials enables optimization of acoustic performance

Design of mixtures becomes an optimization problem



a) Recycled rubber



b) Recycled plastic



c) Sand



Different thicknesses of samples: 10 mm, 20 mm, 30 mm, 40 mm, 50 mm



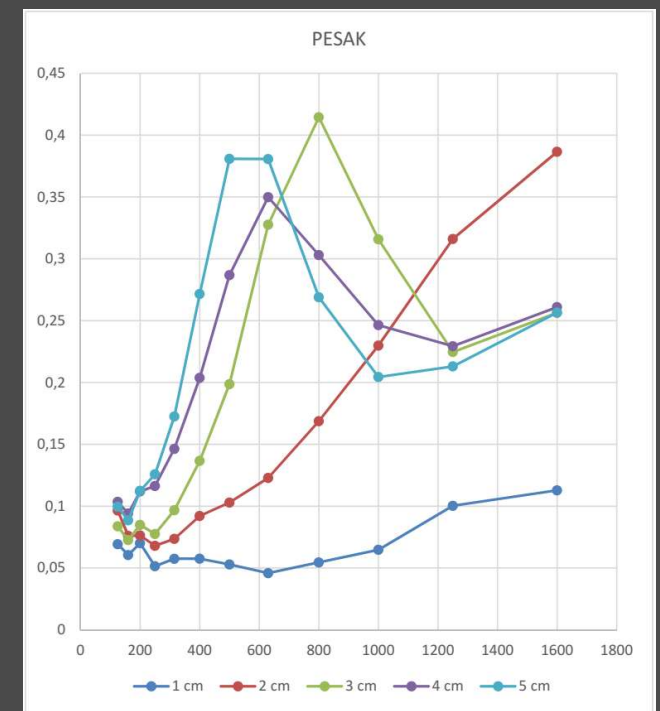
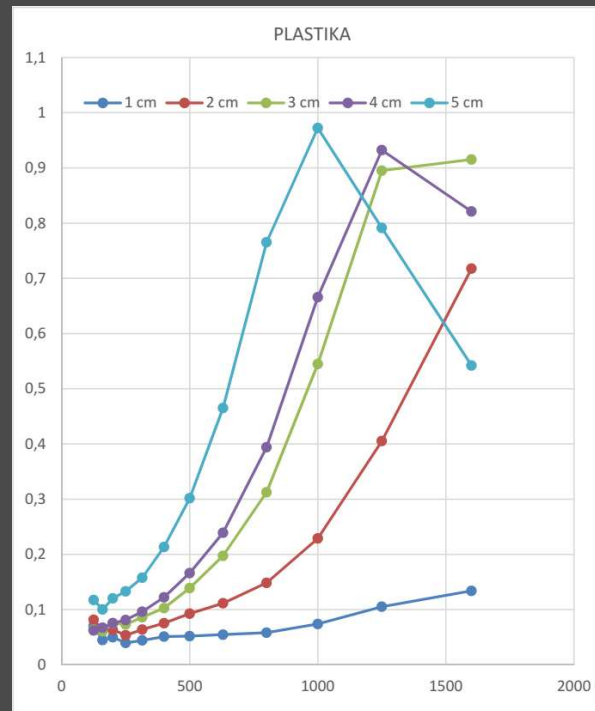
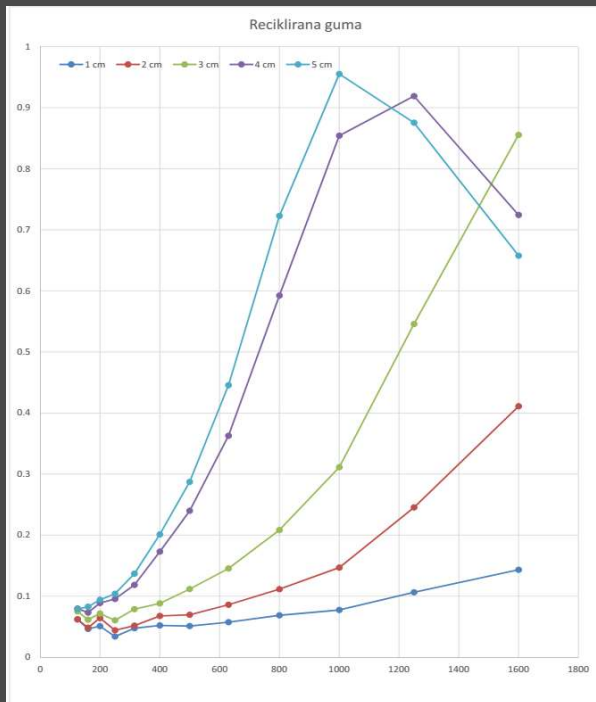
a) Recycled rubber



b) Recycled plastic



c) Sand

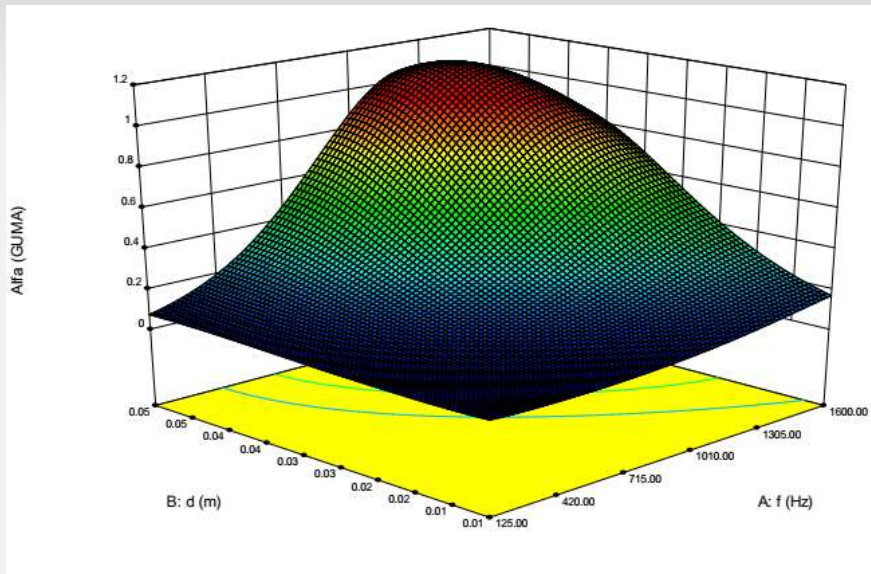


Sound absorption coefficient at normal incidence

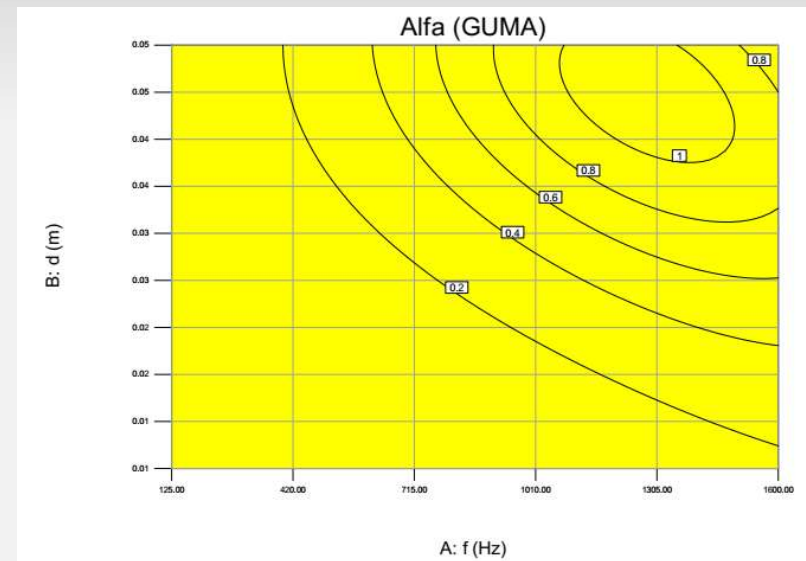
Sound absorption coefficient for recycled rubber:

