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Distributed algorithm-enabled green packaging cost and environmental protection collaborative optimization decision-making model

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Abstract In order to solve the problem that cost and environmental performance cannot be balanced in green packaging design, this paper takes both as the constraints of green packaging design to construct a dual optimization model, and adopts an improved distributed genetic algorithm (ODGA) to solve the model. By introducing a distributed system into the genetic algorithm to improve the solving efficiency of the genetic algorithm, and based on the characteristics of the dual optimization model, a "clan algorithm" is proposed to improve the crossover operator of the traditional genetic algorithm, which further improves the solving performance of the dual model in this paper. At the same time, in order to ensure that the application of this paper's model for green packaging design process as little as possible to lose the other performance of the packaging, this paper to other performance as a comprehensive constraints on the solution to limit the results, and cushioning performance as an example to study the model in the cushioning performance, environmental performance and cost constraints under the solution effect. The study shows that the model and solution algorithm in this paper can successfully obtain the Pareto optimal solution with maximum environmental performance (440), minimum cost (1.1) and medium cushioning performance (280), which provides a new way of thinking for balancing the environmental protection, cost and other performances in the design of green packaging.

Index Terms ODGA, dual optimization, environmental performance, cost, green packaging design

I. Introduction

In today's competitive market environment, product green packaging design, as an important carrier of brand image, plays a crucial role in enhancing product competitiveness and market share [1], [2]. Green packaging design starts from the concept of environmental protection and creates an ecological environment that is pollution-free and conducive to human survival and sustainable development through design [3]-[5]. Designers should take the environmental protection function as the design premise and evaluation criteria, so that the packaging products play a role in protecting the environment and natural resources after disposal, and truly convey the spiritual concept of green and environmental protection [6]-[8].

Essentially, the most fundamental purpose of green packaging design is to fully adjust the relationship between man and nature, so in the actual design process must pay attention to the protection of environmental resources and cost optimization, to ensure that the smallest cost effective reduction of product packaging in the environment there is a possibility of pollution factors [9]-[12]. In this regard, green packaging design often must meet the following requirements, first, to ensure that the use of minimal materials and resources to carry out the design of packaging [13], [14]. Second, to ensure that the product packaging in the loss of its function as a packaging at the same time, some of the materials and elements can be fully utilized [15], [16]. Thirdly, the concept of sustainable development is integrated to ensure that the recycling of materials can be carried out in an effective way to reduce the generation of waste [17], [18]. In order to ensure that green packaging can be reused, product packaging designers in the actual design process, but also must pay attention to its own removable and can be fully utilized function [19]-[21]. This requires product packaging designers in the design process, in addition to fully open rate of environmental factors, but also must give sufficient attention to the function of product packaging, to ensure that effective design means to extend its life [22]-[25].

Literature [26] based on a literature review, analyzed the impact of green packaging from the business and consumer perspectives, including its design and materials, costs, marketing strategies and other issues, the results show that the field has received greater attention, providing a reference for the community to understand the field.

Literature [27] establishes a framework that proposes five dimensions affecting consumers' green trust, and takes Taiwanese consumers as the research object, revealing that green packaging design has a strong predictive effect on green trust, and green trust enhances green brand attachment. Literature [28] analyzed the relationship between green production and sustainable consumption, especially green packaging design, and conducted research from the perspectives of consumers and enterprises, and its findings have practical and theoretical significance in promoting green production and sustainable consumption. Literature [29] based on the green concept of CAD technology used in the process of product packaging design, proposed the process of product packaging design with the assistance of design software, avoiding the unnecessary duplication of labor in the traditional packaging design, and promoting the rationality and efficiency of the design process. Literature [30] examined the green packaging awareness of Malaysians, through the questionnaire, it was concluded that the majority of people do not know about green packaging, and the consumer's willingness to buy is affected by the packaging design, which helps companies and marketers to attract consumers to buy by perfecting the green packaging design. Literature [31] examined the relationship between green packaging design and green purchase intention, and concluded that the former has a positive correlation with the latter, and is influenced by green brand equity, attitude, etc., which provides guidance for green marketing efforts. Literature [32] explored the green design strategy of Mount Lu Yunwu tea packaging, pointing out that the current embarrassing situation of Mount Lu Yunwu tea packaging design must be appropriately adjusted to shift to environmentally friendly materials and innovative design techniques, and to inject cultural and historical narratives into the design in order to enhance the image. Literature [33] emphasizes the importance of green packaging solutions and discusses the green packaging of enterprise products, arguing that there is a huge potential for green products and green packaging, and that most of the materials used come from local natural resources, which provides an important reference for enterprises to implement green products and green packaging strategies. Literature [34] analyzed the topic of sustainable packaging from different perspectives based on a literature review and provided a classification and rationalization of recent articles to provide insights and avenues for future research, and that companies can utilize this insight in order to achieve sustainable packaging design. Literature [35] puts forward the concept of “green paper packaging” in order to realize the sustainable development of the paper packaging industry, and describes the appropriate production, recycling, and structural design of green paper packaging materials, and looks forward to the direction of the development of green paper packaging. Literature [36] analyzes the design principles and material application of environmentally friendly packaging based on the perspective of environmental sustainability, showing that the use of environmentally friendly materials, through the appropriate packaging, as well as the flexible application of environmental protection and green concepts, can effectively solve the problem of resource waste and environmental pollution. Literature [37] describes the process of natural cosmetic packaging design based on visual and technical attributes, and emphasizes sustainability and ecological awareness, specifying that the perception of the naturalness and environmental friendliness of the product is influenced by the packaging material more than the graphic elements and colors.

