



Optimization of Rubber Compound Design Process Using Artificial Neural Network and Genetic Algorithm

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ABSTRACT

In the rubber industry, the process of designing rubber compound is of great importance due to the impact on product specifications. The good performance of this process is a competitive advantage for manufacturers in this industry. The process of designing a rubber compound includes a set of activities related to selecting the best amount of raw materials to prepare a composition with the desired physical and mechanical properties. Currently, the most common method for designing a rubber compound is the experimental method based on trial and errors. This method is time consuming and expensive. In addition, the obtained combination is not necessarily the best combination. To improve the performance of the rubber compound we need to design the desired process, this research presented using a combination of artificial neural network and genetic algorithm, with an approach to reduce time and cost, while increasing accuracy. In this method, the behavior of the rubber compound was modeled with artificial neural network. Then, using Genetic Algorithm as a quick search technique. The optimal values of the four raw materials such as carbon, sulfur, oil and accelerator; in order to determine the specified value of the two characteristics .abrasion and rubber modulus at 300% elasticity at the lowest price. To evaluate the method, several samples of rubber compound designed with two method. The results showed that the artificial neural network model has the ability to predict the two characteristics of abrasion and modulus based on the four mentioned raw materials in the trained range with high accuracy. In addition, average results for genetic algorithm, is a price of 17% less and a design accuracy of 84.5% more than experimental method. The design speed with this method is 454 times higher than the experimental design speed. Based on the results, by designing the rubber compound with the integration of artificial intelligence and genetic algorithms has a better performance than the experimental method.

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NOMENCLATURE

Notations	Definitions	Notations	Definitions
i	Index of raw materials in rubber compound	x_i^l	Minimum acceptable value for raw material i
k	Index of Target Functions	x_i^u	Maximum acceptable value for raw material i
C_i	Price per kg of raw material i	Y_k^l	Minimum acceptable value for target Functions k
Y_k^*	The value for the physical-mechanical property of K_m	Y_k^u	Maximum acceptable value for target Functions k
n	Number of rubber compound properties	x_i	Quantity of weight selected from raw material i
m	Number of raw materials	$Y_k(X)$	The K th properties value of the designated mixture

1. INTRODUCTION

Elastomers as a type of polymer material have special physical properties such as flexibility, extensibility, resiliency and durability. These unique properties in rubbers have made them widely used in a wide range of

applications. The required properties such as abrasion, toughness, hardness, tensile strength of rubber products require the mixing of rubber with different amounts of raw materials [1]. One of the important issues in the rubber industry is the choice of type and quantity of these raw materials under the design of rubber compound. If

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the selection of raw materials is not in correct method, problems can arise such as inappropriate selection of raw materials or prolonging the selection process. Inappropriate selection of raw materials causes inefficiency in the product. When designing a rubber compound it is usually not difficult to obtain one of the properties stated in the required specifications alone, but when several properties are to be provided at the same time, due to differences in properties, problem arise. In the usual method, the designer, after receiving the blend specifications, combines his theoretical knowledge and practical experience with the blend selection. The steps for designing a rubber mixture based on the experimental method shown in Figure 1. According to the diagram, each repetition requires the construction of a rubber compound and laboratory tests. Obviously, this method is time consuming and expensive, and from an economic and competitive point of view, it is not an ideal method. On the other hand, in the experimental method, the designer chooses the first combination that has the desired properties, while this combination may not be the best combination in terms of price and properties. In addition, the experimental method depends on the designer's experience. Therefore, finding a precise, fast and inexpensive method to design a rubber compound that is not dependent on the individual is necessary for the rubber industry. The rubber compound designer faced with the problem of the effect of each material on each of the characteristics and choosing the best combination in terms of price and specifications. Of course, it is also important to consider the effect of the interaction of raw materials on properties, and the duration and cost of the design method.