3D representation of the statistical model; 2- contour diagram

01



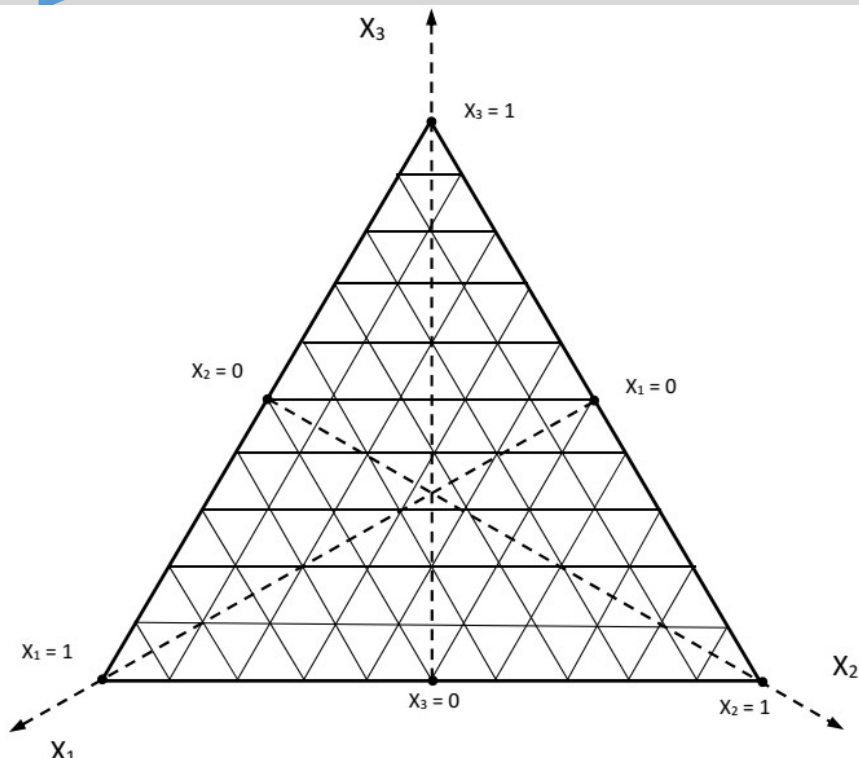
02



Absorption properties of the mixture of granular materials

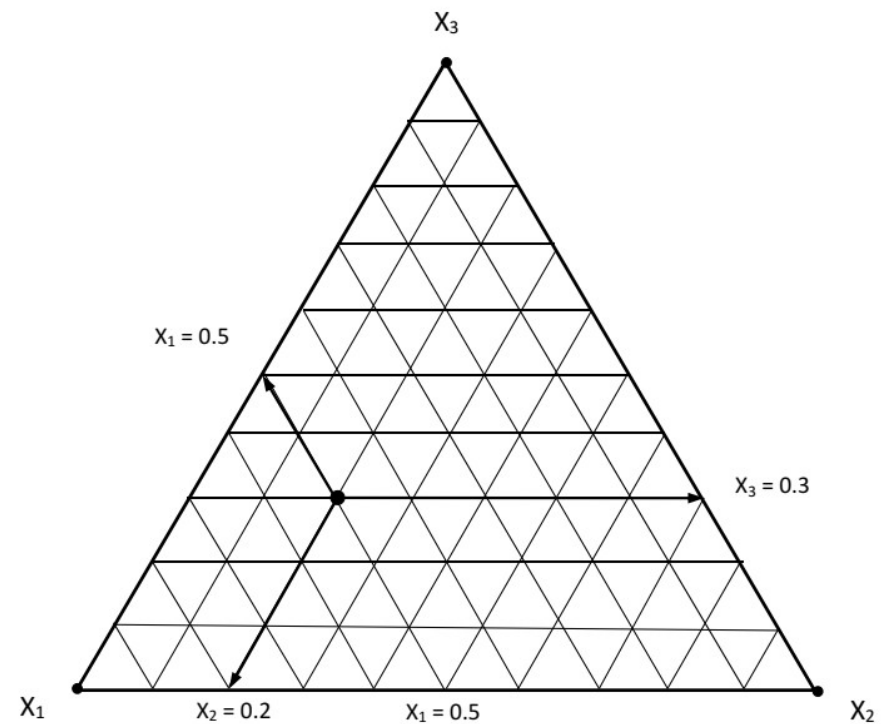
01

$$0 \leq X_i \leq 1; \quad \sum_{i=1}^3 X_i = 1$$



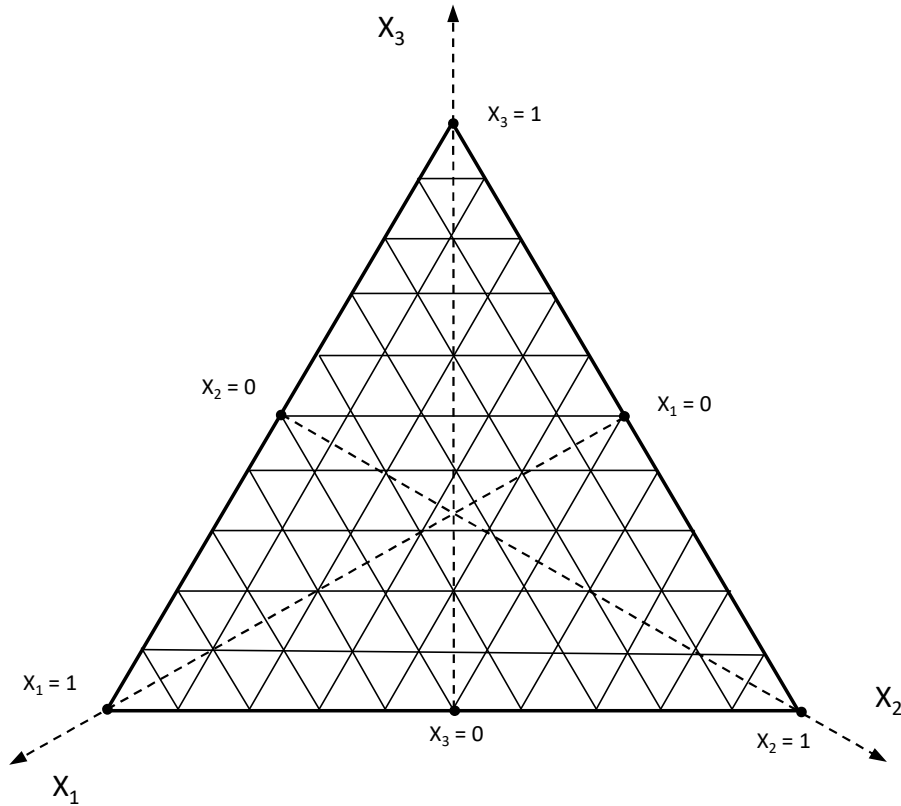
02

Simplex – Centroid design



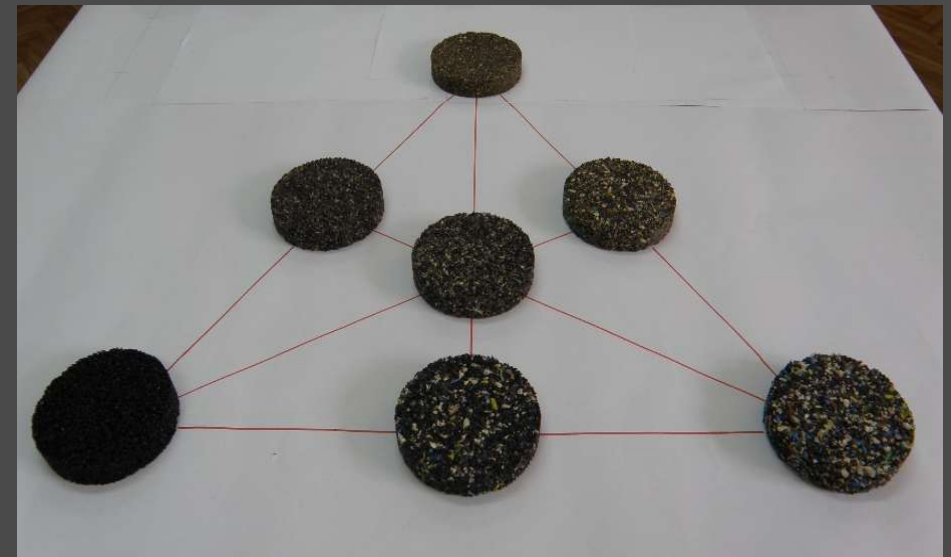
ABSORPTION PROPERTIES OF GRANULAR MATERIALS AND THEIR MIXTURES

Simplex – Centriod Design



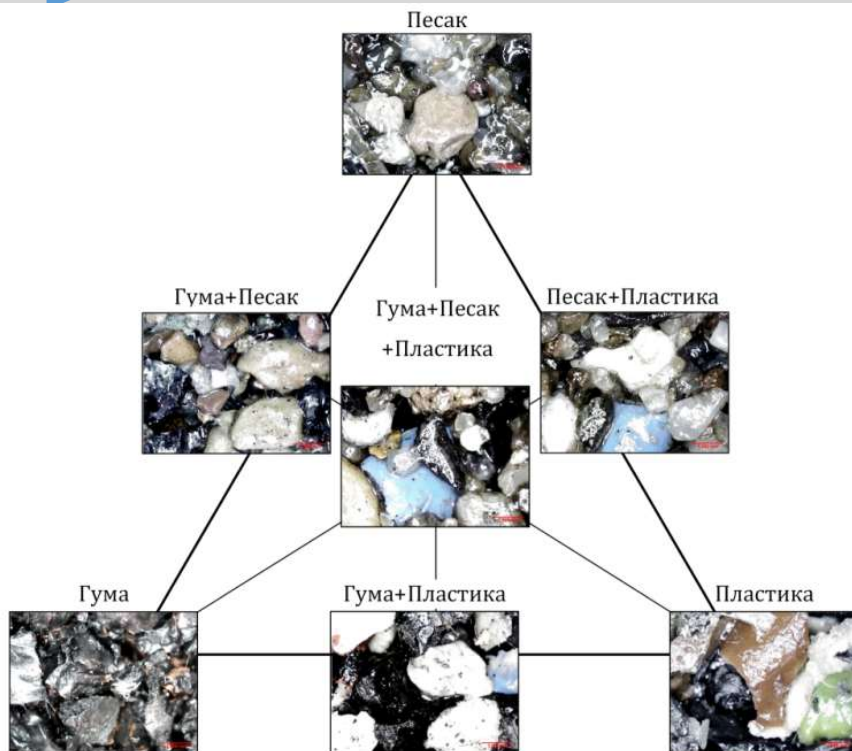
p.бp.	X1	X2	X3	Y
1	1	0	0	
2	0	1	0	
3	0	0	1	
4	1/2	0	1/2	
5	1/2	1/2	0	
6	0	1/2	1/2	
7	1/3	1/3	1/3	

$$0 \leq X_i \leq 1; \quad \sum_{i=1}^3 X_i = 1$$



Three-component Simplex - Centroid design

01



02

р.бр.	X1	X2	X3	Y
1	1	0	0	
2	0	1	0	
3	0	0	1	
4	1/2	0	1/2	
5	1/2	1/2	0	
6	0	1/2	1/2	
7	1/3	1/3	1/3	

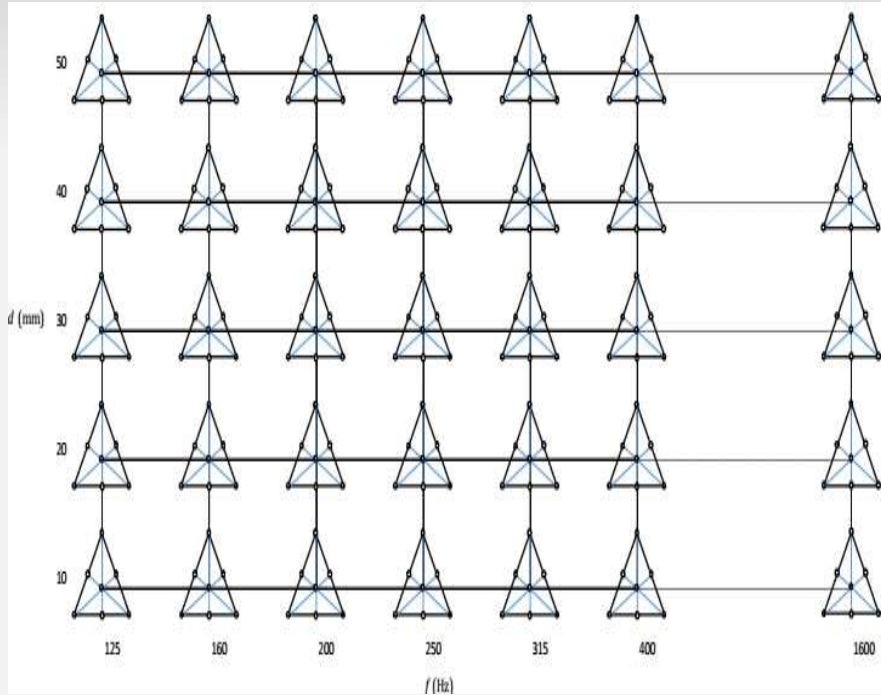
05

ABSORPTION PROPERTIES OF GRANULAR MATERIALS AND THEIR MIXTURES

Mix (seven mixes) - Process

(60 process combinations; 5 sample thicknesses x 12 frequencies)

