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DESIGN PROCESS, OPTIMIZATION, AND LIFE-CYCLE ASSESSMENT OF THE MULTIPURPOSE BAG CLIP

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Abstract: With the aim to preserve food freshness and prevent it from further microbial contamination after bag opening, the multipurpose bag clips were designed and various designs of the bag clips can be found on the market. Once the plastic bag is open, it is not possible to close it again without an additional tool. A review of the market and available literature has identified the potential for the redesign of the existed bag clip in terms of geometry optimization concerning the technological design guidelines of polymers and recyclability and to show the design process of such products. Applying the design theory guidelines, Autodesk Fusion 360 and SolidWorks as tools, and product life cycle assessment (LCA), a polymeric multi-purpose bag clip was designed to the level of a functional prototype. The bag clip consists of four parts, two frames, an insert, and a closure. It is intended for closing and opening candy bags, snacks, and freezer bags. The prototype of the bag clip was 3D printed and functionality was successfully tested. The final product has a mass of 32% less than the initial and it is fully recyclable. According to the LCA, the disadvantage of the proposed bag clip is the high energy consumption for its production.
Keywords: bag clip, design theory, life-cycle assessment, optimization, 3D printing

INTRODUCTION

Polymers are ubiquitous materials in everyday human life. There are various types of polymer products such as various plastic parts in cars, aircraft, insulation materials, various packaging, various medical aids, parts of electrical devices, etc. [1]

Closures belong to the group of packaging, and their main function is food and beverage safety and reducing food and beverage waste. The most commonly used closures are bottle closures, as shown in Figure 1 [2].

Figure 1. Plastic closures

Polymer products are usually produced in large quantities, ie in serial or mass production. This method of production requires a minimum amount of waste, maximum productivity, minimum production time, optimal production conditions, and ultimately full product functionality. The design process can have a significant impact on all of these conditions. Concerning the design process of products from non-plastic materials, the design of polymer products has certain specifics. It is important to provide basic information about the type of material before starting the process to help determine the right guidelines for the design. The choice of material is often based on the mechanical properties of the material. Such information is commonly available in the material specifications provided by the material manufacturers. Polymer closures are made by injection molding, which is also the most common production process by which polymer products are made. Injection molding of polymeric materials is the injection of polymeric substances of certain shear viscosity from the preparation unit (the funnel) in a tempered mold cavity. Injection molding produces a mold that, after the cooling, can be removed from the mold cavity, whereby the mold takes the shape of mold cavities. In the process of polymer products design, it is important to pay attention to the basic strategies of molding, and these are:

- Maximum functionality
- Optimal material
- Minimum mass

Having in mind the maximum functionality, one of the goals of polymer products design is to eliminate as many assemblies and parts as possible by combining components and at the same time achieving as many functions of construction as possible [4]. In this paper, the construction is represented by a bag clip. An analysis of the available literature did not show any work on this topic, however, an analysis of the products available on the market showed that there are different designs of bag clips. The idea for the design came from the polymer bag clip shown in Figure 2. [5]. A 3D model of the bag clip was generated, respecting the set of the requirements and the process of technological design of polymer products. Numerical analysis, optimization, and life-cycle assessment of the newly created product were performed, and the functionality was analyzed using a prototype made by 3D printing.

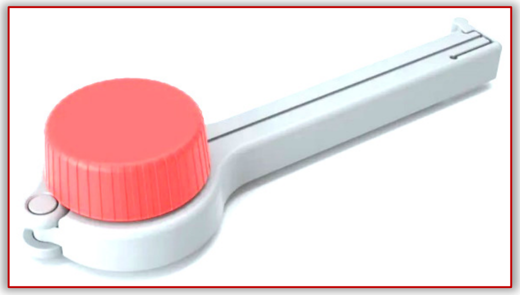

Figure 2. Plastic bag clip

MATERIAL AND METHODS

— Conceptual design of the multipurpose bag clip

After setting the list of requirements and creating a morphological matrix and combining different principles of the solution to perform partial functions for a multipurpose polymer bag clip, four variants were selected. The evaluation procedure determined the optimal solution shown in Figure 3. It should be mentioned that all solutions meet the requirements prescribed in the requirements list.