Using statistical methods to design a rubber compound is one of the topics of research. Leu et al. [2] predicted the effects of changing material compositions on the physical and mechanical properties of composite material by statistical models. They drew behavior curves and according them determined the best combination of the raw materials to have the desired properties. Salvatori et al. [3] were used statistical experimental design for finding the best percentage of weight of three types of elastomer in a combination with the best final properties. In another research, Adamu et al. [4] were used statistical methods to determine the optimal composition for rubber rollers with best specifications. Research on the design of rubber compounds with statistical methods is not very different. However, it should be noted that the behavior of rubber compounds is highly nonlinear, and the use of the second-class model is not entirely reliable. In addition, statistical methods cannot predict the specification of the compound without laboratory testing and with the increase in the number of raw materials, the number of experimental tests increases, which is time consuming and expensive. Therefore, there is a need for a safe and less tested method.

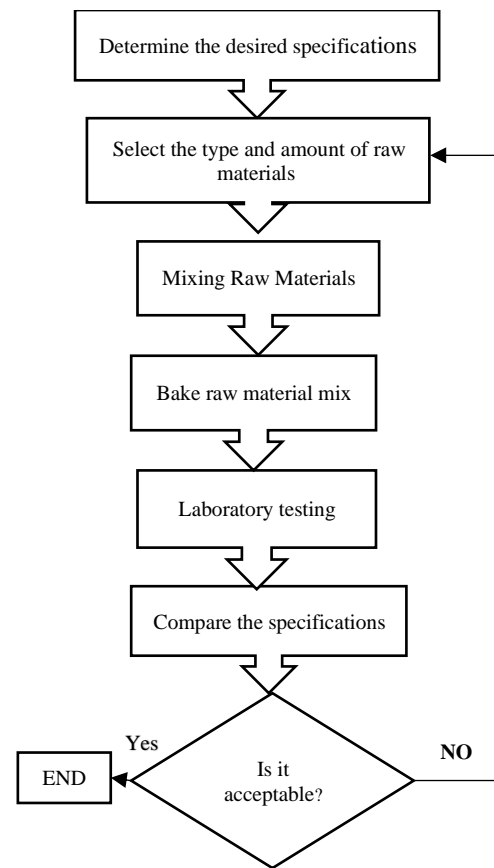


Figure 1. Rubber compound design process

Artificial intelligence modeling methods used to predict the behavior of dependent variables to reduce time and cost. Nateghi and Ahmadi [5] used artificial neural network (ANN) with statistical data to predict the properties of cement composite. They produced 36 different compounds, tested them, and developed the neural network. The design model was accurate enough. Zhang et al. [6] used artificial neural network modeling to predict the mechanical properties of a powder-plastic composite. They achieved optimal point from contour curves. In other work, Diaconescu et al. [7] used artificial neural network with statistical data to predict rubber properties. They generated the mixes with the lowest cost and maximum strength. Wang et al. and Xiang et al. [8, 9] in a separate research used artificial neural network to predict a characteristic value according to other characteristics of the rubber compound. Comparing the results showed that the accuracy of the network designed to predict a properties was better than experimental method. According to researches, the use of artificial neural network modeling is appropriate for predicting the nonlinear behavior of rubber compounds. However, as with the previous method, it requires a series of experimental tests as input data to the model. In previous researches, the optimal combination has been selected

using graphical methods. This method is complicated for examining the effect of several raw materials on several characteristics.

In other studies, has used of metaheuristics methods to select the optimal combination replaced graphical methods. Using these methods to solve optimization problems is an effective method that provides a set of answers in the shortest time. This method used in various engineering sciences. A study conducted by Mehranfar et al. [10] to optimize the supply chain by considering environmental issues and customer demands using a new hybrid metaheuristic based on whale optimization algorithm and simulated annealing as a successful optimizer method. In other study by Safaeian et al. [11], they solved a multi-objective problem by selecting a supplier and assigning an order, taking into account the different costs associated with the Non-dominated Sorting Genetic Algorithm. Fathollahi-Fard et al. [12] used an improved red deer algorithm to design a direct current electric motor. This method reduced design time. In several studies on home health care providers, has used new metaheuristics algorithms to optimize transportation and decision-making in resource allocation. These methods reduced the time, cost of transportation, and created a competitive advantage for the HHC in the supply chain [13-15]. Jalal et al. [16] used genetic algorithms to improve the design and construction of composite vessels. Patel and Suthar [17] used a genetic algorithm to determine the best variables in the design of a car engine. The engine efficiency designed in this way increased by 3.35%. Rahimi and Jafarnejad [18] for the design of automated cellular circuits, reduce the time of the designing by genetic algorithms. Correia et al. [19] optimized the values of three types of raw materials in a rubber mixture with EPDM base to achieve the minimum price. The results showed that it is possible quickly find a combination with the lowest price with metaheuristics methods.