This paper aims to solve the environmental protection and cost balance problem in green packaging design, selects environmental performance, cost and other performance as constraints, and constructs a dual optimization model of green packaging design dominated by environmental performance and cost constraints, and taking into account other performance. The tournament selection method, which is widely used in the game field, is adopted to calculate and select the adaptation degree of the genetic algorithm. The distributed system is introduced into the genetic algorithm to solve the inefficiency problem in the dual optimization model solving process. The basic bit mutation method is used in the mutation part of the genetic algorithm, and the crossover rate P_c and mutation rate P_m are introduced into the adaptive genetic algorithm. The “clan crossover” algorithm is proposed, which utilizes the new population permutations generated by the selection operation to pair the parents to form clans, thus realizing the improvement of the crossover operator of the genetic algorithm. The improved distributed genetic algorithm is used as the solution algorithm of the dual optimization model to search for the Pareto optimal solution that meets the constraints of this paper. Taking the cushioning performance as a representative of other performance of packaging besides environmental protection and cost, the model of this paper is used to study the solution results of four packaging design materials, namely, Expanded Polyethylene (EPE), Expanded Polystyrene (EPS), Ethylene Vinyl Acetate Copolymer Foam (EVA), and Honeycomb under the constraints of cushioning, environmental protection, and cost, to verify that the model of this paper is effective in balancing the environmental protection, cost, and other constraints of green packaging. The model in this paper is used to validate the application value of the model in balancing the environmental performance, cost and other properties of green packaging.

II. Construction and solution of dual optimization models

II. A. Construction of dual optimization model

II. A. 1) Variable settings

The following parameters are defined in this study, and the parameter symbols and the way they are defined are obtained by referring to related studies. For decision-making constraints, elasticity constraints and discount factors, production technology coefficient matrix, etc. are mainly based on the needs of this paper, and the definitions and expressions of the relevant variables are carried out on the basis of reference to the predecessor studies.

\[LPS\]: linear production unit. u : production decision input variable. y : production decision output variable. x : production decision state variable. w : production decision structure variable. f : production decision objective constraints. g^h : decision-making constraints. g^s : elasticity constraint. PDU : production decision unit. γ : decision revenue. π : decision control strategy. ϕ : decision state transfer matrix. ψ : control coefficient matrix. ε : slack variable constraints. θ : production technology coefficient matrix. δ : discount factor.

II. A. 2) Modeling

Assume that there exists a generalized dynamic production decision (DPS), and the DPS decision consists of M production decision units $\left(PDU_i, i=1,\ldots,M\right)$. The goal of decision making is to achieve the optimization of the economic indicators of green packaging design. Among them, the economic indicators can include various factors related to production efficiency, such as output level, output benefit, production cost, etc. Without loss of generality, it is assumed that the production objective is to maximize the benefits, which can be expressed by equation (1):

$$\max \sum_{t=1}^{T} \delta^{-1} r\left(x^{(t)}, u^{(t)}\right) \tag{1}$$

Equation (1) represents the case of the objective value of the discounted production decision state variable that can be achieved at different moments.

where the n -dimensional vector $x^{(t)} = \left[x_1^{(t)}, x_2^{(t)}, \ldots, x_N^{(t)}\right]^T$ denotes the decision's state variables at the (t) moment, e.g. labor force, the capital stock, or other internal and external environmental variables affecting the decision production activity on other internal and external environmental variables. The vector $\left[u_1^{(t)}, u_2^{(t)}, \ldots, u_M^{(t)}\right]^T$ denotes the corresponding decision variables, such as output, price, or other controlled variables, for the m DPS at the (t) moment. The vector $y^{(t)} = \left[y_1^{(t)}, y_2^{(t)}, \ldots, y_M^{(t)}\right]^T$ denotes the corresponding outputs of m DPSs at the moment of (t). Different DPSs can produce green packaging outputs with different attributes, but the value forms of the outputs are measurable and comparable. The decision structure is determined by the vector of output ratios of PDUs $w^{(t)} = \left[w_1^{(t)}, w_2^{(t)}, \ldots, w_M^{(t)}\right]^T$, where:

$$w_i^{(t)} = y_1^{(t)} \Big/ \sum_i y_i^{(t)} \tag{2}$$

Equation (2) expresses the value of each output as a proportion of total output at different points in time, and accordingly the share of the i th output in total output.

