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Multi-response Characteristics Optimization of a Paper-based Composite using Taguchi Method and Particle Swarm Optimization

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Abstract: Our dependency on wood has reduced the number of forests, especially in Indonesia. Hence, many people tried to use another material as a replacement for wood. One of them is composite. Department of Industrial Engineering Universitas Sebelas Maret has developed paper-based composite using newspaper waste in Praktikum Perancangan Teknik Industri (PPTI) II. Unfortunately, the quality of the composite is not so good. Some of the composites are broken when dried up below the sunlight, so we have to do some reworks. Besides, based on historical data, the average tensile, bending, and impact strength of composites in the last practicum are 0, 42 N/mm2, 2,68 N/mm2, and 0,0203 J/mm2. It is still below the Indonesian National Standard (SNI) of particleboard. This paper tried to understand the effect of factors on responses and discover the best combination of factors to obtain the best responses. The responses of this experiment are tensile strength, bending strength and impact value. The factors of this experiment are paper pulp, PVAc glue and water. Taguchi method is used to find the appropriate orthogonal array and Particle Swarm Optimization method to find the optimum combination of the factors. The orthogonal array used in this experiment is L9 (34). Through analysis, all of the factors are significant to tensile and bending strength, but they are not significant to impact value. The best combination of factors is 175 grams paper pulp, 130 grams PVAc glue and 175 ml water. Optimum results obtained for tensile strength of 0.7595 N/mm2 and bending strength of 4.8411 N/mm2.

Keywords: Paper-based composite, tensile, bending, impact, Taguchi, Particle Swarm Optimization.

Introduction

Wood is a material which has many functions to society. It is hard to separate woods from our life. Many people try to replace wood with other materials such as composite. Composite is chosen because of its environmentally friendly nature, economically efficient, and high resistance [1].

Composite is a multi-phase material made of two or more material combination that has different characteristics and combined to obtain a better characteristic from its constituent [2]. Characteristics of a composite depend on the characteristics and distribution of its constituent and the interaction between them [3]. Mechanical properties are the most important characteristics of the composite. It determines a material's behavior when subjected to mechanical stresses. Mechanical properties include elastic modulus, ductility, hardness, and various measures of strength [4]. We used three kinds of strength in this experiment, such as tensile strength, bending strength, and impact strength or impact toughness. Tensile strength is the maximum strength of a material when tension is applied, usually at the moment when the material fails [5]. Bending or flexural strength is the maximum stress that is exhibited by the material because of a three or four-points bending load [6]. Impact strength or toughness is the ability of the material to absorb mechanical energy in the process of deformation and fracture, without plastic deformation under impact loading [7]. The value of the strength depends on the material selection of composite constituent [8]. Mechanical properties are obtained from testing. Usually, ASTM standard is used as a guideline for mechanical testing. Every mechanical testing has a different standardized method [9].

Indonesia is a country with high paper consumption rate. Even though digitalization has affected many aspects of life, it does not affect the consumption rate of paper in Indonesia. In 2017, paper consumption rate in Indonesia reached 27 kg per people per year, and the paper waste reached 17.000 ton. The paper waste-filled 28% of solid waste in a garbage dump [10]. Therefore, the paper used in Indonesia must be recycled to reduce the amount of paper waste. One of the ideas to recycle this paper waste is by using it to make a composite. Some researchers used paper waste by itself to create a composite while some of them combined paper waste with another