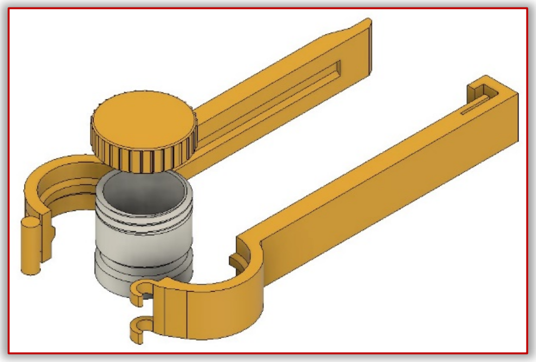

Figure 3. Optimal conceptual design

— Technological design of the multipurpose bag clip

The application of basic design strategies also has a significant impact on the technological design of the mold and these are the maximum molding functionality, optimal material, and the minimum weight. Polypropylene(PP) was selected as the optimal material in accordance with the requirements list. It must be polymeric, recyclable, safe for use in the food industry, have a low density, corrosion-resistant, and deformable. Furthermore, the different color shades of the selected material are welcome.

The review of the design characteristics is given in below:

- The wall thickness of the parts of the bag clip was kept in the range of 1 to 3 mm (Figure 4.).
- The transitions between different wall thicknesses are shaped in a way to prevent the formation of stress concentrations.
- Accumulation of masses on all parts of the structure was avoided
- The optimal value of the radius is set to be 0.5 mm
- The parts of the structure are shaped so that they are symmetrical on at least one axis (Figure 5.)
- A buttress thread SP400-M-8 was chosen as the optimal solution which allows high thread loading forces, while also providing fewer capability deformations during mold cooling.

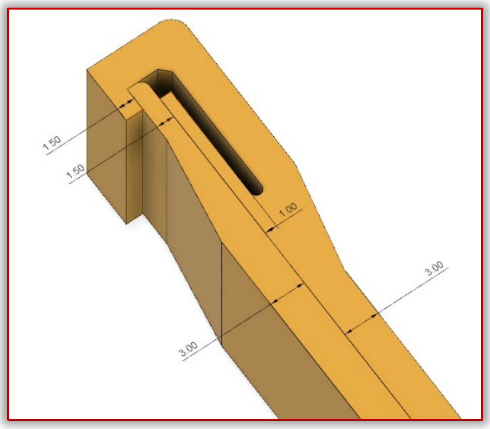

Figure 4. Wall thickness

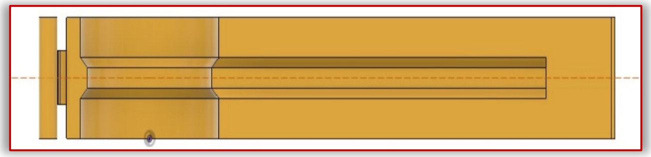

Figure 5. The symmetry of the part

— Numerical analysis of critical points

First of all, it is necessary to simplify the design to facilitate the creation of the initial stress and displacement calculations of the structure. It is assumed that the critical place of the construction is on the first part of the frame in the area on the inside of the buckle. Namely, in order to open the bag clip frame, it is necessary to move the buckle with a finger, which can be physically described as the action of the force of the finger at the beginning of the buckle (Figure 6.) whereby the buckle deformation of the part occurs.

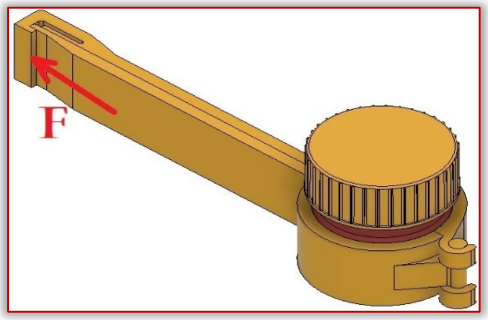

Figure 6. The acting force of the finger

Due to easier analysis, part of the construction has been simplified according to Figure 7., where only the longitudinal part of the frame with the hinged buckle and the rounded part for the insert was taken into account. Furthermore, it was assumed that the part of the frame with the buckle is fixed, and on the part where the buckle acts the finger force of 25 N [6] was applied.