The input-output relationship of decision making (DPS) is represented by the following equation (3). The output of the decision at the moment (t) is determined by the decision vector $u^{(t)}$. The $m \times m$-order square matrix Θ represents the matrix of production technology coefficients. The production technology coefficient is assumed to be constant over the decision cycle and satisfy $R(\Theta) = m$:

$$y^{(t)} = \Theta u^{(t)} \tag{3}$$

Equation (3) represents the output values for each output at different moments obtained from the product of the values of the input variables and the coefficients of the production technology.

Definitional Decision Making (DPS) The process of state transfer from a (t) moment to a $(t+1)$ moment is represented by the following n th order 1 linear decision difference equation. The state transfer is jointly influenced by the state vector $x^{(t)}$ and the decision vector $u^{(t)}$. Where ϕ is the $(m \times m)$ order decision state transfer matrix. In order to ensure the stability of DPS operation, the matrix ϕ should satisfy $R(\Theta) = m$:

$$\begin{cases} x_1(t+1)=\phi_{11}x_1(t)+\ldots+\phi_{1m}x_m(t)+\psi_1 u(t) \\ x_2(t+1)=\phi_{21}x_1(t)+\ldots+\phi_{2m}x_m(t)+\psi_2 u(t) \\ \vdots \\ x_m(t+1)=\phi_{m1}w_1(t)+\ldots+\phi_{mm}w_m(t)+\psi_m u(t) \end{cases} \tag{4}$$

Its matrix expression is:

$$x^{(t+1)}=\phi x^{(t)}+\psi u^{(t)} \tag{5}$$

Equation (4) and Equation (5) represent how the state of the product is transferred from the t moment to the $t+1$ moment under different moment states. It indicates that the optimization of the latter stage of the model proposed in this paper is completed on the basis of the former stage, and the states before and after are closely linked.

It is assumed that the decision is subject to multiple constraints and the constraints are heterogeneous. Two types of constraints are mainly considered, one is the decision-making constraint $\left(g^h\right)$. This type of constraints cannot be violated during the decision-making production process, such as resource constraints, time constraints, etc. The other type is elastic constraint $\left(g^s\right)$. This kind of constraints generally show a certain degree of elasticity, which can be shown in a certain time period to reasonably allocate the intensity of constraints, or relax the constraints through the market-oriented mechanism. An example is some environmental regulatory constraints. Greenhouse gas and pollutant emissions of enterprises are subject to aggregate control. However, within a certain production cycle, the emission level can be rationally allocated to reduce or increase the emission intensity. Or the constraint can be relaxed by paying a certain cost through the emission trading market. It is assumed that the hard and soft constraints can be represented by equations (6) and (7), respectively. The vector $\varepsilon^{(t)}$ is the set of relaxation variables:

$$g^h\left(x^{(t)},u^{(t)}\right)\leq 0 \tag{6}$$

$$g^s\left(x^{(t)},u^{(t)}\right)+\varepsilon^{(t)}=0 \tag{7}$$

Equation (6) and Equation (7) represent the hard constraints and soft constraints of the model in different moment states. Among them, the hard constraint represented by Equation (6) in this paper mainly refers to the cost of resources used in the design of green packaging, and under the same objective or output, the less resources used the more favorable to the design of green packaging. The soft constraint represented by Equation (7), $\varepsilon^{(t)}$ is the relaxation variable. It indicates that the constraint represented by environmental performance has a certain elastic space in the process of green packaging design, and under the same conditions, the more emission reduction in packaging design, the better.

Through the above analysis, the dynamic production decision (DPS) can be represented by the following model:

$$\begin{gathered} \max \sum_{t=1}^{T}\delta^{-1}r\left(x^{(t)},u^{(t)}\right) \\ s.t. x^{(t+1)}=\phi\left(x^{(t)},u^{(t)}\right) \\ y^{(t)}=\Theta u^{(t)} \\ g^h\left(x^{(t)},u^{(t)}\right)\leq 0 \end{gathered} \tag{8}$$

$$g^s\left(x^{(t)},u^{(t)}\right)+\varepsilon^{(t)}=0 \tag{9}$$

$$x\in \mathbb{R}^N, u\in \mathbb{R}^M, g^h:\mathbb{R}^{N\times M}\to \mathbb{R}, g^s:\mathbb{R}^{N\times M}\to \mathbb{R} \tag{10}$$

Equations (8) to (10) are a synthesis of the previously proposed equations. It mainly represents the main part of the model construction in this paper, i.e., the change of the model under the constraints of hard constraints (cost) and soft constraints (environmental performance), the output of each green packaging design scheme at different moments. This model can better help enterprises to realize the cost savings and green packaging design under the environmental performance constraints. It should be noted that, in order to ensure that the green packaging design will not lose too much other performance under the environmental performance and cost constraints, this paper adds constraints on other aspects of performance in the model. The discussion of other aspects of performance constraints will be introduced in detail in the experimental analysis later. The addition of such comprehensive constraints can make the design of green packaging in this paper more in line with realistic scenarios, thus enhancing the application value of the model in this paper.