01



02



Coefficients of sound absorption for the combined process ternary mixture system

	P	G	S	δ [m]	α_{125}	α_{160}	α_{200}	α_{250}	α_{315}	α_{400}	α_{500}	α_{630}	α_{800}	α_{1000}	α_{1250}	α_{1600}
1	1	0	0	0.01	0.070452	0.045009	0.049988	0.039622	0.04424	0.0511	0.05196	0.054693	0.058152	0.073966	0.10531	0.13402
2	0	1	0	0.01	0.062079	0.046224	0.050688	0.033774	0.047438	0.052127	0.051058	0.057375	0.068572	0.077245	0.1062	0.14311
3	0	0	1	0.01	0.069242	0.060486	0.070067	0.051438	0.057444	0.057496	0.052838	0.045833	0.054505	0.06469	0.1003	0.11278
4	0.5	0	0.5	0.01	0.061304	0.036248	0.048701	0.036698	0.042091	0.043814	0.045054	0.051551	0.054799	0.073381	0.1089	0.1525
5	0.5	0.5	0	0.01	0.062953	0.04804	0.05439	0.044433	0.046279	0.049541	0.058912	0.05864	0.068345	0.081494	0.12031	0.17677
6	0	0.5	0.5	0.01	0.063384	0.047264	0.056085	0.037869	0.041937	0.053909	0.055349	0.054347	0.050953	0.060534	0.088065	0.12138
7	0.333333	0.333333	0.333333	0.01	0.063945	0.04625	0.047412	0.036987	0.045137	0.04031	0.046517	0.050349	0.060005	0.057798	0.091821	0.117
8	1	0	0	0.02	0.081595	0.061678	0.063427	0.053593	0.063935	0.07538	0.092672	0.11156	0.14845	0.22894	0.40526	0.71772
9	0	1	0	0.02	0.061709	0.048147	0.064102	0.043948	0.051707	0.067505	0.069412	0.086028	0.11138	0.14664	0.24529	0.41097
10	0	0	1	0.02	0.096456	0.075953	0.076318	0.067965	0.073531	0.092069	0.1029	0.12281	0.16871	0.22988	0.31607	0.38652
11	0.5	0	0.5	0.02	0.076063	0.058565	0.061085	0.043429	0.051713	0.065842	0.069842	0.090939	0.12477	0.20207	0.39709	0.76784
12	0.5	0.5	0	0.02	0.070525	0.057695	0.067191	0.056772	0.067988	0.072218	0.088029	0.095433	0.12375	0.17236	0.29117	0.50631
13	0	0.5	0.5	0.02	0.069716	0.053088	0.056022	0.040519	0.053535	0.06044	0.063834	0.079099	0.095854	0.13028	0.22188	0.42656
14	0.333333	0.333333	0.333333	0.03	0.055764	0.049572	0.058652	0.050239	0.055844	0.054032	0.062872	0.080362	0.1023	0.14315	0.24061	0.45639
15	1	0	0	0.03	0.063608	0.060597	0.075185	0.073073	0.086204	0.10281	0.13902	0.19746	0.31262	0.54481	0.89514	0.91522
16	0	1	0	0.03	0.074983	0.061382	0.071529	0.060364	0.078651	0.08809	0.11152	0.14524	0.20821	0.31118	0.54574	0.85543
17	0	0	1	0.03	0.083674	0.072598	0.084838	0.077476	0.096708	0.1366	0.19858	0.32756	0.41452	0.31575	0.22462	0.25632
18	0.5	0	0.5	0.03	0.070199	0.055836	0.066542	0.056816	0.066865	0.07809	0.10382	0.14289	0.24503	0.47612	0.86704	0.72912
19	0.5	0.5	0	0.03	0.061029	0.04762	0.068866	0.065002	0.083531	0.10365	0.13602	0.19208	0.29267	0.49274	0.83553	0.93465
20	0	0.5	0.5	0.03	0.082031	0.063325	0.072213	0.052395	0.069477	0.081273	0.10389	0.14802	0.22557	0.40767	0.77296	0.85942
21	0.333333	0.333333	0.333333	0.03	0.093553	0.065694	0.075066	0.063166	0.078213	0.092387	0.11411	0.15065	0.22941	0.37302	0.68961	0.9415
22	1	0	0	0.04	0.062299	0.067244	0.075543	0.081245	0.096306	0.1223	0.16619	0.23917	0.39413	0.66599	0.93225	0.82113
23	0	1	0	0.04	0.079582	0.072933	0.088792	0.095229	0.11827	0.17284	0.23979	0.36262	0.5924	0.85416	0.91899	0.72432
24	0	0	1	0.04	0.10345	0.094052	0.11187	0.11633	0.14634	0.20372	0.2868	0.34987	0.30303	0.24638	0.22934	0.26097
25	0.5	0	0.5	0.04	0.072322	0.061728	0.073841	0.073893	0.08784	0.12287	0.16892	0.27597	0.52809	0.83943	0.6975	0.40698
26	0.5	0.5	0	0.04	0.074103	0.06105	0.081838	0.096466	0.11467	0.1599	0.22956	0.35045	0.5957	0.89451	0.93591	0.6952
27	0	0.5	0.5	0.04	0.079104	0.073428	0.082008	0.084074	0.10526	0.14418	0.22217	0.38276	0.68574	0.77131	0.5062	0.34599
28	0.333333	0.333333	0.333333	0.05	0.078842	0.063172	0.083348	0.081497	0.10005	0.13135	0.18318	0.28177	0.49341	0.80483	0.86998	0.61551
29	1	0	0	0.05	0.11737	0.10029	0.12036	0.13322	0.1578	0.21353	0.30182	0.46519	0.76533	0.9724	0.79133	0.54213
30	0	1	0	0.05	0.078801	0.082575	0.093929	0.10363	0.13687	0.20107	0.28714	0.44561	0.72293	0.95535	0.87541	0.65755
31	0	0	1	0.05	0.099541	0.088581	0.1124	0.12575	0.17251	0.27152	0.3808	0.38066	0.26895	0.20439	0.21299	0.25652
32	0.5	0	0.5	0.05	0.085966	0.071743	0.080933	0.087975	0.11026	0.16642	0.24218	0.41564	0.77134	0.86565	0.53466	0.3452
33	0.5	0.5	0	0.05	0.081423	0.074295	0.10126	0.10585	0.14486	0.21671	0.31949	0.50702	0.79872	0.96045	0.80367	0.59629
34	0	0.5	0.5	0.05	0.10515	0.083843	0.097138	0.10215	0.13526	0.19889	0.32398	0.56417	0.71148	0.49569	0.31468	0.2951
35	0.333333	0.333333	0.333333	0.05	0.11707	0.10131	0.11433	0.11487	0.14927	0.21394	0.32696	0.55335	0.82444	0.72728	0.46751	0.37305

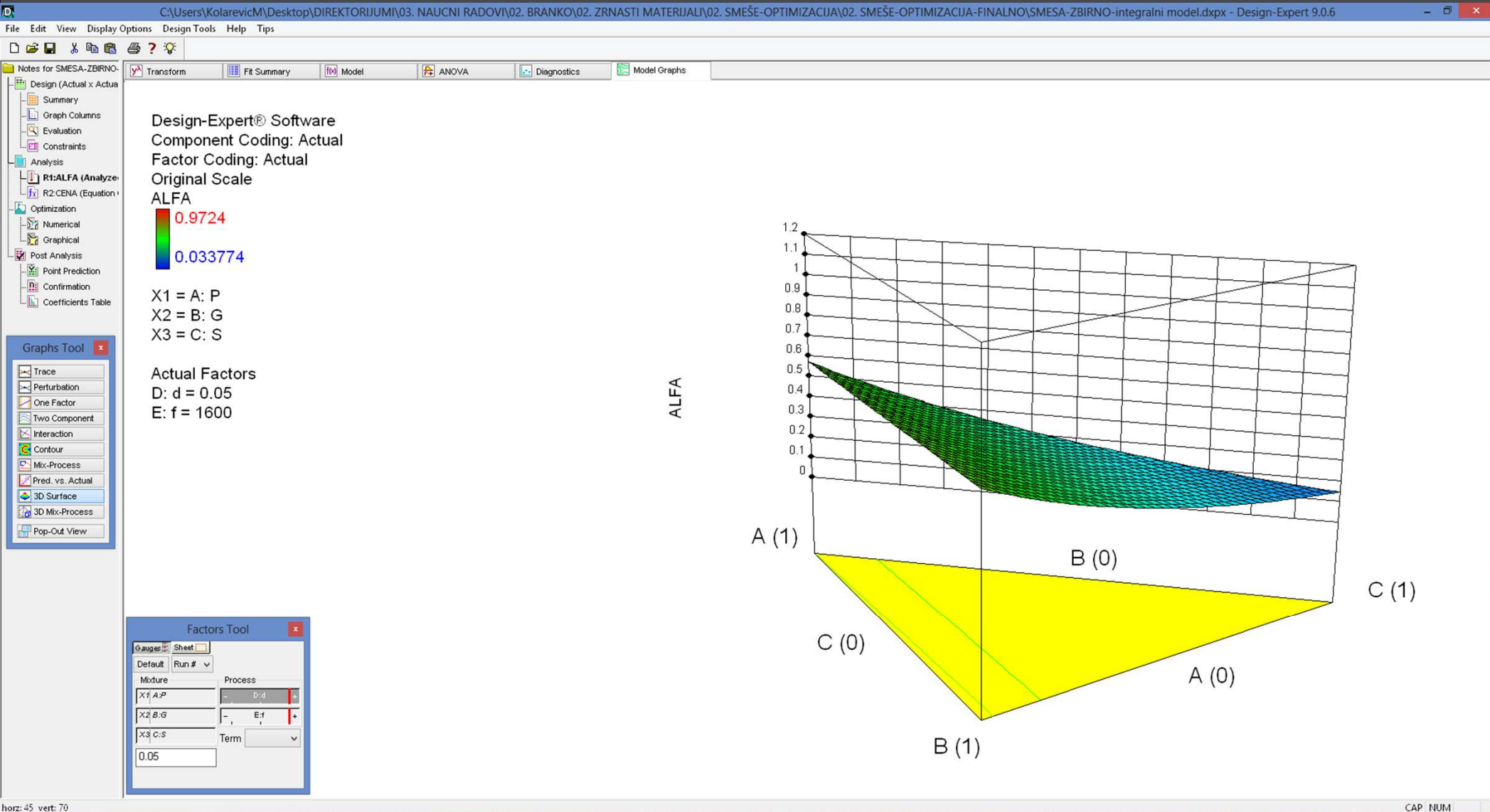
$$\text{Sqrt}(\alpha_{1000}) = +0.092256*P + 0.031084*G + 0.26795*S + 19.66709*P*d + 19.65256*G*d + 6.89378*S*d$$