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reinforcement material. Saputra *et al.* [11] developed a composite using HVS paper and rice husks. They investigated the effect of pressing pressure on the MOR, MOE, and shear press strength of the composite. The results obtained indicated that the addition of pressing pressure would increase the MOR, MOE, and shear press strength of the composite. Prihartini [12] also developed a paper-based composite. She used Sengon wood as the reinforcement material besides newspaper waste. She analyzed the physical and mechanical properties of the composite. Her research showed that the composite developed is still below the standard of modulus of elasticity. Aji [13] used paper waste and 157 BQTN unsaturated polyester resin in his composite experiment. It showed that tensile strength and water absorption was increase along with the addition of paper waste powder volume fraction. Rafi [14] also developed a paper-based composite using newspaper waste as the reinforcement material. His research indicated that the percentage of starch glue in the composite would affect bending strength and impact toughness of the composite. Hapsoro [15] also has similar research with Rafi [14], but he investigated the effect of starch glue to tensile strength and density of paper-based composite. Based on his research, the addition of starch glue to composite will increase tensile strength and density of composite. Our experiment used the same reinforcement material with Rafi [14] and Hapsoro [15] to reduce the number of newspaper waste. However, we used PVAc glue as the matrix of composite instead of starch glue. We chose it because it is non-toxic [16] and environmentally friendly [17]. It has excellent performance and water-soluble [18]. Besides, PVAc glue is usually used for wood adhesive, so it has a greater bonding strength than starch glue.

This paper used the Taguchi method to determine the orthogonal array of the experiment. Taguchi method is an offline quality control method which is preventive quality control as product design or process design before shop floor production [19]. The purpose of the Taguchi design is to produce a product that is robust to the noise factor. Therefore, it is usually called by Taguchi Robust Design [20].

Particle Swarm Optimization (PSO) method is used in this paper to find the optimum level of newspaper pulp, PVAc glue, and water. We chose this method because it can optimize multi-objective problems simultaneously. Particle Swarm Optimization (PSO) is a global optimization method introduced by Kennedy and Eberhart in 1995 based on their research on the behavior of fish and bird herd. Every particle in PSO has its moving speed with the dynamic rate following their historical behavior. Therefore, the particle tends to move towards a better searching area during the searching processes [21]. The particle flies through the searching area by following the current optimum particles [22].

Department of Industrial Engineering in Universitas Sebelas Maret has developed a paper-based composite in their practicum. Paper-based composites are made from newspaper waste, PVAc glue, and water. Newspaper waste is transformed into paper pulp before it can be used. It becomes the reinforcement material of composite. The mixture of water and PVAc glue acts as the matrix in the composite. This composite is used to make a table of college chair in Praktikum Perancangan Teknik Industri (PPTI) II. Unfortunately, the composites made in this practicum are easy to break and have many cracks on their surface. Some of them are broken when dried up below the sunlight, so we have to do some reworks. The average tensile, bending, and impact strength of composites from the last practicum are 0, 42 N/mm2, 2,68 N/mm2, and 0,0203 J/mm2 respectively. These are below the Indonesian National Standard (SNI) of particleboard. Therefore, this research was conducted to investigate the effect of newspaper pulp, PVAc glue, and water composition to tensile, bending, and impact strength of composites. We also investigated the optimum combination of newspaper pulp, PVAc glue, and water to obtain the maximum tensile, bending, and impact strength of the paper-based composite.

Method

The initial stages of this study consist of literature and field studies, problem identification, problem formulation, purposes definition, and problem assumptions and boundary identification. A literature study is conducted to get any information-theoretically that will be used as a foundation to solve the problem. Field study is conducted with initial observation thoroughly on the research object. Problem formulation is arranged to make the question focused on one matter.

This paper discusses the quality of paper-based composite experimented in Praktikum Perancangan Teknik Industri II. So far, the quality of the composite is not good enough. Some of the composites are broken when dried up below the sunlight, so we must do some reworks. Based on historical data in the last practicum, the average of the tensile strength of 0, 42 N/mm2, bending strength of 2,68 N/mm2, and impact value of 0,0203 J/mm2. To improve the quality, we need to conduct an experiment to get the best quality of paper-based composite according to the result of tensile testing, bending testing, and impact testing.

Table 1. Orthogonal array of L_9

Experiment no.	Factor A	Factor B	Factor C	Factor D
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

The purpose of this paper is to determine the optimum composition of paper pulp, PVAc glue, and water to obtain a maximal quality of paper-based composite. In this study we do not not consider the cost of production.