II. B.Solving the dual optimization model

In this paper, an improved distributed genetic algorithm is used to solve the constructed dual optimization model. In this section, the improved distributed genetic algorithm is described in detail.

II. B. 1) Calculation and Selection of Adaptation Levels

Selection is the process of choosing a subset of highly adapted individuals with good traits among all individuals in a population at each generation according to their level of adaptation to the environment, i.e., the study context, and then replicating their genes to eventually participate in mating behavior within the population. The selection criterion is the size of the individual fitness function. In this paper, the tournament selection method [38], which is widely used in the field of games, is utilized to determine the degree of superiority or inferiority of individuals. The selection operator in the genetic algorithm is the key to the entire evolutionary computational process. It consumes about 90% of the overall time in the whole process, and the improvement of the design method of selection operator and the introduction of new technology have significant effect on solving the problem of low efficiency of traditional genetic algorithm to realize combinatorial optimization.

II. B. 2) Introduction of distributed systems

The introduction of the distributed system was mainly in the tournament selection phase, which drastically increased the efficiency of the computation [39]. A local area network (LAN) of 101 computers was used to build the distributed system according to the size of the set population. One computer was set up as the master controller, which was responsible for sending the population information to each of the 100 slaves. 100 slaves received the information from the master and started the tournament selection calculation. Subsequently, the slaves send the points of all individuals in the tournament back to the master. Finally, the host then calculates the fitness and selects the group winner based on this information. A large number of pairwise processes of parameter combinations between the same generations are assigned, thus solving the problem of inefficient training due to the lengthy solution process in the dual optimization model solving problem, and the system architecture is shown in Fig. 1.

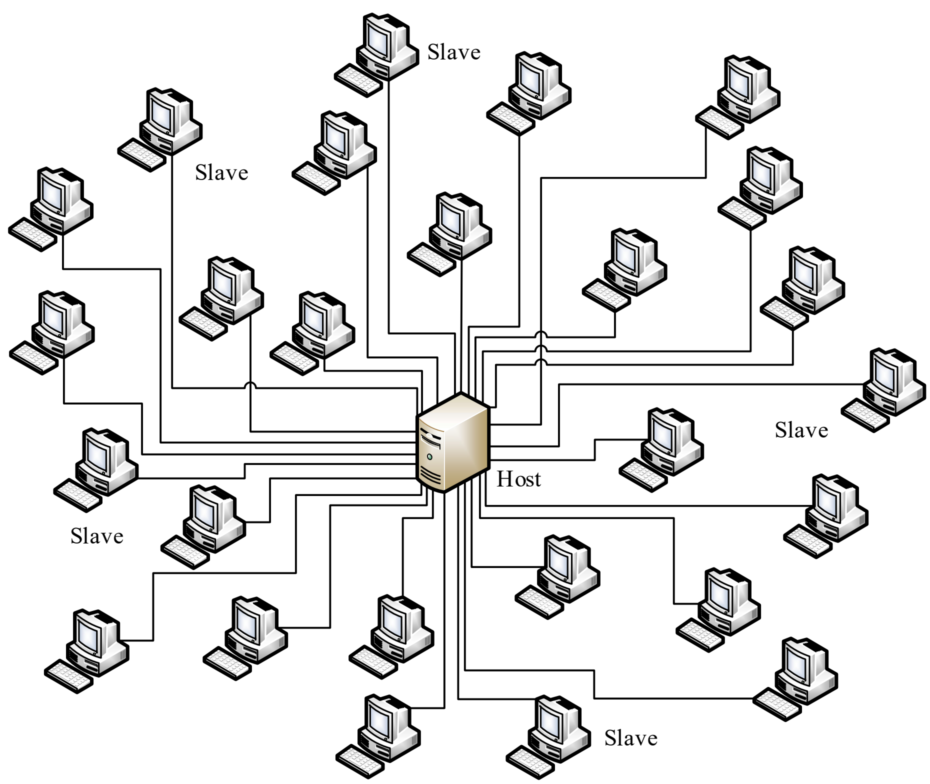


Figure 1: Host-slave framework

II. B. 3) Adaptive cross-variation rates

After the selection operation, a clearing operation is performed on the population and the genes, win rate and fitness values of the 10 randomized group winners from the previous generation population are assigned to individuals numbered 1 to 10 in the new population. The population expansion operation is performed to ensure that the total population size remains unchanged, while keeping both the good gene segments and the randomization of the algorithm. The basic positional mutation method is used in the mutation session.