In recent years, the use of a combination of artificial intelligence and metaheuristics methods has also found applications. In one work, Sebaaly et al. [20] used a combination of artificial neural network and genetic algorithm to optimize the asphalt mix. Their goal was to minimize the thickness of the bitumen, while not exceeding the allowable limit. Since some of the limitations of the problem were the complex functions of the physical properties of the raw materials, artificial neural network modeling used. The optimization problem solved with a genetic algorithm. Laboratory results confirmed this method. In other work, Pavia et al. [21] used the integration of neural network with genetic algorithm to optimize the properties of adhesives. They obtained complex relationships between independent and dependent variables from simulation and solved the problem by converting the objectives into a single goal with the genetic algorithm. The results showed that this method is a powerful tool to help shoe glue designers.

Review of the literature shows the use of a combination of statistical methods with artificial intelligence to model the behavior of rubber compound. However, there is no research to develop a model without multiple experiments. In addition, research does not show a combination of artificial intelligence and metaheuristics methods for designing rubber compounds in a multiple objective problem.

In this study, the aim is to provide a fast, accurate, low-cost method to design a rubber mixture with the desired characteristics and the lowest price. For this reason, artificial neural network used to model the behavior of rubber mixture. To reduce time and cost, the data needed to develop the network obtained from previous designs. Improper genetic algorithms used to select the optimal combination, which makes it possible to study several targets with high speed and ease.

2. RESEARCH METHODS

The present study is an applied research of industrial rubber parts manufacturing companies in which improvement of rubber design process is considered. The steps of the research shown in Figure 2.

2. 1. Mathematical Model of Rubber Compound Design Problem

In deciding whether to choose the right amount of raw materials in rubber blends, we articulate the mathematical design theme of rubber as Equation (1). Before describing the mathematical model, the components of the model introduced.

$$\left\{ \begin{array}{l} \min : Z = \{f_1(X), f_2(X), \dots, g(X)\} \quad k = 1, 2, \dots, n \\ f_k(X) = \left| \left(Y_k(X) - Y_k^* \right) \right| \quad k = 1, 2, \dots, n \\ g(X) = \sum_{i=1}^m C_i \cdot x_i \end{array} \right. \quad (1)$$

$$f_k(X) = \left| \left(Y_k(X) - Y_k^* \right) \right| \quad k = 1, 2, \dots, n \quad (2)$$

$$g(X) = \sum_{i=1}^m C_i \cdot x_i \quad (3)$$

s.t.

$$x_i^l \leq x_i \leq x_i^u \quad (4)$$

$$Y_k^l \leq Y(X) \leq Y_k^u \quad X = (x_1, x_2, \dots, x_n) \quad n \in \mathbb{N} \quad (5)$$

Model Indexes:

i: Index of raw materials in rubber compound

k: Index of rubber properties in target function

Model Parameters:

C_i : Price per kg of raw material i

Y_k^* : The ideal value for K th properties

n: Number of rubber compound properties

m: Number of raw materials

x_i^l : Minimum acceptable value for raw material i

x_i^u : Maximum acceptable value for raw material i

Y_k^l : Minimum acceptable value for Y_k

Y_k^u : Maximum acceptable value for Y_k

Model Variables:

x_i : Quantity of weight selected from raw material i

$Y_k(X)$: The design value for K th properties

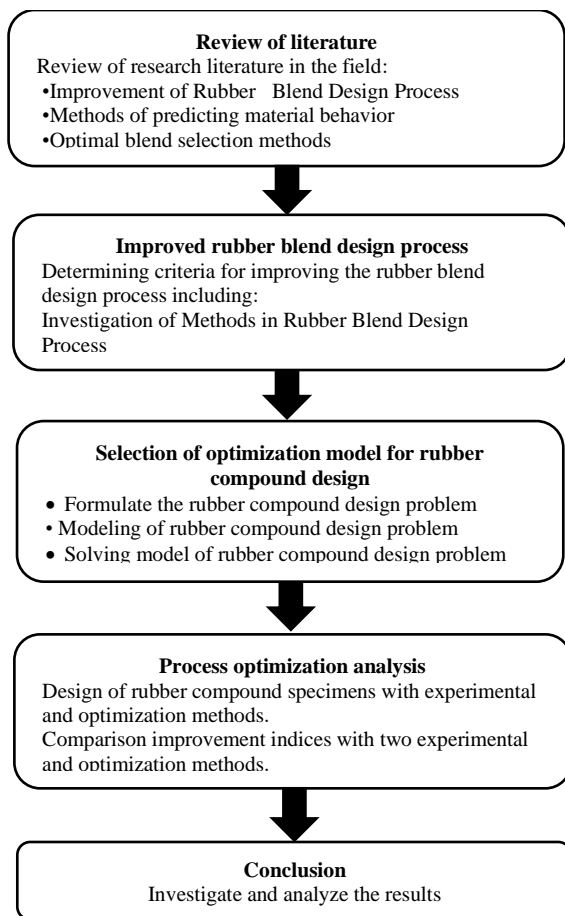


Figure 2. Steps of research

Mathematical Model:

where $f_k(X)$ is the error value for k th properties, with weight composition X of the raw material. In addition, $g(X)$ is the price of the rubber compound for the weight composition X of the raw material. The range of raw materials in rubber compound according to rubber technology given in Table 1.

2. 2. Predicting the Properties of Rubber Compound with Artificial Neural Network

Modeling with ANN used to determine the relationship between the amount of raw materials and the properties of rubber compound. The artificial neural network is a branch of artificial intelligence that be used to detect patterns and predict material behavior. Artificial neural network can simulate nonlinear functions with good accuracy [9]. Artificial neural networks such as the human brain are able to solve new problems using the Knowledge gained from previous experience [7]. In this model, the input is the amount of raw material and the output is the characteristic value of the rubber compound. Artificial neural network design performed in MATLAB software environment. For the modeling, the laboratory information available in the technical section of the rubber company is used. In this study, the ability of the

TABLE 1. Range of Raw Materials

NO	Material name	Minimum (kg)	Maximum (kg)
1	Zinc oxide	3	5
2	Stearic Acid	1	4
3	Antioxidant	0.5	5
4	Ozone	0.5	5
5	Paraffin	0.5	5
6	Carbon	15	85
7	Oil	2	30
8	Sulfur	0.25	5
9	Accelerator	0.25	5

network to predict the behavior of rubber compounds was determined by using the coefficient of determination (R^2) and mean square error (MSE).

2. 3. Finding the Optimal Combination of Raw Materials with Non-Dominated Sorting Genetic Algorithm

A proper search method needed to select the right amount of raw material. Genetic algorithm is the most popular technique in evolutionary computing. This method uses the rules of evolution to search for the best solution for multidimensional problems in finite time [9]. Non-Dominated Sorting Genetic Algorithm is suitable for solving multi-objective problems with conflicting goals. In this way, the best solution sought by forming an initial population of solutions and in an evolutionary manner. In this way, with an evolutionary algorithm searches for the best solutions from an initial population of solutions. In the genetic algorithm, each solution called a chromosome and the independent variables in that solution called genes. In this paper, each solution considered a weighted combination of raw materials. Each gene is the weight value of one of these raw materials. To begin the search, genetic algorithm parameters such as initial population, number of repeats, intersection and mutation ratio, and probability of mutation and range of raw materials specified. Then the genetic algorithm randomly generates a number of different weight combinations of the raw materials in the acceptable range. The artificial neural network model predicts the amount of properties of each compound. These values compared with the desired value. Finally, the best combination selected with the best properties and the lowest price. The design steps of the rubber compound by combining the artificial neural network and the genetic algorithm illustrated in Figure 3.