Experimental Design

The experimental design consists some steps, they are, determining response, quality characteristic, factor, level for each factor, and orthogonal array. Responses used in this experiment are tensile strength, bending strength, and impact strength. In this experiment, we consider the larger, the better performance. Additionally, we consider paper pulp, PVAc glue, and water, as the factors of the design. This experiment also set the press machine as noise factor because two different press machines are used. The number of levels is essential to the accuracy of the result and the cost of the experiment. The more level experimented, the more accurate the result will be, and the cost of the experiment will also be increasing. These experiments used three levels for each factor. The levels of paper pulp factor are 175 grams for level one, 200 grams for level two, and 225 grams for level three. The levels of PVAc glue factor are 70 grams,100 grams, and 130 grams, respectively. The levels of water factor are 175 ml, 300 ml, and 400 ml.

The orthogonal array consists of controllable factors (inner array) and uncontrollable factors (outer array). This experiment used three controllable factors, with three levels for each factor. Thus, the degree of freedom of these factors is six. Therefore, the chosen orthogonal array matrix in this experiment has more than six degree of freedom, and three factors experiment; i.e. L9(34) (see Table 1).

Optimization

Multi-response characteristics used in this study is Particle Swarm Optimization (PSO). PSO is a population-based stochastic optimization algorithm. In PSO, the ongoing optimization process is described as each moving particle. The PSO algorithm consists of three stages, namely the particles generation of position and velocity, velocity updates and position updates.

First, the position x_i and speed v_i of a collection of particles are generated randomly using the upper limit (x_{max}) and lower limit (x_{min}) of the design variable (Ramdania *et al.* [23]), as shown in equations (1) and (2).

$$x_0^1 = x_{min} + rand(x_{max} - x_{min}) \quad (1)$$

$$v_0^1 = x_{min} + rand(x_{max} - x_{min}) \quad (2)$$

where:
$rand$ = random value between 0 and 1.

Position and velocity are represented in vector form where n-dimensional vectors represent the sum of the design of the particle variable with superscript and subscript denoting the particle i at a time k. By this initialization process, a swarm of particles can be distributed randomly to the design space. The position and velocity vectors are shown below [23]:

$$x_k^i = (x_k^{i_1},\ x_k^{i_2}, \dots,\ x_k^{i_n}) \quad (3)$$

$$v_k^1 = (v_k^{i_1},\ v_k^{i_2}, \dots,\ v_k^{i_n}) \quad (4)$$

The second step is updating the velocity of all particles at time *k+1* using the objective function or the fitness value of the current particle position in the design space at time *k*. The fitness value is used to determine which particle has the best global value in the current swarm (p_k^g) and determine the best previous time (p^i). The velocity update formulation uses these two informations for all particles in the swarm with the effect of the current displacement (v_k^i), to provide the direction of search (v_{k+1}^i) for the next generations. The particle speed and position update settings are obtained by the following formula [24]:

$$v_{k+1}^i = \omega \,.\, v_k^i + c_1.r_1.\left(p^i - x_k^i\right) + c_2.r_2\left(p_k^g\ - x_k^i\right) \quad (5)$$

where ω is inertia weight; c_1 and c_2 are the acceleration coefficient that determines the relative learning weights for p^i and p_k^g, called self-cognitive and social influence, respectively; r_1 and r_2 are two random numbers that are evenly distributed above [0,1].