Partial model

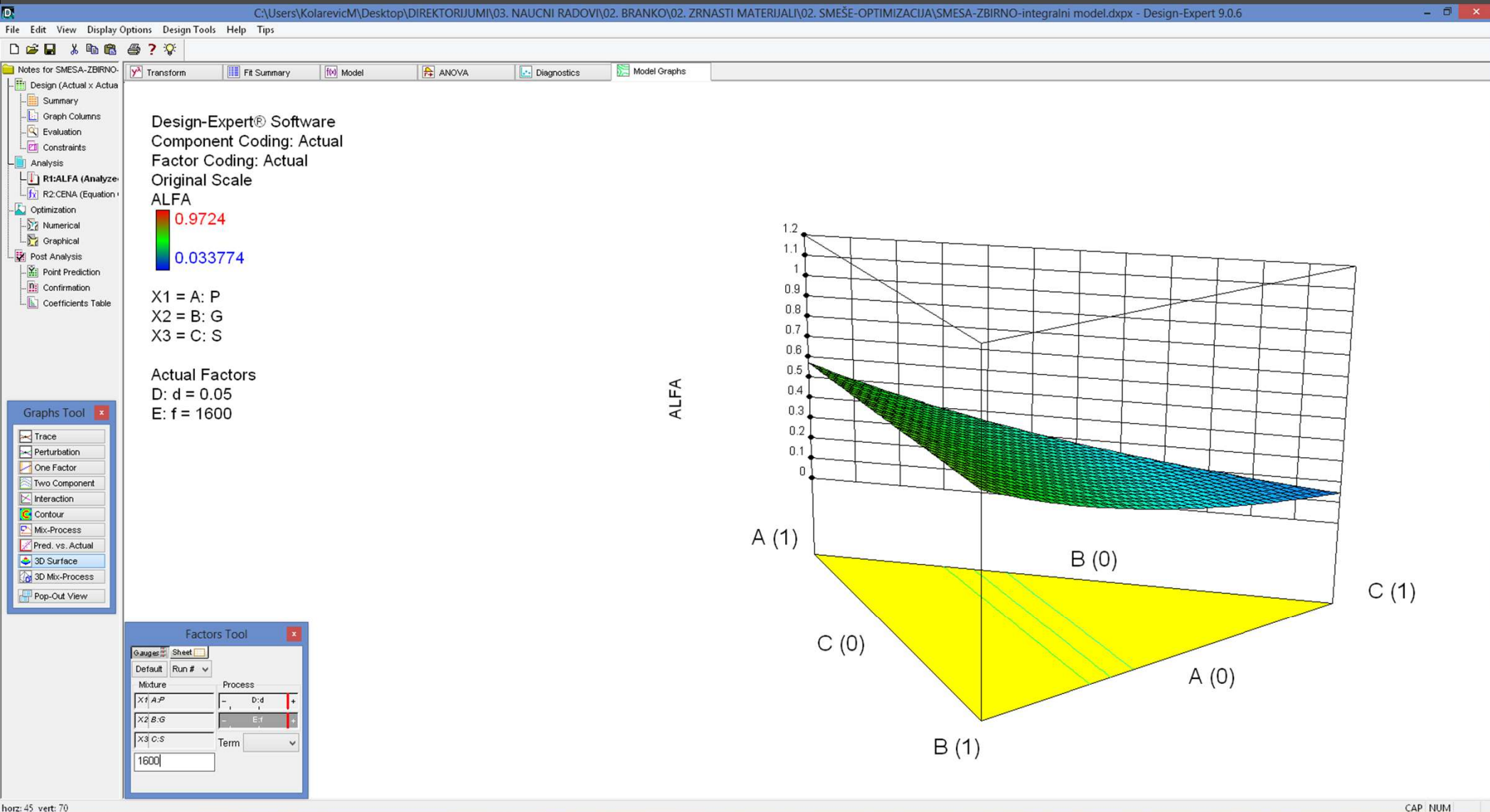
$$\begin{aligned} \text{Ln}(\alpha) = & -2.56640*P - 1.36029*G - 2.66358*S + 39.29944*P*d - 6.46000\text{E-} \\ & 003*P*f - 164.30258 *G*d - 4.94937\text{E-}003*G*f - 17.58893*S*d - \\ & 2.81482\text{E-}003*S*f + 0.29564*P*d*f + 0.25853*G*d*f + 0.22940*S*d*f - \\ & 3113.77780*P*d^2 + 6.16287\text{E-}006*P*f^2 + 4958.39446*G*d^2 \\ & + 4.19122\text{E-}006*G*f^2 + 240.05123*S*d^2 + 1.53284\text{E-}006*S*f^2 - \\ & 2.37633*P*d^2*f - 8.02769\text{E-}005*P*d*f^2 - 1.59404*G*d^2*f - \\ & 8.39546\text{E-}005*G*d*f^2 - 1.79297*S*d^2*f - 7.50789\text{E-}005*S*d*f^2 \\ & + 44834.75170*P*d^3 - 1.73298\text{E-}009*P*f^3 - 47640.77867*G*d^3 - \\ & 9.18196\text{E-}010*G*f^3 \end{aligned}$$

