**FACTA UNIVERSITATIS**
Series: **Working and Living Environmental Protection** Vol. 21, Nº 4, Special Issue, 2024, pp. 305 - 315
https://doi.org/10.22190/FUWLEP241023029D

**Original scientific paper**

# OPTIMIZATION OF NON-ACOUSTIC PARAMETERS OF FIBROUS MATERIALS USING BIOLOGICALLY INSPIRED ALGORITHMS

*UDC 534:699.812.3*

**Tanja Dulović, Branko Radičević, Mišo Bjelić, Marina Ivanović**

University of Kragujevac, Faculty of Mechanical and Civil Engineering in Kraljevo, Serbia

| ORCID iDs: | | |
|---|---|---|
| | Tanja Dulović | https://orcid.org/0000-0003-3265-5661 |
| | Branko Radičević | https://orcid.org/0000-0002-4182-4095 |
| | Mišo Bjelić | https://orcid.org/0000-0002-6148-1982 |
| | Marina Ivanović | https://orcid.org/0000-0002-1576-7613 |

**Abstract**. *This paper deals with the optimization of the acoustic properties of samples made of fibrous materials, using biologically inspired algorithms. Samples with a thickness of 10 mm were tested, and the results showed that cotton fibers bonded with polyurethane resin have excellent absorption properties in a wide frequency range. GWO, BW and Puma were used for optimization. The optimization results showed significant improvements in the acoustic properties of the material, opening up possibilities for further application in sound insulation and other relevant areas.*

**Key words**: *non-acoustic parameters, porous materials, biologically inspired algorithms*

## 1. INTRODUCTION

Acoustic materials play a key role in the design of sound insulation systems, noise reduction and sound comfort enhancement in many branches. Noise control is relevant more than ever in cities, where high noise exposure has proven to have a number of negative consequences for health, namely, stress, sleep disturbance, work performance etc. [1]. One of the common solutions to improve noise performance is the introduction of high sound-absorbing materials, such as fibrous materials [2]. Sound absorption is viewed in terms of the sound absorbing coefficient, which quantifies the energy loss of the sound wave when it strikes a given surface.

However, one of the most important problems in the design of acoustic systems is the choice and optimization of properties of appropriate materials to obtain the best possible

---

Received October 23, 2024 / Accepted November 1, 2024

**Corresponding author**: Branko Radičević
University of Kragujevac, Faculty of Mechanical and Civil Engineering in Kraljevo, Dositejeva 19, 36000 Kraljevo, Serbia
E-mail: radicevic.b@mfkv.kg.ac.rs

results for different ranges of frequency. It was established that fibrous materials, like cotton fibres, are good sound absorbents because of their porous structure that promotes the scattering and absorption of waves. Their applications are particularly great in construction, the automotive sector, and the furniture industry, whereby noise reduction requirements are of primary importance.

The sound absorption performance normally is described by the sound absorption coefficient, experimentally measurable using an impedance tube [3] or predictable using acoustic transmission analysis methods in tandem with experimental measurements [4]. Various models have been developed to accurately determine the sound absorption coefficient of porous materials. The JCA model (Johnson-Champoux-Allard) is one of the most famous in this field, because it allows a detailed analysis by taking into account parameters such as air-flow resistance, porosity, and thermal conductivity of the material [5]. Despite the fact that the JCA model finds extensive application, the determination of its non-acoustic parameters is difficult to obtain. Normally, such parameters relate to a class that is difficult to quantify because of the variation of either structure or geometry from one fibrous material to another, which makes their analysis precise. Biologically inspired optimization algorithms find an increasing application in the effort to avoid these problems.

For a long period of time, the geometrical complexity involved with the material structure or the associated nonlinearity with the problem restricted the traditional methods of optimization. Biologically inspired algorithms like Gray Wolf Optimizer (GWO), Beluga Whale Algorithm (BW), and Puma algorithm (PO) provide novel solutions to these challenges [6,7,8]. These algorithms, inspired by nature make them incredibly much more efficient in searching for an optimum solution in complex multidimensional space. Kolarević et al. [9] showed that the application of the GWO algorithm to porous materials significantly improves the sound absorption coefficient in high-frequency ranges, while the application of hybrid algorithms further increases the efficiency in the middle-frequency range [10]. In addition, in the work of Miodragović et al. [11], different metaheuristic methods were compared in the optimization of sound absorption, where biologically inspired algorithms showed superior results compared to classical optimization methods.