The two most typical control parameters in the crossover and mutation links are the crossover rate P_c and the mutation rate P_m. The crossover rate is the condition to evaluate whether the next generation of individuals can be produced between the parents to be crossed during the crossover process. Setting P_c too high will speed up the rate of producing new individuals, which will increase the possibility of the good patterns in the genetic algorithm to be corrupted. Conversely, the rate of generating new individuals will be much lower. If the mutation rate P_m is set too large, the nature of the genetic algorithm will be subverted into a completely random search process in the specified solution space, and the meaning of the algorithm will be lost. In order to solve the problem, this paper adopts the adaptive genetic algorithm [40], in which P_c and P_m can be changed automatically with the degree of fitness, which is calculated as follows:

$$P_c = \begin{cases} P_{c1} - \dfrac{(P_{c1} - P_{c2})(f' - f_{avg})}{f_{\max} - f_{avg}} & f' \ge f_{avg} \\ P_{c1} & f' < f_{avg} \end{cases} \tag{11}$$

$$P_m = \begin{cases} P_{m1} - \dfrac{(P_{m1} - P_{m2})(f_{\max} - f)}{f_{\max} - f_{avg}} & f \ge f_{avg} \\ P_{m1} & f < f_{avg} \end{cases} \tag{12}$$

where $P_{c1} = 0.90$, $P_{c2} = 0.60$, $P_{m1} = 0.10$, $P_{m2} = 0.001$. $f_{\max}$ is the largest fitness value in the population. f_{avg} is the average fitness value of the population per generation. f' is the larger fitness value of the two individuals to be crossed; f is the fitness value of the individual to be mutated.

II. B. 4) Improvements to the intersection operator

Based on the characteristics of the dual optimization model in this paper, a "clan crossover" operator is proposed. After the selection operation, individuals 1~10 of the new population are the champions of each of the 10 randomized groups. Before crossover, the 10 individuals are firstly combined into 45 pairs of parents according to the permutation, i.e. the process of forming a clan. Next, sequentially, the crossover rate is used to determine whether the pair of parents satisfies the conditions for conducting the crossover, and if so, the crossover is conducted. Crossover inserts the resulting new individuals into the new population. Conversely, traverse subsequent parent combinations. The traversal process is limited by the population capacity, when a round of traversal is completed for 45 parent combinations if the population capacity is not reached then 2 rounds of traversal are performed until the upper limit is reached.

III. Simulation experiment and result analysis

III. A. Performance analysis of the solving algorithm

III. A. 1) Test functions

In this paper, an improved distributed genetic algorithm is used to solve the dual optimization model of cost and environmental protection in green packaging design. In order to verify the solution performance of the algorithm, the genetic algorithm with adaptive adjustment of crossover probability and variance probability (SAGA), the improved adaptive genetic algorithm (WAGA), the cosine-improved adaptive genetic algorithm (CAGA), as well as the improved distributed genetic algorithm (ODGA) proposed in this paper are used in the optimization of four representative complex functions. The four optimization functions used in the experiment are shown in Table 1. Among them, f_1 is a single-peaked function, but the function is pathological because there is a narrow deep valley at $y = x^2$, which is easy to fall into the local extremes, and the global minimum point of this function is $f(1,1) = 0$. The function f_2 has six local minima, including two global minima. The function f_3 has four local mechanisms, but only one global maximum point $f(0,0) = 3600$, and the function f_4 is a multi-peak function with one local maximum at each peak and only one global maximum point $f(0,0) = 1$.

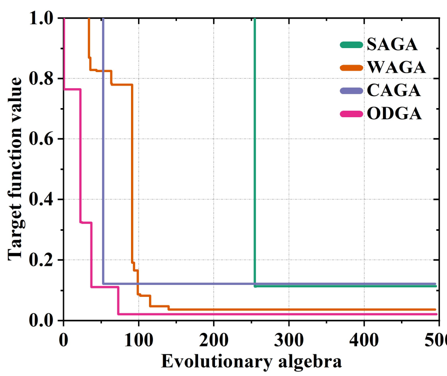
Table 1: Test function

Function	Search range
$f_1(x,y)=100(x^2-y^2)+(1-x)^2$	[-2.172,2.172]
$f_2(x,y)=(4-2.1x^2+\frac{x^4}{3})x^2+xy+(-4+4y^2)y^2$	[-20,20]
$f_3(x,y)=\left[\frac{3.0}{0.05+(x^2+y^2)}\right]^2+(x^2+y^2)$	[-5.38,5.38]
$f_4(x,y)=-\left[x^2+2y^2-0.4\cos(3\pi x)-0.6\cos(4\pi y)\right]$	[-30,30]