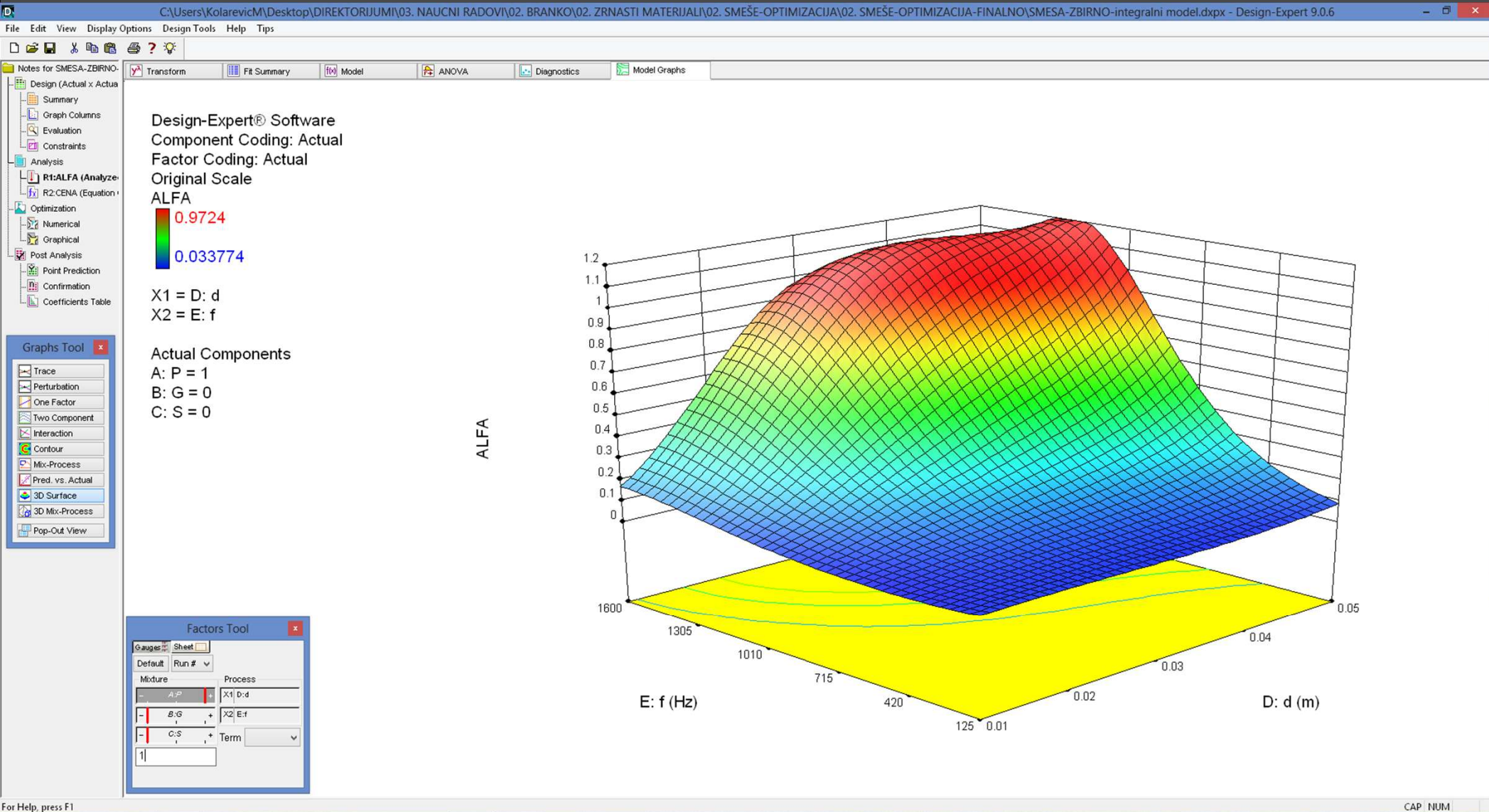
Integral model

Mixture combination - process

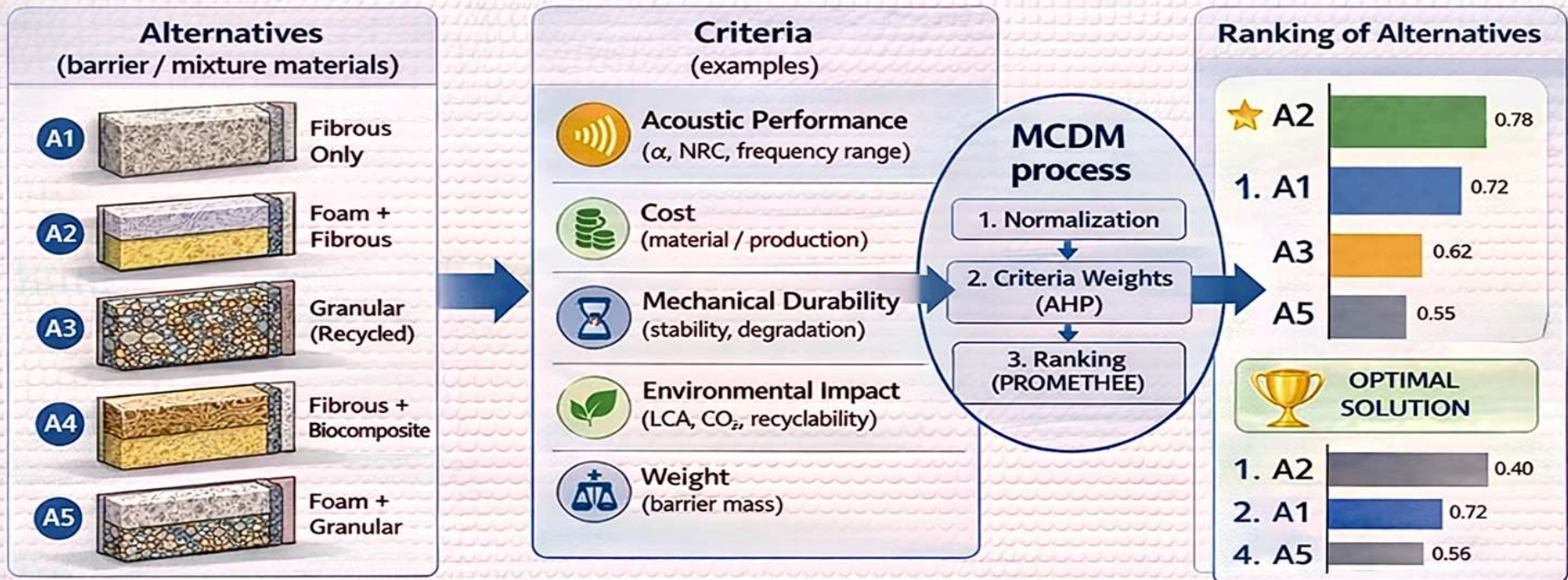


Mixture combination - process





Multi-Criteria Optimization (MCDM) Selection of the Best Barrier / Mixture



Goal: Find the best barrier / mixture through a compromise between multiple criteria
Optimization requires balancing acoustic, cost, durability, and sustainability



Why is Noise Barrier Design a **Complex Problem**?

Looks Simple

Panel



Absorber



Reality



Standards



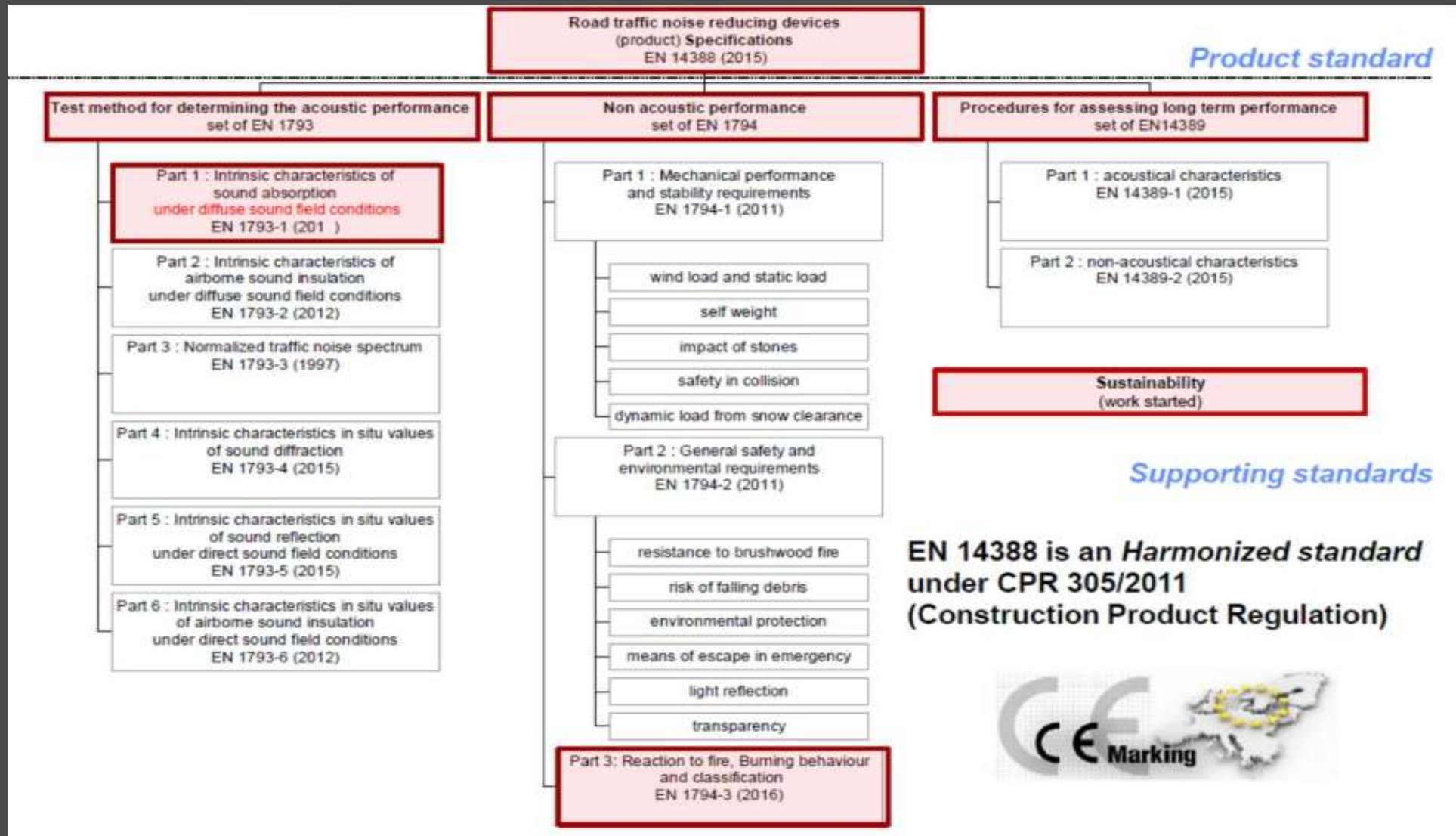
Constraints



Conflicting Criteria

! Optimization under Constraints \neq Simple Design

MULTI-CRITERIA OPTIMIZATION FOR THE SELECTION OF SOUND-ABSORBING MATERIALS



Overview of acoustic standards (EN 1793)

- EN 1793-1 (Laboratory)
- CEN/TS 1793-5 (In-situ)

Reflection

Source



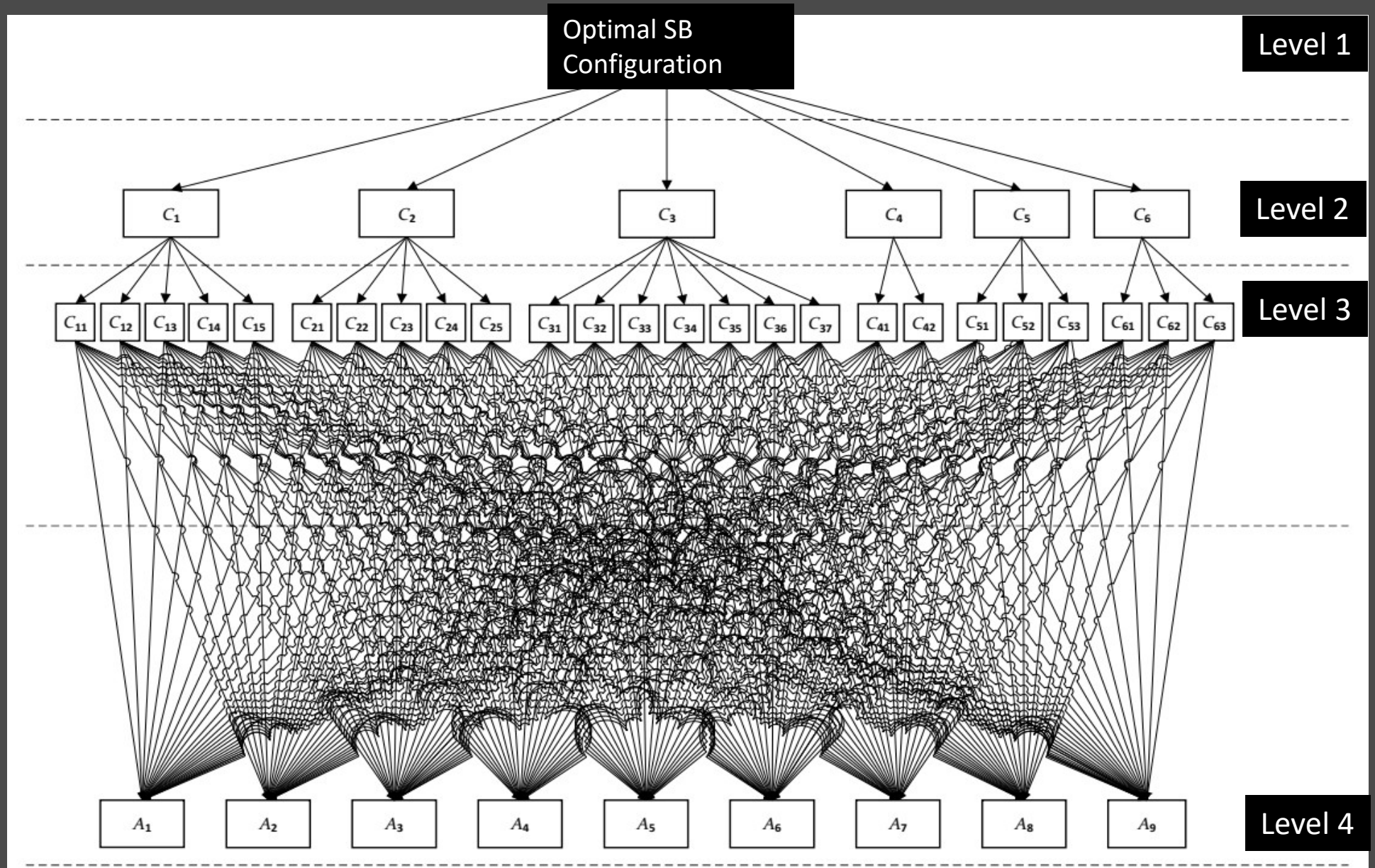
- CEN/TS 1793-4 (In-situ)