The aim of this work is to optimize the acoustic properties of fiber materials, especially cotton fibers bonded with polyurethane resin, using GWO, BW and PO. The optimization is aimed at increasing the sound absorption coefficient in a wide frequency range, which is of key importance for applications in areas such as construction and the automotive industry. The application of biologically inspired algorithms allows solving problems related to the determination of non-acoustic parameters and opens new opportunities for more efficient use of fibrous materials in acoustic applications.

## 2. METHODOLOGY

In this work for the analysis of the sound absorption in porous materials, the JCA model was applied. The JCA model is widely used for describing the acoustic properties of materials because it gives the possibility to make detailed modeling of a coefficient of sound absorption, taking into account non-acoustic parameters: air-flow resistance, the porosity of the material, and thermal conductivity [5]. These parameters are very important in predicting the behavior of materials for running various frequency ranges. However, determining the exact value of these parameters is quite demanding due to such diversified and complex structure of fibrous materials. In this paper, optimization is performed using biologically inspired algorithms to provide closer-to-real values of the model parameters and hence increase the coefficient of sound absorption.

As the basic material for testing, cotton fibers were used, which are known for their good absorption properties due to their porous structure, which enables efficient absorption and dispersion of sound waves. These fibers are bonded with polyurethane resin to increase mechanical stability and durability. Cotton fibers were chosen due to their environmental benefits, ease of processing and already proven effectiveness in sound applications, especially in the construction and automotive industries [12].

### 2.1. Biologically inspired algorithms

Biologically inspired algorithms were used to optimize model parameters and improve the acoustic properties of the material. These algorithms have become popular due to their ability to solve complex optimization problems in multidimensional spaces, where classical methods often fail. Three algorithms were used in this work: Gray Wolf Optimizer (GVO), Beluga Whale Algorithm (BW) and Puma algorithm, due to their proven effectiveness in optimizing acoustic parameters. Below is given a brief overview of each algorithm.

The Gray Wolf algorithm, also known as the Gray Wolf Optimizer (GWO), was proposed by Seyedali Mirjalili, Seyed Mohammad Mirjalil, and Andrew Lewis [6], and is based on the behavior of gray wolves during the search, pursuit, and hunt for prey. Gray wolves are social animals that live in packs, adhering to a strict social hierarchy. The pack is led by the dominant male or female, collectively known as alpha (α), who makes the most important decisions. The second rank is beta (β), who assists the alpha in organizing the pack and can be a potential successor. The lowest rank is omega (Ω), subordinate to all. Additionally, deltas (δ) execute the orders of alpha and beta, and this group includes sentinels, hunters, and caretakers. Gray wolves also exhibit highly organized hunting behavior, which involves three main phases: tracking and approaching, pursuing and encircling the prey, and attacking. These social and hunting behaviors have been mathematically modeled to design the GWO algorithm [6]. In the hierarchy, the best solution is represented by alpha (α), followed by beta (β) and delta (δ), with omega (Ω) representing other potential solutions.