3. CASE STUDY

The rubber compound design is applicable to all industrial rubber parts companies and tire manufacturers.

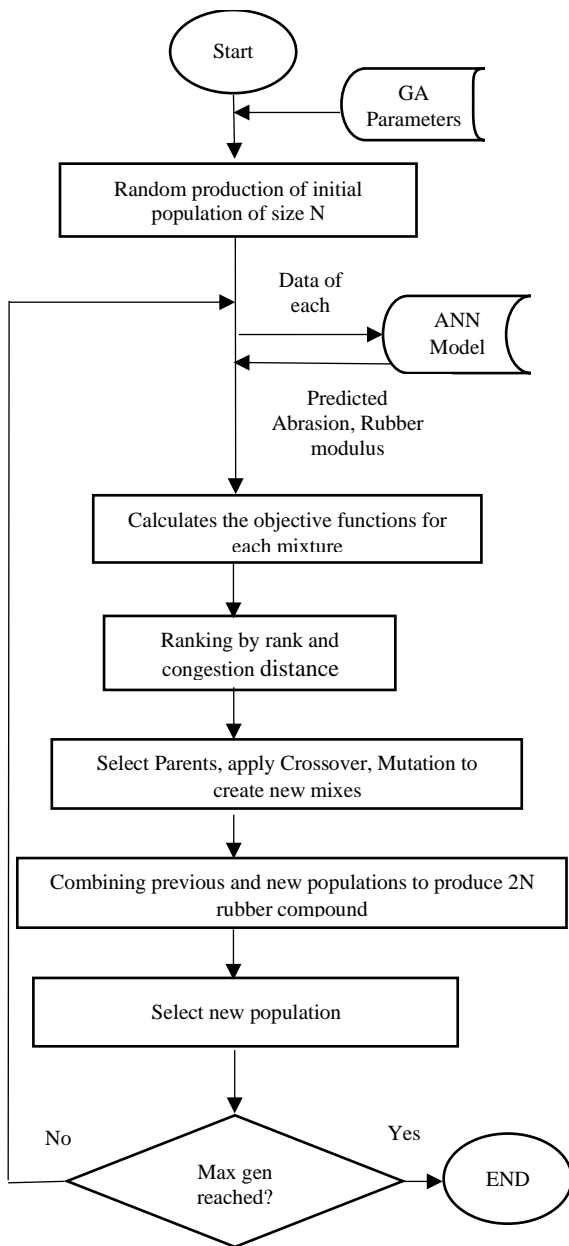


Figure 3. Flow chart for the ANN-GA approach

However, for manufacturers of industrial rubber parts due to product variety, the issue of rubber compound design is more important. In this study, to investigate the effectiveness of the proposed method, an industrial rubber parts company is considered Natural Rubber/ Styreen-Butadeen Rubber -based composites (NR/ SBR are the most widely used in rubber industry.

In addition, the two characteristics of abrasion and modulus are important for most industrial components. For this reason, a NR / SBR-based rubber compound designed, with a specific value for abrasion and modulus and at the lowest price. For the design of the blend, the amount of four raw materials of carbon, oil, sulfur and

accelerator is variable and the amount of other materials is constant. The specific values for modulus, abrasion, and their acceptable ranges given in Table 2.