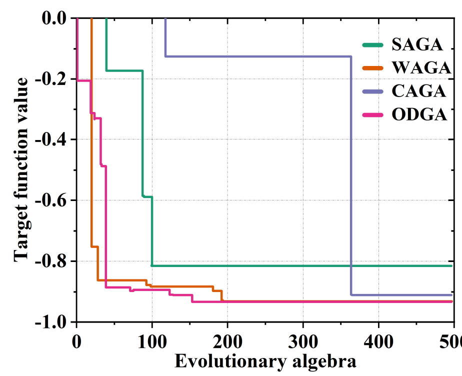
III. A. 2) Performance analysis

SAGA, WAGA, CAGA and OWAGA all use binary coding, fitness scaling selection, two-point crossover and multi-locus variation. Parameters of each genetic algorithm: Chromosome length is 50 and population size is 100.In addition, in SAGA, $k_1=k_3=0.5, k_2=k_4=1.0$. In WAGA, $P_{c1}=0.8, P_{c2}=0.5, P_{m1}=0.3, P_{m2}=0.03$. In CAGA, $P_{c\max}=1.0, P_{c\min}=0.5, P_{m\max}=0.3, P_{m\min}=0.05$. In the ODGA proposed in this paper, $P_{c1}=0.9, P_{c2}=0.6, P_{m1}=0.1, P_{m2}=0.01$.

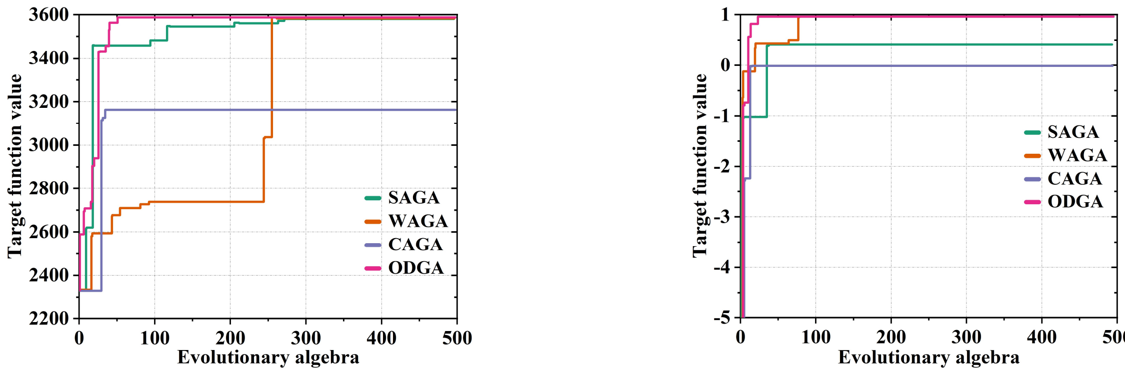
Fig. 2 shows the performance comparison of the maximum function values of SAGA, WAGA, CAGA and ODGA under the 4 tested functions, (a)~(d) are the optimization results of the functions $f_1 \sim f_4$, respectively.Although the corresponding curves of the WAGA algorithm converge to the global optimal solution, the curves are prone to long time horizontal stagnation in the changes, so that the algorithm converges too slowly. From Fig. 2(c) and Fig. 2(d), it can be seen that the curve corresponding to the SAGA algorithm is prone to show a trend of flat state when approaching the global optimal solution, which indicates that the algorithm often falls into the local optimal solution in the later stage due to the influence of its super-individuals in the early stage, and thus fails to converge to the global optimal solution.The CAGA algorithm is deficient in the searching ability and the ability of jumping out of the local optimum, and the curve corresponding to this algorithm evolution curve has maintained a very small evolution rate, especially in Fig. 2(c), the curve has maintained a trend of no further change after converging to the vicinity of 3163 in about 35 generations. Compared with the previous three algorithms, the change curve represented by the ODGA algorithm proposed in this paper has a shorter stagnation state in the overall evolution and is able to converge to the globally optimal solution within the minimum number of generations, which indicates that the algorithm has better convergence and optimality searching ability, and is able to jump out of the locally optimal solution with a fast speed to push the evolution to continue when it is stagnant.



(a) Function f_1 optimization results



(b) Function f_2 optimization results



(c) Function f_3 optimization results (d) Function f_4 optimization results

Figure 2: Performance comparison of algorithms

Table 2 shows the optimization test results after 50 runs of each of the four test functions. Comparing the SAGA, WAGA and CAGA algorithms, the average convergence value of the function solved by the ODGA algorithm proposed in this paper is the closest to the global optimal value of the function, and the number of times converging to the global optimal solution is also the closest to the number of experimental times, and even reaches 100% convergence rate in the optimization of the function f_3 and the function f_4 optimization even reaches 100% convergence rate, so the stability of ODGA is better. In terms of the average number of convergence generations, ODGA is always the fastest algorithm to converge to the global optimal solution, indicating that the convergence ability of the algorithm in this paper is the best among several algorithms.