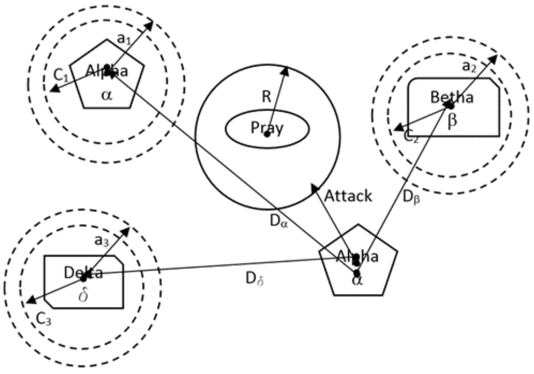

**Fig. 1** Illustration of updating search agent positions in the GWO algorithm [6]

Inspired by the swim behaviors while hunting and “falling” of the beluga whale, Changting Zhong, Gang Li, and Zeng Meng proposed the Beluga Whale Algorithm (Beluga whale optimization - BWO) [5]. Belugas are social animals that live in groups ranging from 2 to 25 members. It has been observed that a pair of belugas often swim in sync or in a 'mirror' mode. Belugas typically feed together in groups, directing fish into shallow water and sharing information about the position of the best candidate. During migrations and hunting, belugas face threats from humans, killer whales, and polar bears, and some do not survive, ending up on the seabed – a phenomenon known as “whale fall”. These three key behaviors of beluga whales have been mathematically formulated into an optimization algorithm.

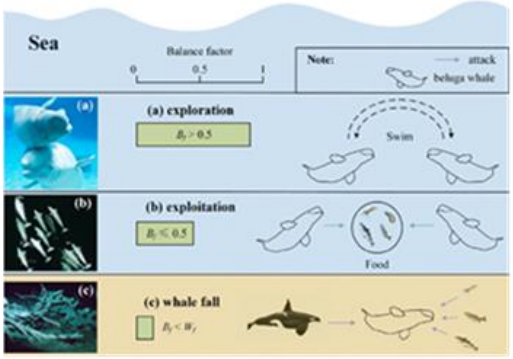

**Fig. 2** Behaviors of beluga whales, (a) swim-exploration phase; (b) foraging – exploitation phase, (c) whale fall-whale fall phase [5]

PO is a newly developed metaheuristic algorithm inspired by solving optimization problems with extended search spaces [8]. Like many metaheuristic algorithms, it draws from natural phenomena, mimicking puma behavior for guiding searches. PO separates exploration and exploitation phases, each with distinct mechanisms to balance the search, allowing it to explore new areas while efficiently exploiting known solutions. A key feature is its intelligent phase-switching mechanism, automatically balancing exploration and exploitation based on the problem’s nature, improving adaptability and performance. Despite its complexity, PO maintains computational efficiency, applying the cost function only once per agent per iteration, making it robust in optimizing non-acoustic parameters and navigating complex search spaces.

**Fig. 3** PO optimization procedure [8]

## 3. RESULT AND DISCUSSION

In the present study, three nature-inspired algorithms, BW, PO, and GW, were applied for the acoustic optimization of cotton fibers bonded with polyurethane resin. The objective of the optimization was the maximization of the sound absorption coefficient. The main parameters to be optimized were: the air-flow resistance σ, tortuosity $\alpha_\infty$, and the parameters c and c′ describing the shape factor and scale factor of the pore cross-section. Every algorithm tried to find these parameters as precisely as possible, based on experimental data and model assumptions. The solution space consisted of four parameters, and the number of agents was set at 50 with a maximum of 1000 iterations. Convergence analysis and the search process were conducted along with the accuracy of the results obtained for each algorithm and compared to the values obtained experimentally. While the convergence of the algorithms is presented diagrammatically, the results from both experimental and algorithmic modeling are presented in a comparative graphical form.

The BW algorithm demonstrated extremely fast convergence, as shown in Fig. 4. The trend of decreasing or maintaining the best-obtained value persists throughout the entire search process, as illustrated in Fig. 5. In some cases, this would be a good characteristic of the algorithm, but on the other hand, it indicates the risk of falling into a local minimum and being unable to escape that zone. This is demonstrated in Fig. 5, where the algorithm does not attempt to leave the local minimum zone. The results of the algorithm are presented in Tab. 1 and the algorithm’s execution time was 458.950541 seconds. Figure 6 provides a comparative presentation of sound absorption coefficients obtained experimentally and those obtained through the BELUGA algorithm. The error obtained (using the least squares method) is 4.80676633 %, which is quite a significant deviation, as shown in Fig. 6.