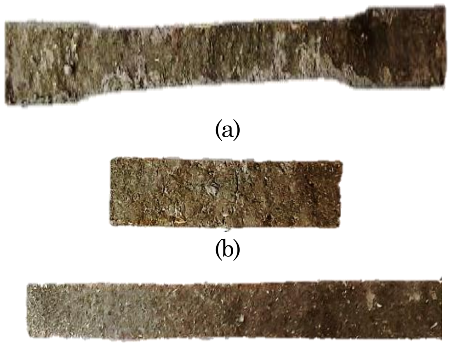
The last step of the iteration is updating the position of each particle with velocity vector with the following equation [23].

$$x_{k+1}^i = x_k^i + v_{k+1}^i \quad (6)$$

The three stages above will be repeated until the convergence criteria are fulfilled. These criteria are very important in avoiding adding evaluation functions after the optimum solution has been obtained. There are many ways to build a stop condition, such as stopping iteration when the PSO has reached the maximum iteration or the PSO has found a certain optimum value [25].

Table 2. Factors level settings

Code	Factors	Level		
		1	2	3
A	Paper Pulp (grams)	175	200	225
B	PVAc Glue (grams)	70	100	130
C	Water (ml)	175	300	400



(a)

(b)

(c)

Figure 1. Specimen for: (a) tensile testing (b) bending testing (c) impact testing

Results and Discussions

The experiments were conducted in two steps, namely manufacturing and testing steps. The composite manufacturing was produced at Laboratory of Product Planning, and Design Universitas Sebelas Maret and composite testing were conducted at Laboratory of Quality System Universitas Sebelas Maret.

The composites were made of newspapers, water, and PVAc glue. First, we crushed the newspapers into paper pulp. Then, we mixed paper pulp, water, and PVAc glue with different compositions according to its level settings, as shown in Table 2. In the next step, we put the mixture of paper pulp, water and glue into a press machine and pressed it for about 5 minutes until it becomes a composite. In this experiment, the pressures are considered as a noise factor. The composites were dried at room temperature for about 24 hours. After 12 hours, we turned over those composites so that they will not be curved. After the composites were dried, we cut them into several specimens (Figure 1). The size is based on the American Society for Testing and Materials (ASTM) standard for measuring the tensile, bending and impact. We use ASTM D 638-02 for tensile testing, ASTM D-780-02 and ASTM 5942-96 for bending testing and impact testing, respecttively.

We used a single-column vertical machine test for testing the tensile and bending. On tensile testing, the neck of the specimen was pinched using a clamp. The machine moved upward so that it pulled the clipped specimen ((Figure 2).

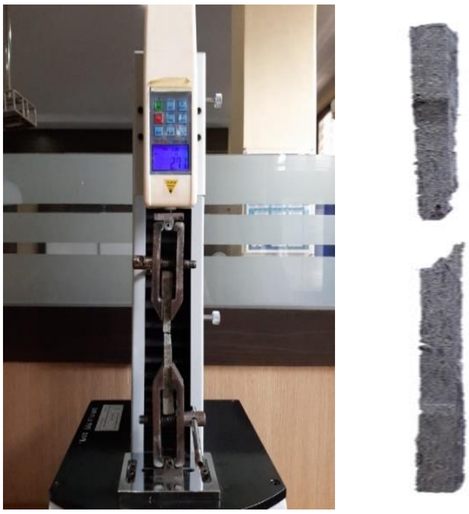


Figure 2. Tensile testing : Single-column vertical machine and the specimen.

Figure 3. Bending testing: Single-column vertical machine and the specimen

Figure 4. Impact testing: Charpy impact test equipment and the specimen

Table 3. Test results

		Run								
		1	2	3	4	5	6	7	8	9
Controllable Factors	A	175	175	175	200	200	200	225	225	225
	B	70	100	130	70	100	130	70	100	130
	C	175	300	400	300	400	175	400	175	300
Tensile Strength (N/mm^2)	R1	0,30	0,24	0,52	0,13	0,17	0,34	0,06	0,21	0,14
	R2	0,54	0,30	1,05	0,26	0,34	0,55	0,12	0,53	0,16
	Mean	0,42	0,27	0,78	0,20	0,25	0,44	0,09	0,37	0,15
Bending Strength (N/mm^2)	R1	2,18	3,50	3,88	0,73	1,29	3,50	0,86	2,47	2,08
	R2	2,53	2,59	4,59	1,49	2,09	3,20	0,81	1,60	2,99
	Mean	2,35	3,05	4,23	1,11	1,69	3,35	0,84	2,03	2,53
Impact value (J/mm^2)	R1	0,0199	0,0208	0,0176	0,0208	0,0232	0,0223	0,0194	0,0191	0,0209
	R2	0,0293	0,0241	0,0174	0,0281	0,0285	0,0276	0,0299	0,0271	0,0210
	Mean	0,0246	0,0224	0,0175	0,0245	0,0258	0,0249	0,0246	0,0231	0,0209