Diffraction

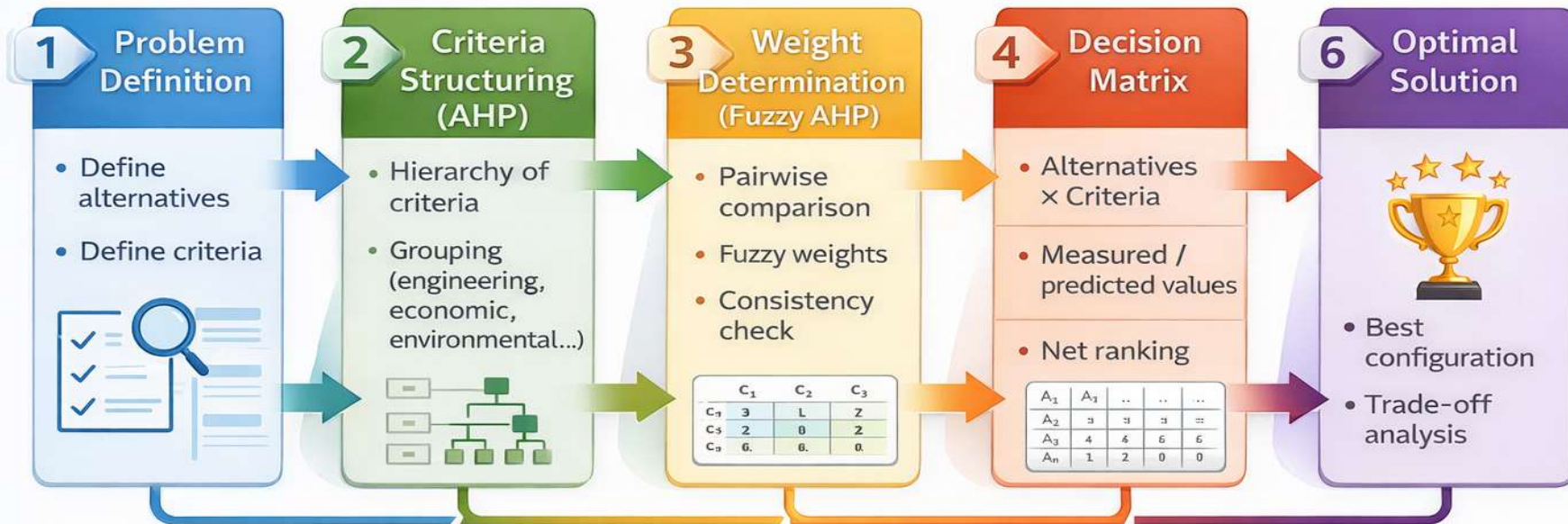
Receiver

Transmission

- EN 1793-2 (Laboratory)
- EN 1793-6 (In-situ)



Multi-Criteria Optimization Workflow (AHP + PROMETHEE)



Trade-off Visualization

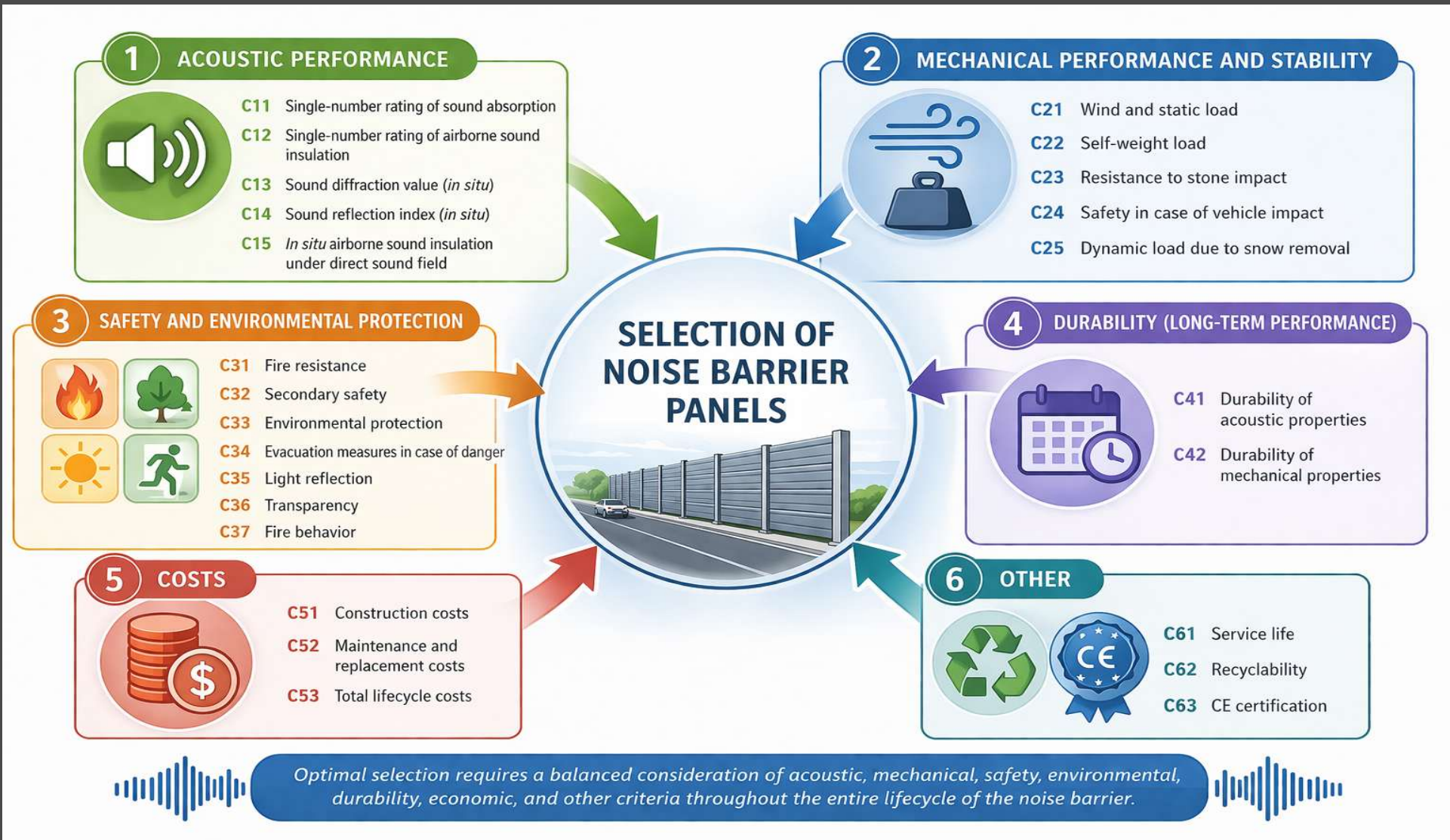
- Acoustic performance \uparrow
- Cost \downarrow
- Sustainability \uparrow



- Preference functions
- Positive / negative flows
- Net ranking



Classification of criteria for selecting traffic noise barriers



Calculation of criteria weighting coefficients

Fuzzy Analytic Hierarchy Process Excel Spreadsheet Decision Support System



University of Kragujevac. Faculty of Mechanical and Civil Engineering in Kraljevo
Department of Production Engineering



Version 1.1

Saaty's scale for comparison in pairs

Judgments of the pairwise comparison (presude u uporedivanju parova)																		
Factor <i>i</i>	Factor weighting score																Factor <i>j</i>	
	More important than								Equal	Less important than								
value	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	value
	9	8	7	6	5	4	3	2	1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9	
If the judgment value is on the right side of 1, we put the reciprocal value																		
If the judgment value is on the right side of 1, we put the reciprocal value																		

Number of Criteria

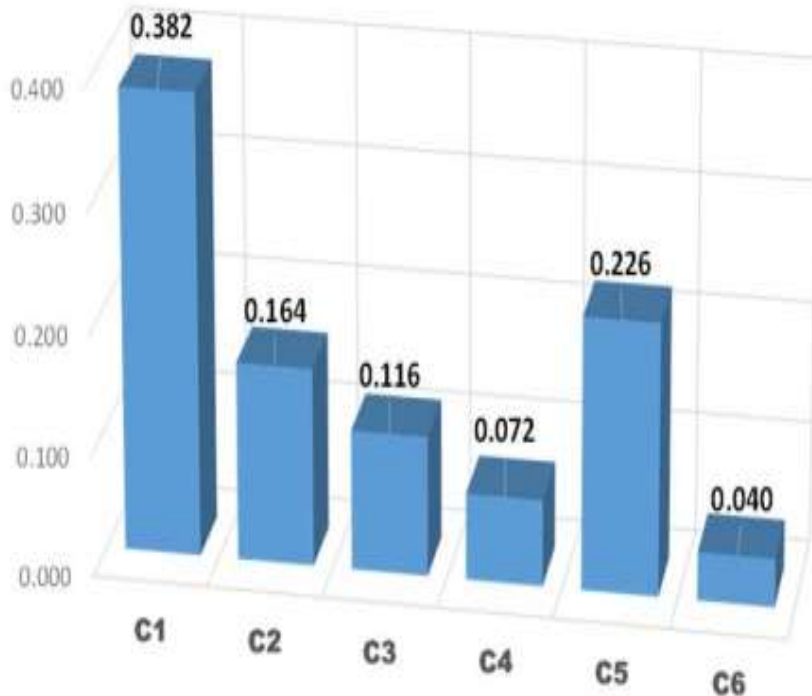
≤ γ ≤

Comparison matrix (Matrica proredenja kriterijuma)

Criteria																					
		1		2		3		4		5		6		7		8		9		10	
		C1	γ ₁	C2	γ ₂	C3	γ ₃	C4	γ ₄	C5	γ ₅	C6	γ ₆	C7	γ ₇	C8	γ ₈	C9	γ ₉	C10	γ ₁₀
1	C1	1	1	3.00	0.67	4.00	0.75	5.00	0.75	2.00	0.50	9.00	0.70								
2	C2			1	1	2.00	0.50	3.00	0.50	0.50	0.50	4.00	0.67								
3	C3					1	1	2.00	0.55	0.50	0.67	4.00	0.67								
4	C4							1	1	0.33	0.60	2.00	0.50								
5	C5									1	1	5.00	0.67								
6	C6											1	1								
7	C7													1	1						
8	C8															1	1				
9	C9																	1	1		
10	C10																			1	1

Importance of criteria in the model

Criteria significance levels in a model
(Prikaz važnosti kriterijuma u modelu)



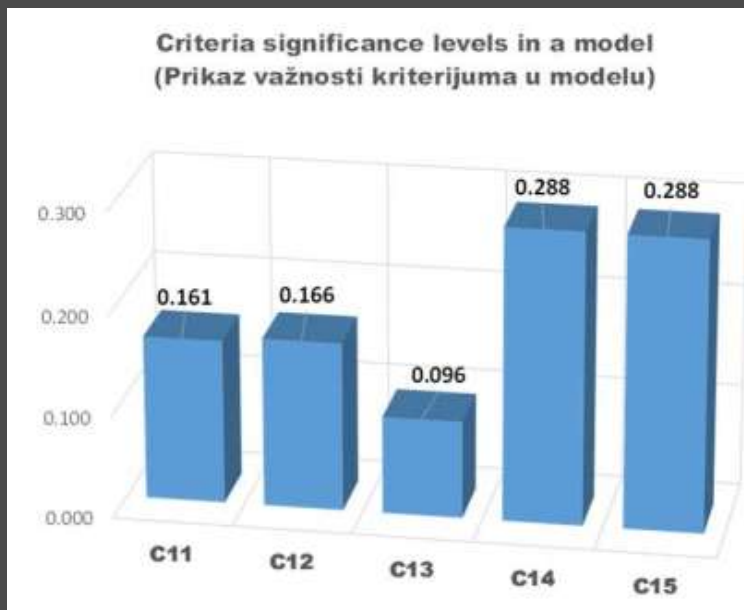
Consistency analysis

C_i	W_i	Sv_i	C.M.
C1	0.382	2.4736	6.467
C2	0.164	1.0476	6.390
C3	0.116	0.7423	6.407
C4	0.072	0.4514	6.284
C5	0.226	1.4354	6.359
C6	0.040	0.2571	6.401
SUM	1.000	$\lambda_{\max} =$	6.385
		CI =	0.077
		Ri =	1.236
		C.R =	0.062