**Table 1** BW algorithm results

| σ | $\alpha_\infty$ | c | c' | The best solution | Algorithm duration time [sec] |
|---|---|---|---|---|---|
| 1120.71900 | 4.00000 | 2.60275 | 2.16378 | **0.0480676633** | 458.9505410000 |

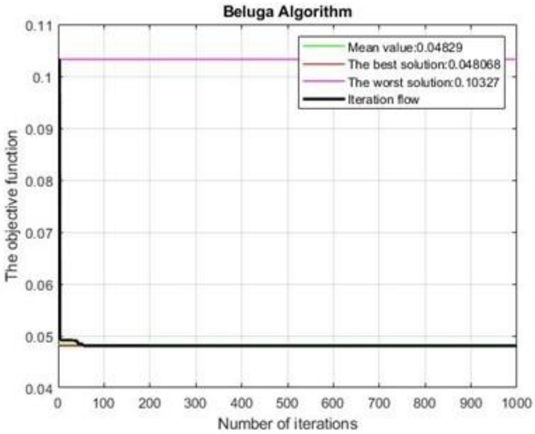

**Fig. 4** Convergence diagram of the BW algorithm

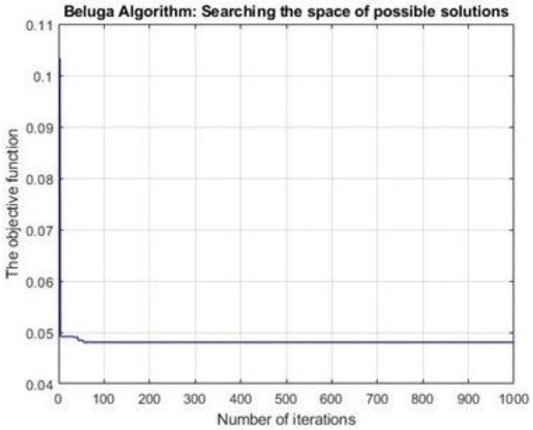

**Fig. 5** BW algorithm search process

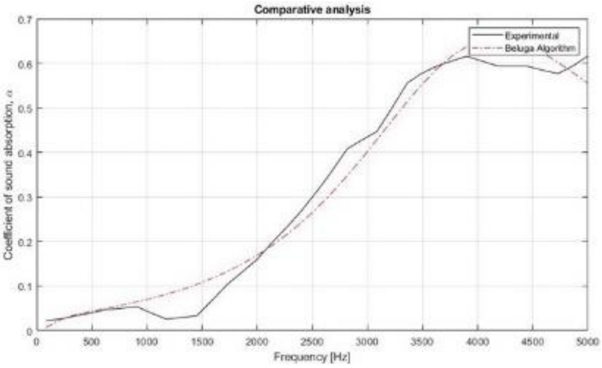

**Fig. 6** Comparative presentation of experimental results and results obtained by BW algorithm

The main characteristic of the PO algorithm, also evident in this case, is its extremely fast convergence. After about 10 iterations, Fig. 7, convergence occurs, and the algorithm enters a local minimum. However, the algorithm does not show the ability to escape the local minimum, as demonstrated in Fig. 8, which shows the search process through the possible solution space. As can be seen from Fig. 8, the algorithm attempted to exit the local minimum zone – there are peaks between the 20th and 30th iterations – but quickly returned to the local minimum and did not leave it for the remainder of the iterative process. The results of the algorithm are presented in Tab. 2 and the execution time of the algorithm was 416.9659089 seconds. Figure 9 shows a comparative presentation of sound absorption coefficients obtained experimentally and those obtained through the PO algorithm. The error obtained (using the least squares method) is 4.80406358 %, which is still considered a significant deviation, as shown in Fig. 9. The convergence of the PO algorithm is similar to that of the BW algorithm – extremely fast. Both the PO and BW algorithms showed no inclination to exit the local minimum zone, although the PO algorithm attempted to do so in the first 20 iterations by exploring another part of the solution space.

The result obtained by the PO algorithm is slightly better than that of the BW algorithm (4.80406358 % < 4.80676633 %), and the execution time is shorter (416.9659089 < 458.950541 seconds), but the result is still unsatisfactory.