Table 2: Optimize test results

Function	Algorithm	Convergence times	Average convergent algebra	Average convergent value
f_1	SAGA	10	364	0.0094
	WAGA	18	251	0.0019
	CAGA	9	373	0.0278
	ODGA	25	92	0.0003
f_2	SAGA	12	217	-0.8348
	WAGA	23	89	-1.1386
	CAGA	15	208	-0.8679
	ODGA	28	39	-1.0001
f_3	SAGA	18	134	3392
	WAGA	21	129	3571
	CAGA	14	203	3386
	ODGA	27	17	3600
f_4	SAGA	17	239	0.7382
	WAGA	20	174	0.8473
	CAGA	15	258	0.5986
	ODGA	26	91	1.0000

III. B. Dual optimization model analysis

As can be seen from the dual optimization model constructed in the previous section, in order to ensure that the green packaging design can not lose other packaging performance under the dual constraints of environmental protection and cost as much as possible, this paper adds other constraints into the model to ensure the performance of the designed packaging. In this section, we take the buffering performance of the package as the representative of other constraints, and study the application effect of this paper's dual optimization model in green packaging design under the constraints of environmental protection, cost and buffering performance. Meanwhile, in order to verify the generalization ability of this paper's model, the model is applied to four packaging materials, including expanded polyethylene (EPE), expanded polystyrene (EPS), ethylene vinyl acetate copolymer foam (EVA), and honeycomb paperboard (Honeycomb), respectively. The four materials are redistributed to improve the cushioning performance of the packaging materials by reducing the response and equalizing the vibration energy distribution of the packaging materials while improving the environmental performance and cost reduction rate of the green packaging design.

III. B. 1) Parameterization

(1) Cushioning performance score

For EPE, EPS, EVA, Honeycomb liner each cut six square specimens with a size of 120mm × 120mm × 50mm, according to GB/T8168-2008 "Dynamic compression test method for cushioning materials for packaging", respectively, static compression test and dynamic compression test. The static compression test was carried out with the universal material testing machine of S Testing Instruments Co., Ltd. and the results were characterized by the cushioning coefficient c -stress curve. The dynamic compression test was carried out using a falling hammer impact test system from Y Company. The obtained results were characterized by the maximum acceleration-static stress curve, and the results are shown in Figures 3 and 4. Scattered dots of different colors in the figures indicate specimens of different materials, and the lines are the fitted curves for the materials. It can be seen from the figure that the lowest point exists in each curve, and the buffer coefficient and maximum acceleration of the four materials can be compared through the lowest point. At the same time, random vibration test of the same working condition under the protection of different materials of cushioning liner is carried out for the green package design to obtain the vibration response of the designed package.

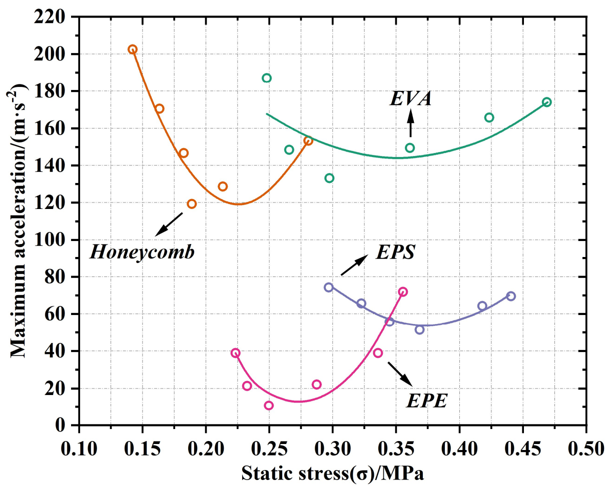


Figure 3: Maximum acceleration-stress curves of different materials

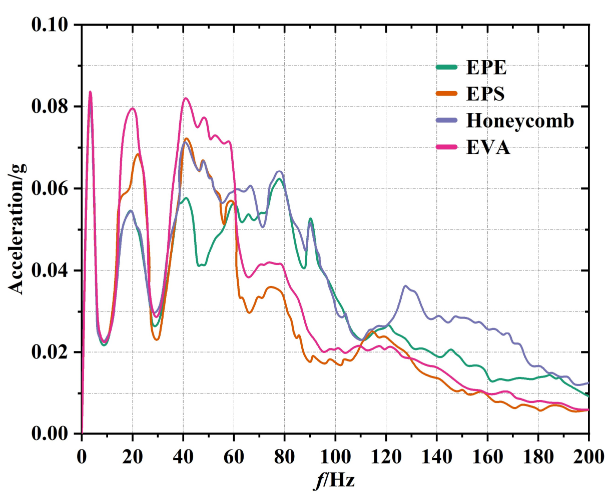


Figure 4: Comparison of acceleration response under different materials

Combining the results of static compression test, dynamic compression test and random vibration test, the cushioning performance scores of the four cushioning materials were evaluated in a comprehensive comparison, and the specific scoring results are shown in Table 3. Table 1-6 indicates the six specimens selected for the experiment, and the cushioning performance scores are given to each specimen according to its performance in the experiment, and finally the average value of cushioning performance scores of different materials is calculated. As can be seen from the table, the mean values of the cushioning performance scores of the four materials are 26.12, 44.00, 84.29 and 80.77, respectively, and there is a large difference between the cushioning performance scores of EPE and EPS, and the cushioning performance scores of EVA and Honeycomb. In contrast, EVA material packaging material can obtain better cushioning performance in practical applications.