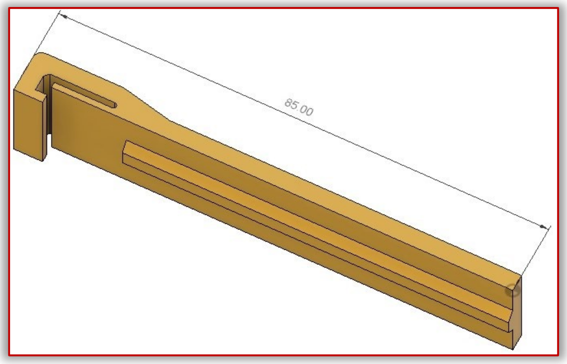

Figure 7. The simplified structure

The main parameters of the numerical analysis are given in Table 1. The finite element mesh is presented in Figure 8. The fine mesh was set on the critical side of the part.

Table 1. Parameters of the numerical analysis

The parameters	Values
Mesh type (element)	tetrahedron
Force	25 N
Material	Polypropylene
Element size (fine mesh)	0,6 mm
Element size (coars mesh)	1,7 mm
Nodes	25.781
Elements	24.285
Boundary condition	Fixed support

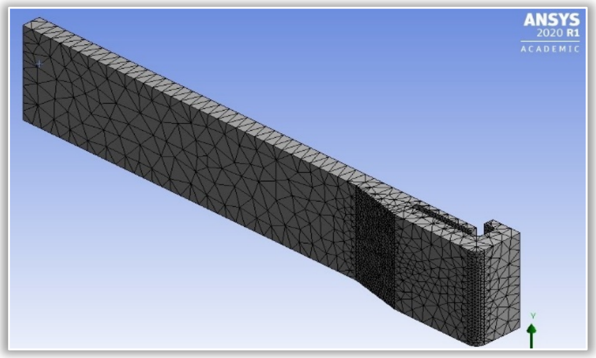

Figure 8. Tetrahedron mesh (fine and coarse)