**Table 2** PO algorithm results

| $\sigma$ | $\alpha_\infty$ | c | c' | The best solution | Algorithm duration time [sec] |
|---|---|---|---|---|---|
| 1000.0000 | 4.00000 | 2.75627 | 2.27319 | **0.0480406358** | 416.9659089000 |

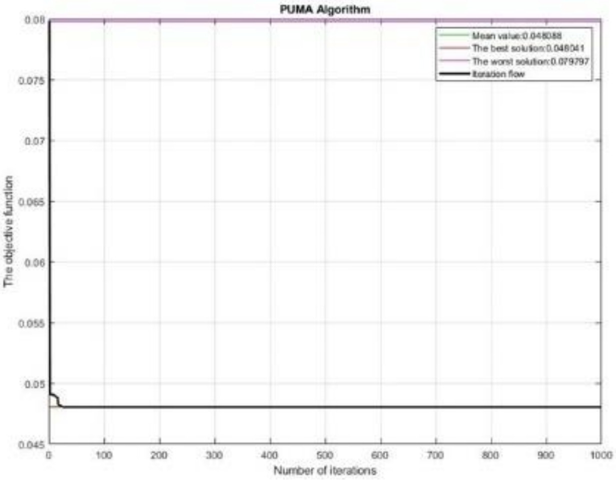

**Fig. 7** Convergence diagram of the PO algorithm

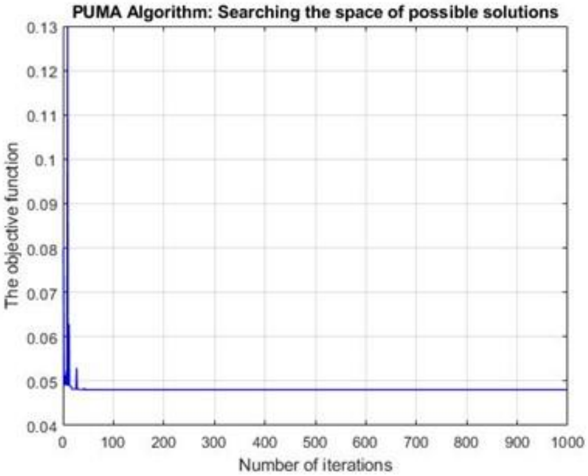

**Fig. 8** PO algorithm search process

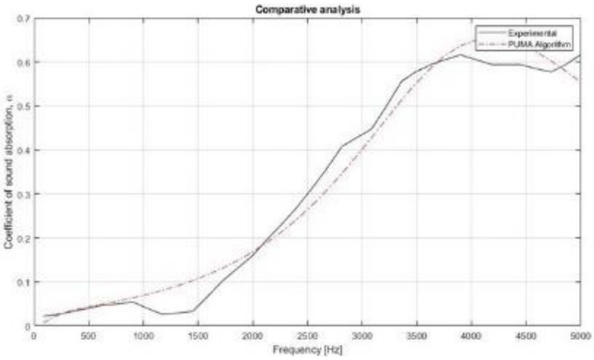

**Fig. 9** Comparative presentation of experimental results and results obtained by PO algorithm

The Grey Wolf algorithm produced worse results compared to the PO and BW algorithms. The error obtained was 4.93304091 %. Unlike the PO and BW algorithms, the Grey Wolf algorithm has somewhat slower convergence, as shown in Fig. 10, but its execution time is shorter (223.2760058 seconds). While the PUMA and BELUGA algorithms did not search the entire possible solution space during the iterative process, the Grey Wolf algorithm explored the entire solution space throughout the entire iterative process, as shown in Fig. 11. Figure 12 provides a comparative presentation of sound absorption coefficients obtained experimentally (by measurement) and those obtained through the Grey Wolf algorithm.