Table 4. Regression equation of each response

Response	Regression equation
Tensile Strength	-3.28 + 0.0267 A + 0.0549 B - 0.01150 C - 0.000342 AB + 0.000020 AC + 0.000062 BC
Bending Strength	-1.47 + 0.0259 A + 0.1535 B - 0.0397 C - 0.000778 AB + 0.000111 AC + 0.000135 BC
Impact Value	0.0504 - 0.000234 A - 0.000298 B + 0.000117 C + 0.000002 AB - 0.000000 AC -0.000001 BC

Note: A: paper pulp (grams); B: PVAc glue (grams) and C: water (ml).

Table 5. ANOVA of responses

Responses	Source	DF	Adj SS	Adj MS	F-value	p-value	R^2
Tensile Strength	Regression	6	0.661529	0.110255	4.01	0.022	68.62%
	Error	11	0.302449	0.027495			
	Lack-of-Fit	2	0.033249	0.016624	0.56	0.592	
	Pure Error	9	0.2692	0.029911			
	Total	17	0.963978				
Bending Strength	Regression	6	18.5423	3.0904	13.62	0	88.16%
	Error	11	2.4956	0.2269			
	Lack-of-Fit	2	0.316	0.158	0.65	0.544	
	Pure Error	9	2.1797	0.2422			
	Total	17	21.0379				
Impact Value	Regression	6	0.000083	0.000014	0.7	0.654	27.83%
	Error	11	0.000216	0.00002			
	Lack-of-Fit	2	0.000024	0.000012	0.57	0.584	
	Pure Error	9	0.000192	0.000021			
	Total	17	0.000299				

While bending testing was done by using the three-point bending method (Figure 3). The number on the force gauge showed how many kilograms of load were used to pull or push the specimen until breaks. Before doing the testing, we measured the width and height of the specimen.

To obtain the load of the given specimen, we multiplied the displayed mass by 9.8 m/s^2, i.e., the acceleration due to the gravity. Additionally, we used Charpy impact test for testing the impact. To do the test, we banged the pendulum on the surface of the specimen, so that the specimen received a sudden load (Figure 4). The indicators on the Charpy impact test only showed certain angles, so it is necessary to calculate first to determine the impact value of the specimen. Table 3 shows the test results of tensile strength, bending strength and impact value on paper composite specimens.

The analysis includes regression modelling to determine the effect of each independent variable on the dependent variable. This regression equation will be used as an objective function in the process of optimizing tensile strength, bending strength and impact value with particle swarm optimization (see Table 4).

Table 6. Weight of scalarization

Response	Weight $\left(w_i = \frac{2(n+1-i)}{n(n+1)}\right)$
Tensile strength	0.333
Bending strength	0.667

Table 7. Result of combined objectives

Run	Paper	Glue	Water	Normalized Tensile Strength	Normalized Bending Strength	CO
1	175	70	175	0.24	0.37	0.33
2	175	100	300	0.18	0.72	0.54
3	175	130	400	0.47	0.81	0.70
4	200	70	300	0.08	0.00	0.03
5	200	100	400	0.12	0.14	0.13
6	200	130	175	0.28	0.72	0.57
7	225	70	400	0.00	0.03	0.02
8	225	100	175	0.15	0.45	0.35
9	225	130	300	0.08	0.35	0.26
10	175	70	175	0.48	0.46	0.47
11	175	100	300	0.25	0.48	0.40
12	175	130	400	1.00	1.00	1.00
13	200	70	300	0.20	0.20	0.20
14	200	100	400	0.28	0.35	0.33
15	200	130	175	0.49	0.64	0.59
16	225	70	400	0.06	0.02	0.03
17	225	100	175	0.47	0.23	0.31
18	225	130	300	0.10	0.58	0.42