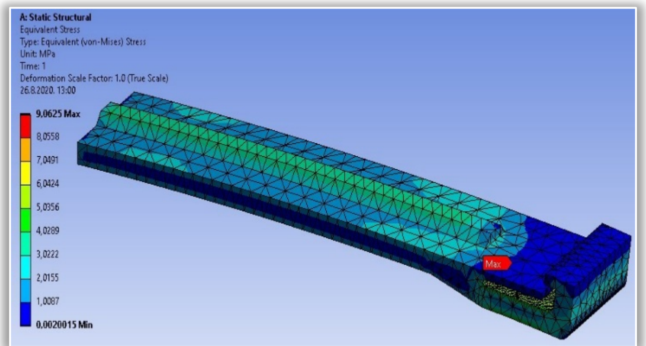

Figure 9. The Von-Mises Stress distribution

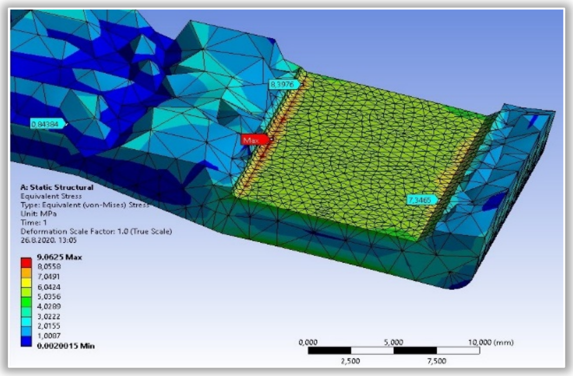

Figure 10. The Von-Mises Stress distribution

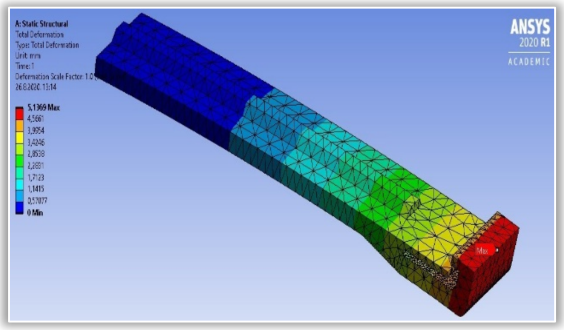

Figure 11. The total deformation on the inside of the buckle

The results of the numerical calculation are satisfactory. The criterion according to which the value of the maximum equivalent stress must be less than the allowable stress value of the material, which in this case is 9,0625 MPa < 26,2 MPa is satisfied. A total displacement of 5,1369 mm is acceptable for polypropylene polymer construction. In comparison with steel structures, this is a significant shift, however, the modulus of elasticity of selected polypropylene is 200 times smaller than the modulus of elasticity of steel which provides it a significantly higher possibility of deformation. The results of this calculation confirmed that this construction can take over the set load within the specified limits of allowable stress and displacement. In other words, during the opening, the frame will not break or permanently deform. The mass of the whole construction is 0,022502 kg or 22,502 g, while the mass of the simplified part for calculation is 0,0051473 kg or 5,1473 g.

— Bag clip optimization

The production of polymer products is unprofitable for small batches due to high mold prices. It was assumed that hundreds of thousands of pieces will be produced. Therefore it is necessary to minimize production costs as much as possible. Since the costs can be directly associated with the surface of the product, it is reasonable to minimize the amount of material required for its production. Hence, it is necessary to determine the minimum mass of the product with optimization compliance with the set of the limits, and then according to the obtained results (optimized parameters) proceed with the final design of the entire multipurpose bag clip.

The geometry consists of four parts, namely frame, buckle, frame amplification, and groove. The frame is the biggest part whose dimensions of the rectangular profile (width and height) will be optimized. The second part is the buckle, looking at the profile of the buckle the width remains fixed (1,5 mm) and the height of the profile was optimized. The value of the buckle height is equal to the height of the frame profile. The third is a fixed part of the amplification of the frame that was not optimized but the length of that part is equal to the height of the profile.

The fourth part is a groove that has fixed dimensions and has not changed during the optimization.

In Figure 12 an overview of the input and output optimization parameters is given. Input parameters were the width of the rectangular frame profile (3 mm) and the height of the profile (18 mm). The output parameters were the mass (5,1473 g), maximum equivalent stress (9,0625 MPa), and total displacement (5.1369 mm). The constraints of the input parameters (Figure 13.) for this structure are geometric and arise from a profile of the structure which is rectangular. The width (thickness) of the structure must not be less than 1 mm and more than 3 mm according to Figure 4., therefore, a profile width limit of 1 to 3 mm was set. The profile height limit is in the range of 10 to 20 mm. Furthermore, Figure 14 shows the optimization constraints related to the equivalent stress and total deformation. For the process of direct optimization to optimize the bag clip, the software was selected to generate 100 different samples according to given constraints. Then, from these samples, select the three most acceptable results in accordance with the objective function (minimum mass) and set limits.

Outline of All Parameters

	A	B	C	D
1	ID	Parameter Name	Value	Unit
2	Input Parameters			
3	Static Structural (A1)			
4	P11	profile_height	18	mm
5	P15	profile_width	3	mm
*	New input parameter	New name	New expression	
7	Output Parameters			
8	Static Structural (A1)			
9	P6	Geometry Mass	0,0051473	kg
10	P13	Equivalent Stress Maximum	9,0625	MPa
11	P14	Total Deformation Maximum	5,1369	mm
*	New output parameter		New expression	
13	Charts			

Figure 12. Outline of the parameters

Table of Schematic B2: Optimization

	A	B	C	D
1	Input Parameters			
2	Name	Lower Bound	Upper Bound	
3	P11 - profile_height (mm)	10	20	
4	P15 - profile_width (mm)	1	3	
5	Parameter Relationships			
6	Name	Left Expression	Operator	Right Expression
*	New Parameter Relationship	New Expression	<=	New Expression

Figure 13. The constraints of input parameters

Table of Schematic B2: Optimization

	A	B	C	D	E	F	G
1	Name	Parameter	Objective		Constraint		
2			Type	Target	Type	Lower Bound	Upper Bound
3	Minimize P6	P6 - Geometry Mass	Minimize		No Constraint		
4	P13 <= 26,2 MPa	P13 - Equivalent Stress Maximum	No Objective		Values <= Upper Bound		26,2
5	P14 <= 10 mm	P14 - Total Deformation Maximum	No Objective		Values <= Upper Bound		10
*		Select a Parameter					

Figure 14. Stress and deformation constraints

In Figure 15, the change of the goal function during the optimization process is shown, the diagram shows that the mass of the structure gradually increases as the values of input parameters grow. Thus, by increasing the geometric parameters of the structure, the mass of the structure grows, and the values of the maximum equivalent stresses and the total displacement are declining. The results of the optimization process are given in Figure 16.