Table 3 GWO algorithm results

| σ | $\alpha_\infty$ | c | c' | The best solution | Algorithm duration time [sec] |
|---|---|---|---|---|---|
| 1583.79635 | 3.97780 | 2.13780 | 1.90663 | **0.0493304091** | 223.2760058000 |

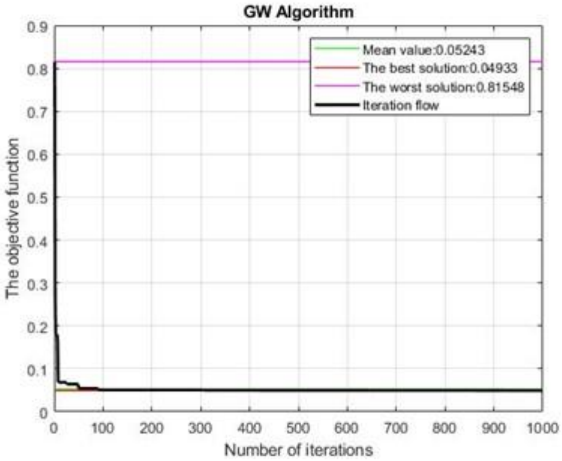

**Fig. 10** Convergence diagram of the GW algorithm

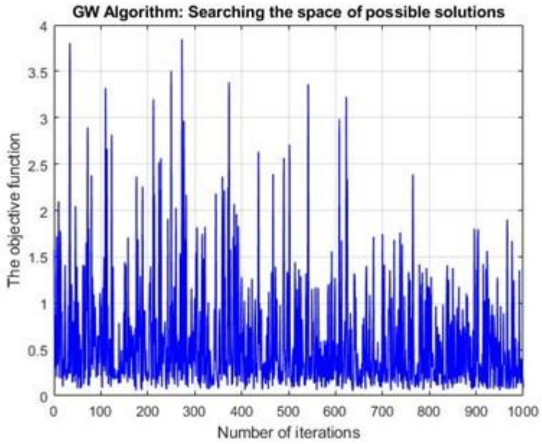

**Fig. 11** GW algorithm search process

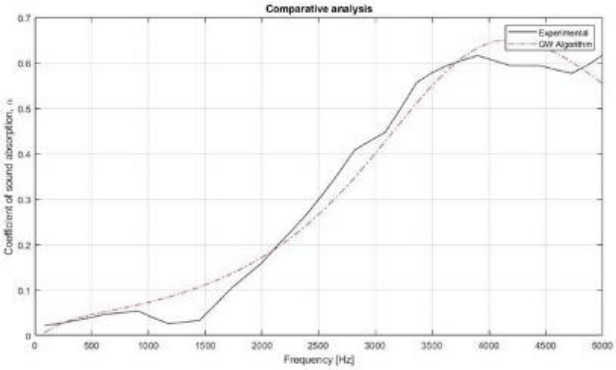

**Fig. 12** Comparative presentation of experimental results and results obtained by GW algorithm

A comparative analysis of all algorithms Tab. 4 shows that the PUMA algorithm achieved the best results in terms of the smallest error (4.80 %) and execution time (416.97 seconds), but it still has the problem of escaping local minima. The BELUGA algorithm was slightly less accurate but significantly faster. The Grey Wolf algorithm, although slower in convergence, offers better coverage of the solution space but with a higher error rate.

**Table 4** Comparative result analysis

| Algorithm | $\sigma$ | $\alpha_\infty$ | c | c' | The best solution | Algorithm duration time [sec] |
|---|---|---|---|---|---|---|
| Beluga | 1120.71900 | 4.00000 | 2.60275 | 2.16378 | 0.0480676633 | 458.9505410000 |
| Puma | 1000.0000 | 4.00000 | 2.75627 | 2.27319 | **0.0480406358** | 416.9659089000 |
| GW | 1583.79635 | 3.97780 | 2.13780 | 1.90663 | 0.0493304091 | **223.2760058000** |

## 4. CONCLUSION

This study demonstrated that biologically inspired algorithms are powerful tools in the search for optimal acoustic properties of fibrous materials. Each of them has some specific strengths and weaknesses. Among the tested algorithms, PUMA showed the best overall efficiency with the smallest error and relatively short execution time. On the other hand, this algorithm also demonstrated its limitations concerning getting stuck in local minima. The BELUGA algorithm was faster, but with ultra-fast convergence, it tended to skip the deeper investigation of possible solutions; hence, it gave a higher error. The GW algorithm, on the other hand, converged the slowest but succeeded in searching a broader solution space; however, it was less precise compared to the other two algorithms.