Sub-criteria comparison matrix

	C11	γ_1	C12	γ_2	C13	γ_3	C14	γ_4	C15	γ_5
C11	1	1	1.00	0.67	2.00	0.60	0.50	0.50	0.50	0.67
C12			1	1	2.00	0.50	0.50	0.50	0.50	0.50
C13					1	1	0.33	0.67	0.33	0.67
C14							1	1	1.00	0.67
C15									1	1

Display of the importance of subcriteria in the model



Consistency analysis

Cij	W_i	Sv_i	C.M.
C11	0.161	0.8517	5.275
C12	0.166	0.8720	5.247
C13	0.096	0.4964	5.167
C14	0.288	1.5198	5.268
C15	0.288	1.5198	5.281
Σ	1.000	$\lambda_{max} =$	5.247
		CI =	0.062
		Ri =	1.116
		C.R =	0.055

Alternatives

- **A1:** Magnum AC
- **A2:** Magnum AL12
- **A3:** UniCon A
- **A4:** UniCon R
- **A5:** KOHLHAUER ALUMNA
- **A6:** KOHLHAUER LIGNA
- **A7:** KOHLHAUER LIGNA 2
- **A8:** KOHLHAUER ALUFERA
- **A9:** KOHLHAUER PLANTA

Decision matrix

		1				
		АКУСТИЧКЕ ПЕРФОРМАНСЕ				
W_i		0.372				
		1.1	1.2	1.3	1.4	1.5
ij			Изолација од ваздушног звука	Дифракциј а звука	Рефлексиј а и изолација звука In Situ	In Situ вредност изолације ваздушног звука
	КРИТЕРИЈУМ СТАНДАРДА	EN 1793-1	EN 1793-2	EN 1793-4	EN 1793-5	EN 1793-6
Анекс стандарда						
W_{ij}		0.162	0.162	0.101	0.282	0.292
W_{ij}		0.060	0.060	0.038	0.105	0.108
ИНДИКАТОР		DL_{α} [dB]	DL_R [dB]	ΔDL [dB]	DL_{Ri} [dB]	DL_{S1} [dB]
		C11	C12	C13	C14	C25
A1	Magnum AC	5	4	0	0	0
A2	Magnum AL12	5	4	0	0	0
A3	UniCon A	4	4	0	0	0
A4	UniCon R	0	4	0	0	0
A5	KOHLHAUER ALUMNA	4	4	0	0	0
A6	KOHLHAUER LIGNA	4	4	0	0	0
A7	KOHLHAUER LIGNA 2	4	4	0	0	0
A8	KOHLHAUER ALUFERA	4	4	0	0	0
A9	KOHLHAUER PLANTA	4	4	0	0	0

Evaluation and ranking of alternatives



Method **MODIPROM** Version 1.2

Decision Support System

University of Kragujevac. Faculty of Mechanical and Civil Engineering in Kraljevo
Department of Production Engineering



Project Title: *Звучне баријере*

Date: 04.05.2024.

Signature: *М. Коларевић*

DESCRIPTION:

Избор оптималног панела за саобраћајну звучну баријеру

Alternatives: **9**

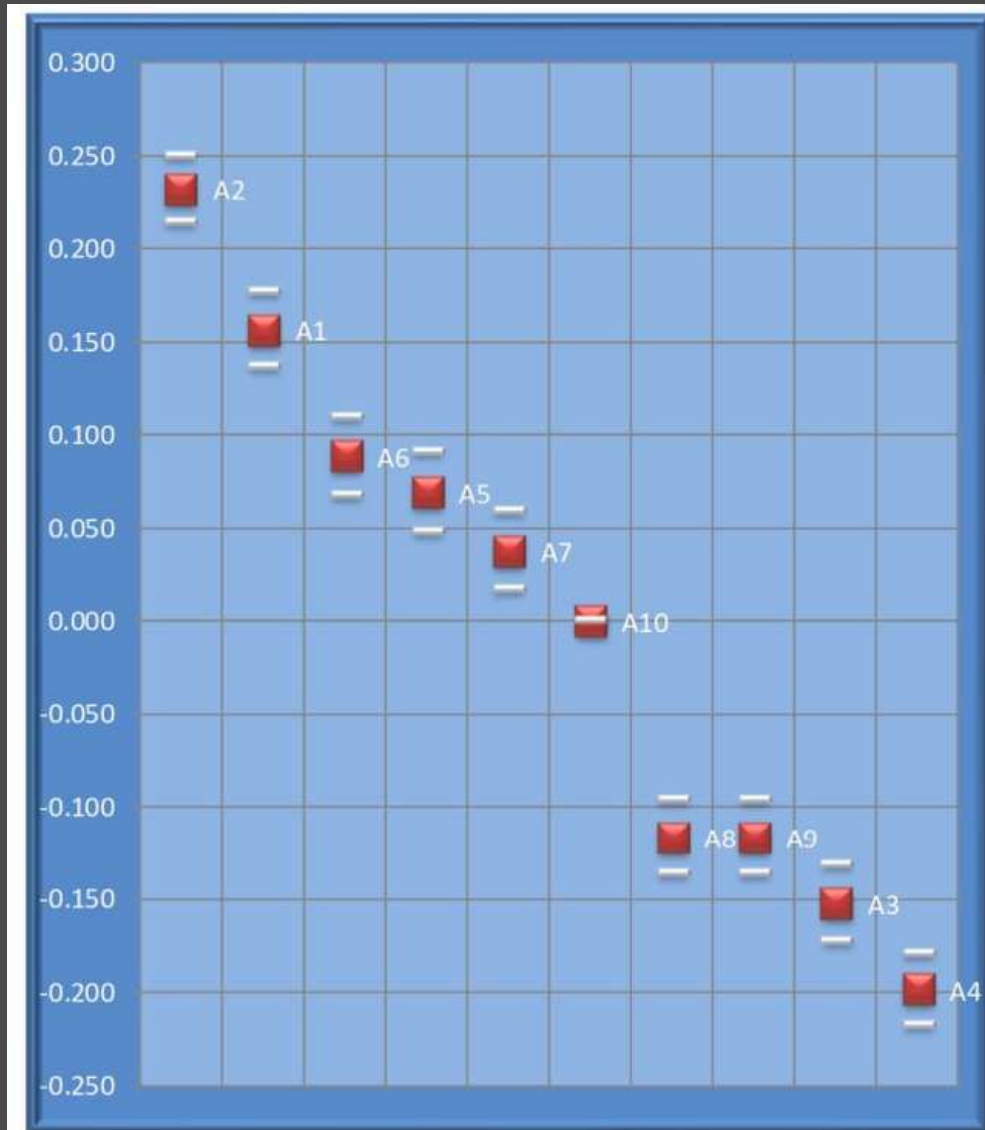
Criteria: **25**

$\alpha =$ **0.15**

Decision matrix

		Alternatives										Weight Wj	min/max
		A1	A2	A3	A4	A5	A6	A7	A8	A9	A10		
Criteria	C1	5	5	4	0	4	4	4	4	4	4	0.0618	max
	C2	4	4	4	4	4	4	4	4	4	4	0.0636	max
	C3	0	0	0	0	0	0	0	0	0	0	0.0367	max
	C4	0	0	0	0	0	0	0	0	0	0	0.1103	max
	C5	0	0	0	0	0	0	0	0	0	0	0.1101	max
	C6	1	1	1	1	1	1	1	1	1	1	0.0475	max
	C7	1	1	0	0	1	1	1	1	1	1	0.0166	max
	C8	1	1	0	0	1	1	1	0	0	0	0.0258	max
	C9	1	1	0	0	1	1	1	0	0	0	0.0476	max
	C10	1	1	0	0	1	1	1	0	0	0	0.0265	max
	C11	0	1	0	0	1	1	0	0	0	0	0.0284	max
	C12	0	1	0	0	1	1	1	1	1	1	0.0177	max
	C13	0	1	0	0	1	0	0	1	1	1	0.0175	max
	C14	0	1	0	0	1	1	1	1	1	1	0.0108	max
	C15	0	1	0	0	1	1	1	1	1	1	0.0109	max
	C16	0	0	0	0	0	0	0	0	0	0	0.0021	max
	C17	0	1	0	0	1	1	0	0	0	0	0.0284	max
	C18	20	20	20	20	20	15	15	15	15	15	0.0359	max
	C19	20	20	20	20	20	15	15	15	15	15	0.0359	max
	C20	130	150	215	215	215	205	205	160	160	160	0.0453	min
	C21	100	100	120	120	120	115	115	150	150	150	0.0457	min
	C22	315	345	515	515	515	360	360	450	450	450	0.1347	min
	C23	25	30	30	30	30	20	20	15	15	15	0.0101	max
	C24	100	100	100	100	100	30	30	100	100	100	0.0101	max
	C25	0	0	0	0	1	1	1	0	0	0	0.0200	max