Out of all one hundred generated samples, the software singled out the three best solutions characteristics shown in Figure 17. According to the goal function (mass reduction), the first solution is the best, it gives the smallest mass. However, the first solution has the maximum value of the maximum equivalent stress and the total displacement. The third solution has a maximum mass and total displacement. Out of the three offered solutions, the variant under number two was chosen as the optimal solution. Although the chosen variant does not have the least mass concerning other solutions, due to the acceptable weight of the structure and the lowest values of stress and a total displacement of all the offered variants, this solution was chosen. The function of the optimization goal is fulfilled, the initial mass was reduced from 5,1473 g to 3,1268 g which is a 40% reduction in weight! A ton of polypropylene whose price is approx. € 1400, there is approx. € 560 in savings. The final design of a bag clip is shown in Figure 18.

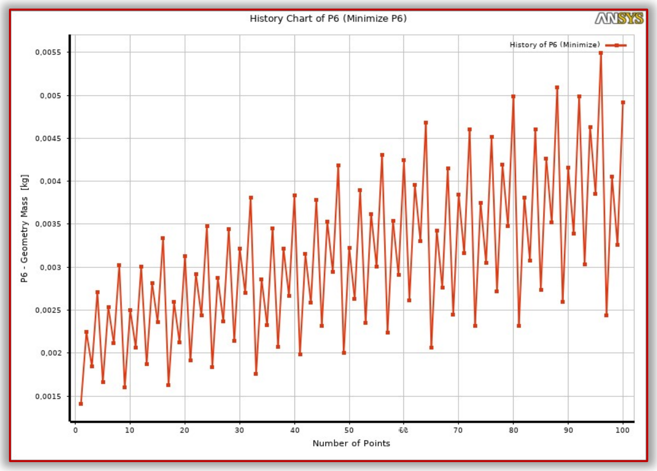

Figure 15. The mass change

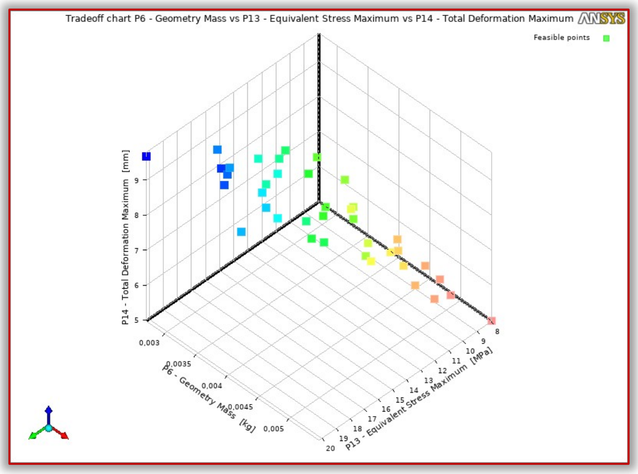

Figure 16. The results of the optimization

Candidate Points	Candidate Point 1	Candidate Point 2	Candidate Point 3
P11 - profile_height (mm)	10,35	11,95	13,75
P15 - profile_width (mm)	2,51	2,5725	2,2913
P6 - Geometry Mass (kg)	0,0027089	0,0031268	0,0032151
P13 - Equivalent Stress Maximum (MPa)	20,203	16,284	17,354
P14 - Total Deformation Maximum (mm)	9,6827	8,5966	9,714

Figure 17. The three best solutions

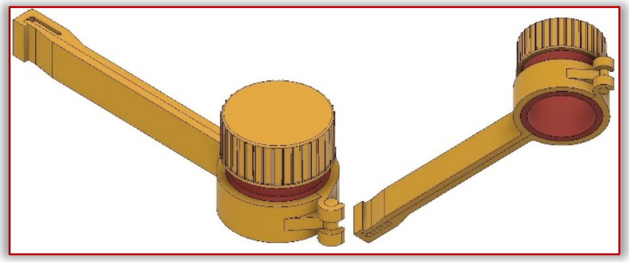

Figure 18. The final optimal design of the bag clip

To test the product functionality, the bag clip prototype was 3D printed using the hobby-grade 3D printer Creality Ender 3. No functionality issues were found.