To model the behavior of rubber blends, data on 47 rubber blends including the weight of the four raw materials and the two properties collected from the rubber company archive. Then this data used as input for training artificial neural network. For each of the two characteristics a multilayer perceptron neural network model developed in MATLAB software. The accuracy of the networks measured based on R^2 and MSE values. Then to search for the optimal combination, the genetic algorithm designed with the toolbox in MATLAB software. The algorithm parameters defined in accordance with Table 3.

The input data to the genetic algorithm is the desired values of modulus and abrasion and the acceptable range for it according to Table 2. Other input data is the acceptable value for the four raw materials according Table 1 and the raw material price. Genetic algorithms created 100 combinations of the four materials as the initial population. For each combination, the data sent to the ANN and the modulus and abrasion values were determined. Price was also determined for each combination with mathematical Equation (3).

The values of the objective functions calculated from Equations (2) and (3). After doing 400 repetitions, 35

TABLE 2. Desired Specification Value

Rubber Compound	Desired Specification Value	
	Abrasion(mm ³)	Modulus(MPa)
1	120±5	10±2
2	150±5	8±2
3	105±5	12±2

TABLE 3. Parameters of Genetic Algorithm

Parameter	Value
Initial population	100
The number of repetitions	400
Intersection ratio	0.7
Mutation ratio	0.1
Probability of mutation	0.02

TABLE 4. The select sample properties

Rubber compound	Abrasion(mm ³)		Modulus(MPa)	
	Ideal	Design	Ideal	Design
1	120	120.03	10	10.07
2	150	150	8	8.32
3	105	105	12	12.09

mixtures with the best target values presented. The amount of abrasion and rubber modulus for the selected sample from the 35 compounds given in Table 4.

This method evaluated by laboratory tests. For this purpose, a rubber compound designed experimentally for the desired specifications. The samples tested for abrasion and rubber modulus according to standard DIN 53516 and standard ASTM D 412 [22]. The results are presented in Table 5. A comparison of the values of objective functions in the optimization method with the experimental method given in Table 6.

4. RESULTS AND DISCUSSION

- According to the results obtained, it be said that more than 90% of the predicted values for abrasion and rubber modulus have a linear relationship with the results obtained from the laboratory test. Therefore, it is possible to predict the rubber modulus and abrasion of the rubber compound for the four raw materials of sulphur, accelerator, carbon and oil using an artificial neural network.
- The results show that this relationship is better for abrasion compared to modulus. Thus, we cannot use one model for all properties. In this method, the designed models has the necessary accuracy. Given that in this method the model is designed using data collected from previous mixtures, it should be said that this method is better in terms of time and cost than the methods presented in previous research.
- The results in Table 5 show that the accuracy of the model is higher in the trained range.
- The results collected in Tables 5 and 6 show that for different compounds designed by the optimization method, the abrasion values and the rubber module are closer to the ideal value. The average difference in the three compounds is 99% for abrasion and 80% for the rubber module. In addition, the design speed with the presented method is 454 times higher than the design speed with the experimental method. Therefore, by combining the genetic algorithm and the artificial neural network, it is possible to design a rubber compound with acceptable accuracy and speed.
- Using this method allows access to a set of answers and increases the designer's decision-making ability. In graphical methods, the problem solved as a single goal, which is long and time consuming and is complicated to examine the effect of several raw materials on several characteristics.
- The results show an improvement in process performance. This improvement was aimed at attracting customer satisfaction and gaining a competitive advantage for the organization. Other research on rubber blending has been done to improve

TABLE 5. The desired values of the properties and them by experimental and optimization methods

Rubber compound	Abrasion (mm ³)			Rubber modulus (MPa)		
	Des	Exp	Opti	Des	Exp	Opti
1	120	118.17	120.03	10	10.5	10.07
2	150	151	150	8	8.5	8.32
3	105	106	105	12	12.7	12.09

TABLE 6. Reduction of quality indicators in two method

Rubber compound	Reduction abrasion error (%)	Reduction modulus error (%)	Reduction price (%)	Reduction design time (%)
1	98	86	27	564
2	100	36	18	244
3	100	87	5	553
Average	99	70	17	454

the characteristics of a blend, and less research has been done on improving the rubber blending design process.