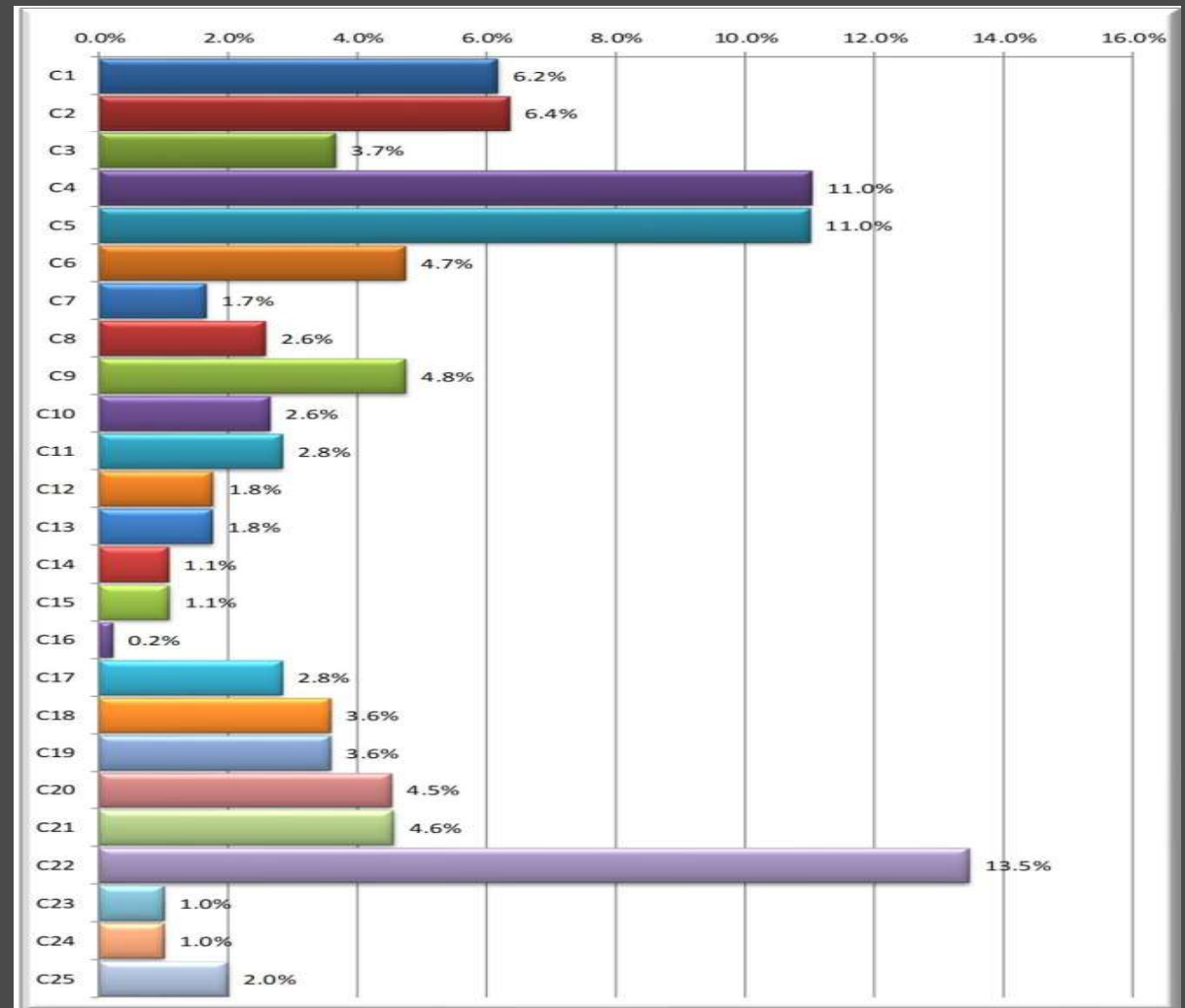
Ranking of alternatives



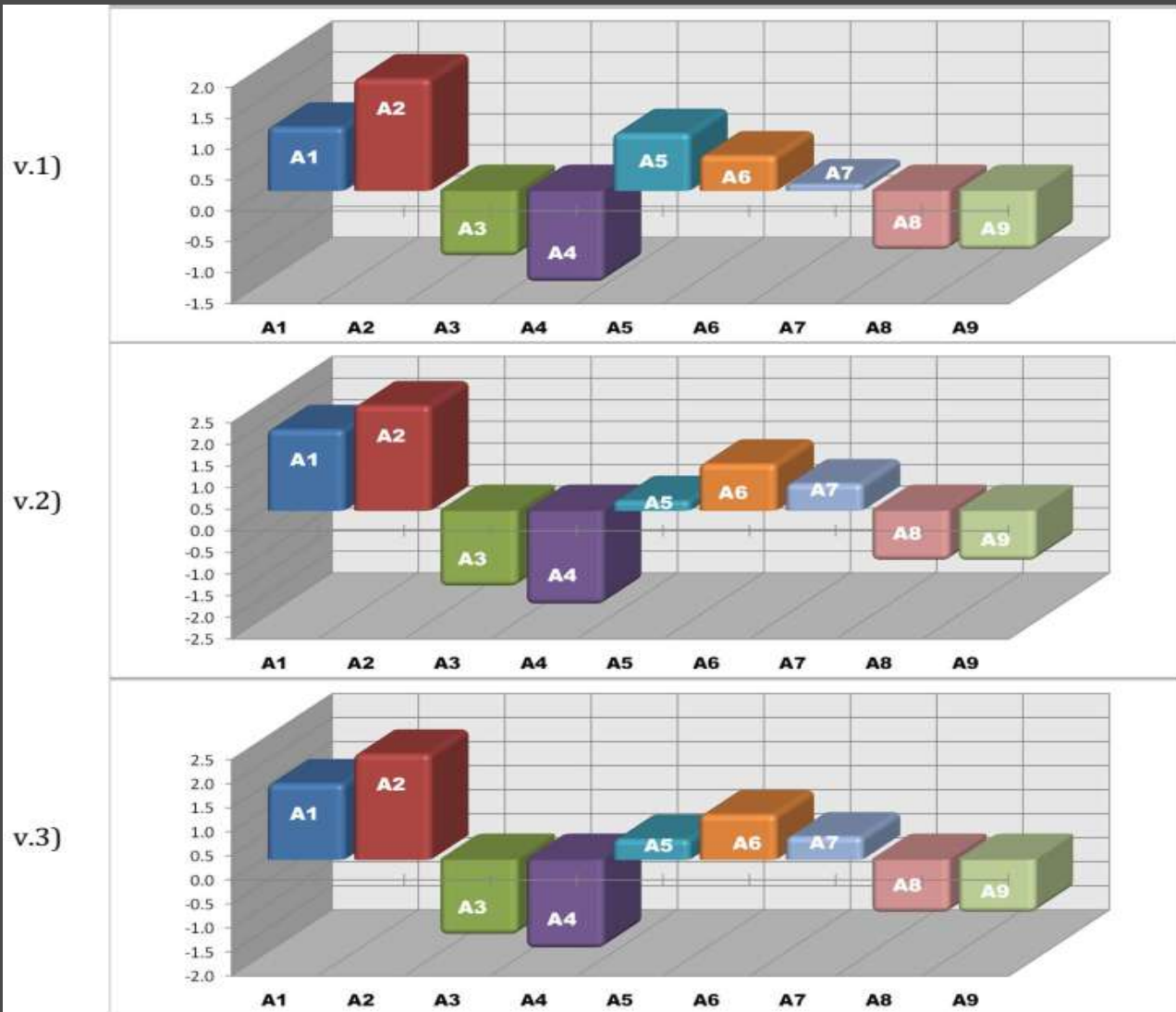
	Ai	Cij
1	A1	0.82442
2	A2	1.00000
3	A3	0.10718
4	A4	0.00000
5	A5	0.62168
6	A6	0.66668
7	A7	0.54872
8	A8	0.19060
9	A9	0.19060
10	A10	*

Sensitivity analysis

Критеријуми	Вредности релативних тежина			
	v.0	v.1	v.2	v.3
C1	6.2%	6.2%	6.2%	4.2%
C2	6.4%	6.4%	6.4%	3.4%
C3	3.7%	3.7%	3.7%	3.7%
C4	11.0%	16.0%	6.0%	16.0%
C5	11.0%	14.0%	6.0%	6.0%
C6	4.7%	4.7%	4.7%	4.7%
C7	1.7%	1.7%	1.7%	1.7%
C8	2.6%	2.6%	2.6%	2.6%
C9	4.8%	4.8%	4.8%	4.8%
C10	2.6%	2.6%	2.6%	2.6%
C11	2.8%	2.8%	2.8%	2.8%
C12	1.8%	1.8%	1.8%	1.8%
C13	1.8%	1.8%	1.8%	1.8%
C14	1.1%	1.1%	1.1%	1.1%
C15	1.1%	1.1%	1.1%	1.1%
C16	0.2%	0.2%	0.2%	0.2%
C17	2.8%	2.8%	2.8%	2.8%
C18	3.6%	3.6%	3.6%	3.6%
C19	3.6%	3.6%	3.6%	3.6%
C20	4.5%	4.5%	4.5%	4.5%
C21	4.6%	4.6%	4.6%	4.6%
C22	13.5%	5.5%	23.5%	18.5%
C23	1.0%	1.0%	1.0%	1.0%
C24	1.0%	1.0%	1.0%	1.0%
C25	2.0%	2.0%	2.0%	2.0%



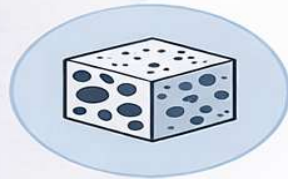
Sensitivity analysis by tested variants



Alternative **A2**
(Magnum AL12)
is the best.

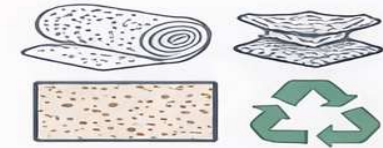


Key Conclusions



Porous materials characterized

- Foams, fibrous, biocomposites, granular (recycled)



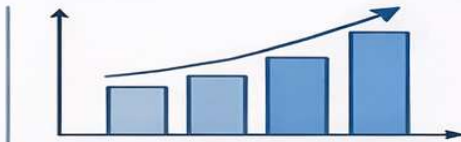
Multiple modeling approaches analyzed

- DB, JCA, Statistical, AI/ML



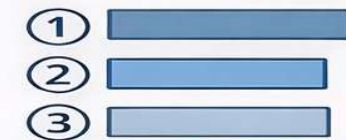
Model accuracy & limitations

- Frequency dependence (α , NRC)
- Influence of structure & parameters



Multi-criteria optimization for decision making

- AHP + PROMETHEE
- Ranking of barrier / mixture alternatives



Integrated modeling + MCDM → Reliable acoustic characterization

Future Research Directions



AI & Hybrid Models

- ✓ Physics-informed ML / hybrid approaches
- ✓ Data-driven prediction of acoustic properties



Advanced & Sustainable Materials

- ✓ Biocomposites with tailored properties
- ✓ Recycled / circular materials for barriers



Inverse Characterization

- ✓ Estimating properties from limited data
- ✓ Reduced-parameter identification



Optimization & Decision Support

- ✓ Multi-objective / many-criteria optimization
- ✓ Real-time design of barrier systems



Applications & Validation

- ✓ Noise barriers & building applications
- ✓ Experimental validation & field testing

From material design to intelligent acoustic systems

THANK YOU FOR YOUR ATTENTION !

Questions