— Qualitative life-cycle assessment of the bag clip

ECODESIGN Assistant Pilot [7] was used only for qualitative LCA analysis due to the extensiveness of quantitative analysis, i.e. collection and processing of large amounts of data. The purpose of the qualitative analysis was to show the environmental impact of this polymeric bag clip during its life cycle.

The LCA analysis aimed to:

- determine the type of product (A-E)
- suggest at least 3 proposed strategies to increase sustainability

Table 2 presents the set of estimated parameters used for the LCA analysis. The results can be divided into two parts, product classification, and recommendations for strategic improvements. The results of the analysis (Figure 19) show that the multipurpose bag clip is a B type of product. These are the products that require high production requirements, and they are characterized by the following [8]:

- production requires large amounts of energy,
- parts are transported over long distances,
- the product is difficult to repair, i.e. it requires new production.

Table 2. Parameters of the numerical analysis

The parameters	Values
Product Life Time	5 years
Material	Polypropylene
Energy input	50 kWh
Waste per unit	5% of the mass
Production per year	100.000
Means of transportation (Truck)	1.000 km
Frequency of use	300 uses/year

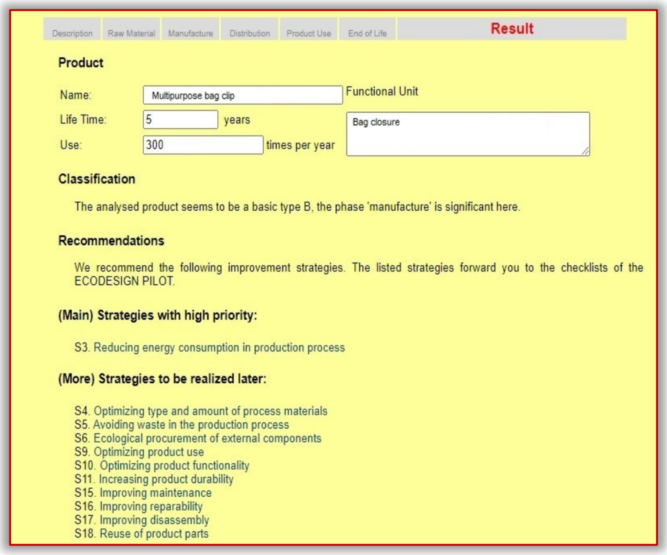

Figure 19. The recommendations and strategies for bag clip improvement

CONCLUSIONS

The construction of polymer products has its specifics. First of all, it is important to pay attention to the basic design strategies of molding: maximum functionality, optimal material, and minimum weight. The basic rules of technological design are also important, e.g. design as thin walls as possible, anticipate bevels, avoid undercuts, etc. Applying design recommendations for assembly (DFA) for polymer products can significantly reduce the cost of materials, mold making, etc. Namely, due to increasing competition in the market and the development of the technology, the application of the DFA principles is not a possibility but a need. Due to the reduction of plastic waste generation, already in the process of construction of polymer products, it is important to take into account the method of reuse of plastic waste. LCA analysis has shown that the selected material ensures the reuse of the product, which means that at the end of exploitation does not end up in nature as garbage but is completely recycled and used for the new processing. Finally, the initial mass of a product was reduced by 32 %. In the case of the production process, the high priority should be to reduce energy consumption.

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Note: This paper was presented at IIZS 2022 – The XII International Conference on Industrial Engineering and Environmental Protection, organized by Department of Mechanical Engineering and Department of Environmental Protection of the Technical Faculty "Mihajlo Pupin" Zrenjanin, from the University of Novi Sad, in cooperation with partners – University Politehnica Timisoara, Faculty of Engineering, Hunedoara (ROMANIA), University "St. Kliment Ohridski", Technical Faculty, Bitola (MACEDONIA), "Aurel Vlaicu" University of Arad, Faculty Of Engineering, Arad (ROMANIA), University of East Sarajevo, Faculty of Mechanical Engineering East Sarajevo, Sarajevo (BOSNIA & HERZEGOVINA) and University of Giresun, Faculty of Engineering, Giresun (TURKEY) – in Zrenjanin, SERBIA, in 06–07 October, 2022.

ISSN: 2067-3809