Future research should be directed at hybrid algorithms that will be capable of both fast convergence and escaping from the local minima. Another probable research direction might be the combination of strengths from the PUMA and GW algorithms, exploiting the ability of the GW algorithm for more thorough explorations of the solution space with faster convergence of the PUMA algorithm. This can result in drastic improvement in accuracy for the prediction of acoustic properties in materials. This research thus shows the opening of a very interesting perspective toward new applications in industrial sound insulation systems and the relevance of continuous acoustic materials optimization as a key factor for the development of really effective noise control in several applications.

**Acknowledgement**: *This work is co-financed by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia on the basis of contract no 451-03-66/2024- 03/200108. The authors thank the Ministry of Science, Technological Development and Innovation of the Republic of Serbia for supporting this research.*

## REFERENCES

1. Marquis-Favre C., Premat C., Aubrée D, Noise and Its Effects—A Review on Qualitative Aspects of Sound. Part II: Noise and Annoyance, *Acta Acustica United with Acustica*, Vol.91, No. 4, 2005., pp. 626-642.
2. Cao L., Fu Q., Si Y., Ding B., Yu J., Porous materials for sound absorption, *Composites Communications*, Vol.10, 2018, pp. 25-35. DOI 10.1016/ j.coco.2018.05.001
3. Berardi U., Iannace G., Acoustic characterization of natural fibers for sound absorption applications, *Building and Environment*, Vol.94, No.2, 2015, pp. 840-852. DOI 10.1016/ j.buildenv.2015.05.029
4. Fouladi M. H., Nor M. J. M., Ayub M., Leman Z. A., Utilization of coir fiber in multilayer acoustic absorption panel, *Applied Acoustics*, Vol.71, No.3, 2010, pp. 241-249. DOI 10.1016/j.apacoust.2009.09.003
5. Allard J. F., Champoux Y., New empirical equations for sound propagation in rigid frame fibrous materials, *Journal of the Acoustical Society of America*, Vol.91, No.6, 1992, pp. 3346-3353.
6. Mirjalili S., Mirjalili S. M., Lewis A., Grey Wolf Optimizer, *Advances in Engineering Software*, Vol.69, No. 22, 2014, pp. 46-61. DOI 10.1016/j.advengsoft.2013.12.007
7. Zhong C., Li G., Meng Z., Beluga whale optimization: A novel nature-inspired metaheuristic algorithm, *Knowledge-Based Systems*, Vol. 251. DOI 10.1016/j.knosys.2022.109215
8. Abdollahzadeh B., Khodadadi N., Barshandeh S. *et al*, Puma optimizer (PO): a novel metaheuristic optimization algorithm and its application in machine learning, *Cluster Comput* , Vol. 27, 2024, pp. 5235-5283, DOI 10.1007/s10586-023-04221-5
9. Kolarević M., Radičević B., Bjelić M., Miodragović T., Miodragović G., Application of Biologically Inspired Algorithms for Determining the Coefficients of Empirical Models for Determining Sound Absorption, *Proceedings of the X International Conference "Heavy Machinery-HM 2021"*, Vrnjačka Banja, June 23-25, 2021 pp. F.13 – F.19.
10. Miodragović T., Radičević B., Miodragović G., Ivanović M., Hybrid optimization algorithm for determining sound absorption, *Proceedings of the 27th International Conference Noise and Vibration*, Niš, 2022.

11. Miodragović T., Radičević B., Miodragović G., Bjelić M., Comparative analysis of the application of different metaheuristic methods for determining the coefficients of empirical models for determining sound absorption, *Proceedings of the 17th International Conference Acoustics and Vibration of Mechanical Structures - AVMS 2023*, Timisoara, Romania, May 26-27, 2023, e-ISBN 978-3- 031-48087-4.
12. Yang T., Hu L., Xiong X., Petrů M., Noman M.T., Mishra R., Militký J., Sound Absorption Properties of Natural Fibers: A Review, *Sustainability*, Vol.12, No.20, 2020. DOI 10.3390/su12208477