5. CONCLUSION

In this study, with the aim of reducing time and cost and increasing accuracy and ease in the process of designing rubber mixes, the issue of optimizing the process of designing rubber mixes has been investigated. The design of rubber blends has complexities such as nonlinear behavior of rubber mixtures, the effect of raw materials on each other and the effect on composition properties, large number of raw materials and characteristics, conflicting behavior of some characteristics, limitations in raw materials and characteristics. In addition to these issues, the price of the blend designed and the speed of the design is important. Given the complexities and the multiplicity of independent and dependent variables, this is a Non-deterministic Polynomial type (NP-hard) , and the Non-dominated Sorting. Genetic Algorithm used to select the optimal combination. In problem, the relationship between the amount of raw materials and the amount of properties modeled with an artificial neural network. This relationship is completely nonlinear. The behavior of different characteristics is quite different with constant raw materials, so a synthetic neural network model designed for each characteristic. In order for the method to be applicable in terms of product is designing for the customer, the available data in the organization were used to train the artificial neural network. The designed model had the necessary precision to predict the characteristics of the rubber compound. Of course, the model has a higher accuracy in the trained range. With a genetic algorithm designer, choose the final

answer based on the importance of each characteristic or price. The results showed that the process of designing rubber compound with this method has better results than the experimental method.

Finally, it was suggested to technical specialists of the rubber-producing units to apply this method in parallel with the experimental method and then replace it with confidence. It also suggested to researchers that use this method for other rubber compound characteristics such as hardness and tensile strength and for other rubber bases such as EPDM and chloroprene.

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Persian Abstract

چکیده

در صنعت لاستیک، فرآیند طراحی آمیزه لاستیکی به دلیل تاثیر بر خواص محصول از اهمیت بالایی برخوردار است. عملکرد خوب این فرآیند یک مزیت رقابتی برای تولید کنندگان این صنعت به شمار می آید. فرآیند طراحی آمیزه لاستیکی شامل فعالیت های مربوط به انتخاب بهترین مقدار از مواد اولیه برای تهیه ترکیبی با خواص فیزیکی مکانیکی مورد نظر است. در حال حاضر، روش معمول برای طراحی آمیزه لاستیکی، روش تجربی مبتنی بر حدس و خطا است. این روش زمان بر و پرهزینه است. علاوه بر این ترکیب بدست آمده الزاما بهترین ترکیب نیست. در این تحقیق، با هدف بهبود عملکرد فرآیند طراحی آمیزه لاستیکی، روشی تلفیقی از شبکه عصبی مصنوعی و الگو ریتم، با رویکرد کاهش زمان و هزینه و افزایش دقت طراحی ارائه شده است. در این روش، رفتار آمیزه لاستیکی با شبکه عصبی مصنوعی مدل سازی شد. سپس از الگو ریتم ژنتیک به عنوان یک تکنیک جستجوی سریع استفاده شد. مقدار بهینه از چهار ماده اولیه کربن، گوگرد، روغن و شتاب دهنده برای ساخت آمیزه لاستیکی با کمترین قیمت و مقدار مورد نظر از سایش و مدول لاستیکی در ۳۰۰٪ کشش تعیین شد. برای ارزیابی روش، چند نمونه آمیزه لاستیکی با دو روش طراحی شد. نتایج نشان داد، شبکه عصبی مصنوعی توانایی پیش بینی دو ویژگی را براساس چهار ماده اولیه ذکر شده در محدوده آموزش داده شده با دقت بالایی دارد. علاوه بر این با الگو ریتم ژنتیک به طور میانگین قیمت ۱۷٪ کمتر و دقت ۸۴.۵٪ بیشتر از روش تجربی بود. سرعت طراحی ۴۵۴ مرتبه بیشتر بود. براساس نتایج امکان طراحی آمیزه لاستیکی با ادغام هوش مصنوعی و الگو ریتم ژنتیک وجود دارد و عملکردی بهتر از روش تجربی دارد.