Table 8. ANOVA of the combined objectives

Response	Source	DF	Adj SS	Adj MS	F-value	p-value	R^2
	Regression	6	0,98207	0,16368	15,79	0,000	
	Error	11	0,11404	0,01037			
CO	Lack-of-Fit	2	0,00140	0,00070	0,06	0,946	89.60%
	Pure Error	9	0,11264	0,01252			
	Total	17	1,09611				

Next, we used ANOVA for examining the effect of factors on the response of tensile strength, bending strength and impact value (see Table 5). The ANOVA assumptions have fulfilled in this calculation. Based on the ANOVA calculation, the p-value for regression equation is less than 0.05, which means that there is a significant influence between the factors in the experiment with the response of the tensile strength and bending strength. In contrast to the impact value,

the p-value is more than 0.05 which means there is no significant effect of the factors in the experiment to the response. Therefore, it will not be included in the next optimization process. Besides, the value of R-squared for the impact value is only 27.83%. It means paper pulp, PVAc glue and water only contribute little to impact value. There are other factors, outside of these experiments that have not been considered, that significantly affect the impact value.

The next step was the optimization process to maximize the value of tensile strength and bending strength of composite simultaneously. In general, this optimization process can be done by uniting all responses into one objective function, through the scalarization method by giving the weight for each response [26]. Rank-sum (RS) weight was used in this scalarization (see Table 6).

One objective function is called combined objectives (CO). The value of CO is expressed by adding up the multiplication of each response and its weight. Besides, to provide a sense of fairness between each response, it is necessary to do normalizing to the data. The CO results are shown in Table 7 and ANOVA processing results to determine the significance of the factors on CO response shown in Table 8.

The ANOVA shows that the p-value for regression equation is less than 0.05, which means there is a significant influence between the factors in the experiment with the CO response. Therefore, we can construct the CO response based on the results summarized in Table 7, as follows:

$$CO = -1.5 + 0.01346\ A + 0.0449\ B - 0.01065\ C - 0.000249\ AB + 0.000026\ AC + 0.000044\ BC.$$

where A-paper, B- PVAc glue, C- Water.

The regression equation is used in the PSO optimization process as an objective function to predict the optimum value of each independent variable. We use xlOptimizer 1.1.6.0 demo version for processing the PSO optimization. Table 9 shows several parameters needed in the PSO.

Table 9. Parameters in PSO

Parameters	Value
Number of particles	20
Number of iterations	30
Inertia weight (ω_0)	0,8
c_1	2
c_2	2
Gamma	0,4
x_{min}	[175 70 175]
x_{max}	[225 130 400]

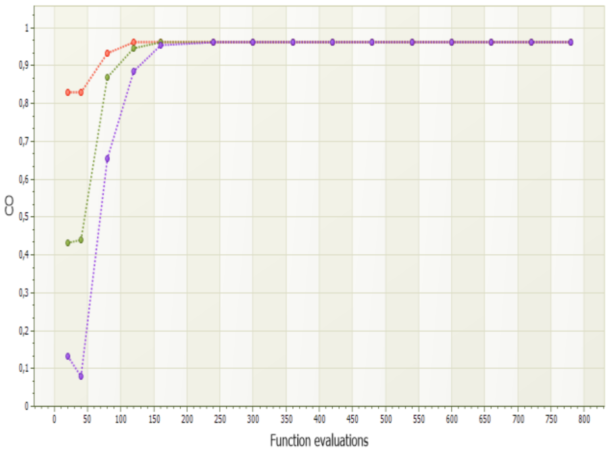


Figure 5. Convergence graph for the combine objectives

Table 10. Parameters in PSO

	Value
Paper Pulp (grams)	175
PVAc Glue (grams)	130
Water (ml)	175
Tensile Strength (N/mm^2)	0.7595
Bending Strength (N/mm^2)	4.8411
CO	0.9613

Figure 5 shows a convergence graph for optimal combine objectives. It is seen from the figure that best value of combine objectives is 0.9613.

Table 10 shows the result of optimization using PSO which shows the optimal value of each parameter to produce the maximum tensile strength, bending strength and impact value. Based on the results of optimization using PSO, it was found that maximum value from single objective function (CO) is 0.9613. Then, the optimal value of tensile strength and bending strength of composite were in amount of paper pulp as much as 175 grams, the amount of PVAc glue as much as 130 grams and the amount of water as much as 175 ml. The optimal value for the tensile strength and bending strength is 0.7595 N/mm^2 and 4.8411 N/mm^2, respectively. The 3D surface of CO is depicted in Figure 6.

Conclusion

Experiments of paper-based composite in this study using the Taguchi method and for its multi-response characteristics optimization using PSO. Nine experiments performed on each test, including tensile testing, bending testing and impact testing. Through analysis, all of the factors are significant to tensile and bending strength, but they are not significant to impact value Based on PSO result, to produce paper-based composite with optimum tensile strength and bending strength simultaneously can be achieved at paper pulp of 175 grams, PVAc glue of 130 grams and water of 175 ml. From these 3 factors, the order of significant factors is PVAc glue, paper pulp and water. Optimum results obtained for tensile strength of 0.7595 N/mm^2 and bending strength of 4.8411 N/mm^2. It is still below the Indonesian National Standard (SNI) 03-2105-2006 of particle board. So, for apply in industrial level needs a further research to be done to achieve the minimum SNI standards, but it is better for Praktikum Perancangan Teknik Industri II needs.

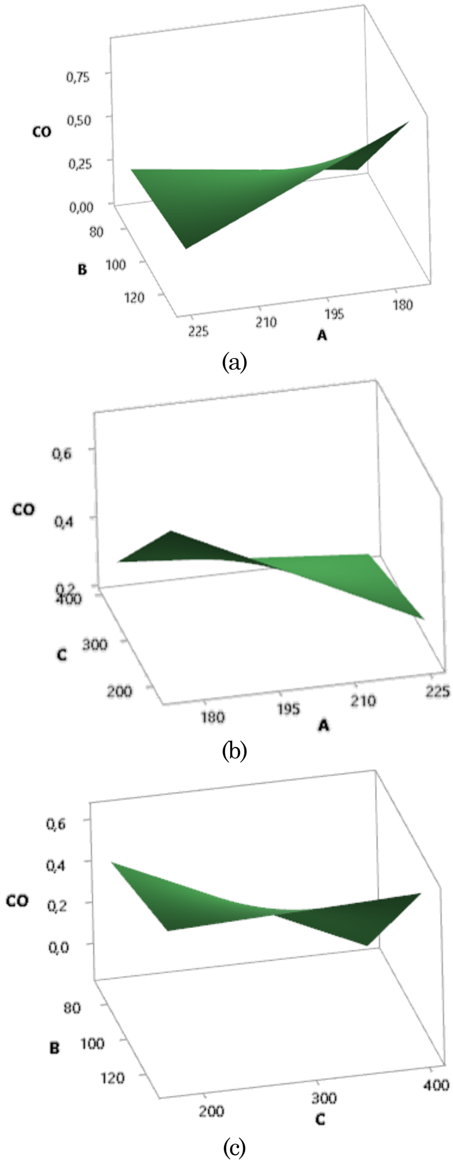


Figure 6. Surface Plot: (a) CO vs. A, B (b) CO vs. A, C (c) CO vs. B, C

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