Table 3: Performance evaluation of four materials

Materials	EPE	EPS	EVA	Honeycomb
1	25.48	45.14	83.26	80.06
2	23.56	43.29	81.78	78.27
3	25.71	40.87	85.47	74.38
4	24.98	44.71	86.32	85.74
5	27.62	43.16	83.49	82.19
6	29.38	46.83	85.44	83.97
Mean	26.12	44.00	84.29	80.77

(2) Environmental performance score

Due to the limitations of the real conditions, this paper analyzes the environmental performance of these four materials only by reviewing the relevant literature and the development trends and hot spots in the packaging industry in recent years. The specific scoring situation is shown in Table 4. Since the material of honeycomb paperboard is mainly composed of paper, it is evaluated as the packaging material with the highest environmental performance. On the contrary, since regions and countries such as Europe, Japan, South Korea and Australia restrict the import of EPS foam packaging materials, they are evaluated as packaging materials with the lowest environmental performance. For EPE and EVA, both are new environmentally friendly foam packaging materials in recent years, but due to the lack of direct comparison of the literature on the environmental performance of the two, these two materials are evaluated as packaging materials with medium environmental performance.

Table 4: Cost and environmental performance evaluation of four materials

Materials	EPE	EPS	EVA	Honeycomb
Specification/ (mm ×mm ×mm)	800×1800×20	800×600×20	500×1000×20	1500×1300×20
Price/yuan	28	7	49	1.8
Single volume/ (mm ×mm ×mm)	50×30×20	60×80×20	60×50×20	80×50×20
Single price/yuan	0.2348	0.1486	1.2437	0.000618
Environmental performance rating	32	68	68	94

(3) Cost

For the cost of the four selected packaging materials nearly refer to the selling price information of an online sales platform, without considering the assembly cost as well as the waste cost, etc., the relevant data are listed in Table 4.

III. B. 2) Green Packaging Optimization Design Results

(1) Algorithm operation results

Through the improvement of distributed genetic algorithm solving to get the green packaging environmental performance and cost reduction as the dominant, taking into account the cushioning performance of the design approach. Based on the model and the problem in this paper, the initial population is defined as the original unoptimized design way of four materials: EPE, EPS, EVA and Honeycomb, with Honeycomb as the material 1, EPE as the material 2, EVA as the material 3, and EPS as the material 4. The initial population is set to be 150, the variance probability is set to be 0.3, the crossover probability is set to be 0.7, and the number of iterations is set to be 200, combined with each index parameter determined in the previous section, and the design of the green packaging will be carried out in the same way as the original design. The number of iterations is set to 200, combined with the parameters of the indicators determined in the previous section, the resulting parameters are inputted into the algorithm, and the Pareto solution set satisfying the objective function is obtained as shown in Fig. 5, in which

EP, BP and Cost denote the environmental protection performance, buffering performance and cost, respectively, and the optimal solution is at the red star. The relationship between buffering performance, environmental performance and cost is shown in Fig. 6, where (a)-(c) denote the relationship between buffering performance and environmental performance, buffering performance and cost, and environmental performance and cost, respectively. The results in Fig. 5 and Fig. 6 show that this paper constructs a dual optimization model dominated by environmental performance and cost constraints and solves it using an improved distributed genetic algorithm, which is able to obtain the Pareto optimal solution for green packaging design. Analyzing the three-dimensional spatial distribution of environmental performance, cost and cushioning performance as well as the relationship between environmental performance, cost and cushioning performance, the Pareto optimal solution of green packaging design in this paper ensures the highest environmental performance and the lowest cost to the greatest extent, which effectively achieves the goal of the dual optimization model in this paper. In terms of cushioning performance, compared with other solutions in the Pareto solution set, a part of the cushioning performance is lost in the design of the optimal solution, but the cushioning performance of the optimal solution (280) is still in the middle level. And this loss gets the highest environmental performance (440) and the lowest cost (1.1), so it still shows the effectiveness of the model and the solution algorithm in this paper.

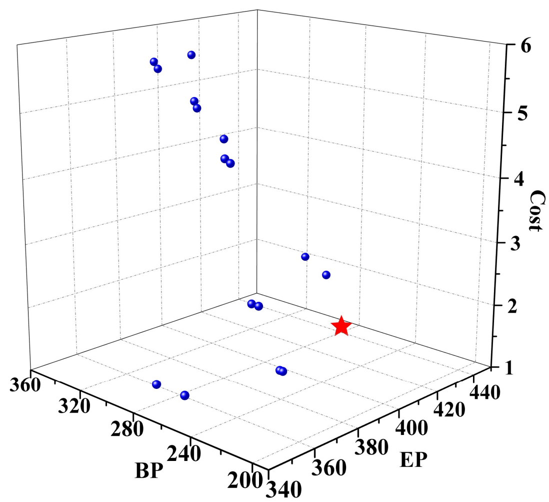
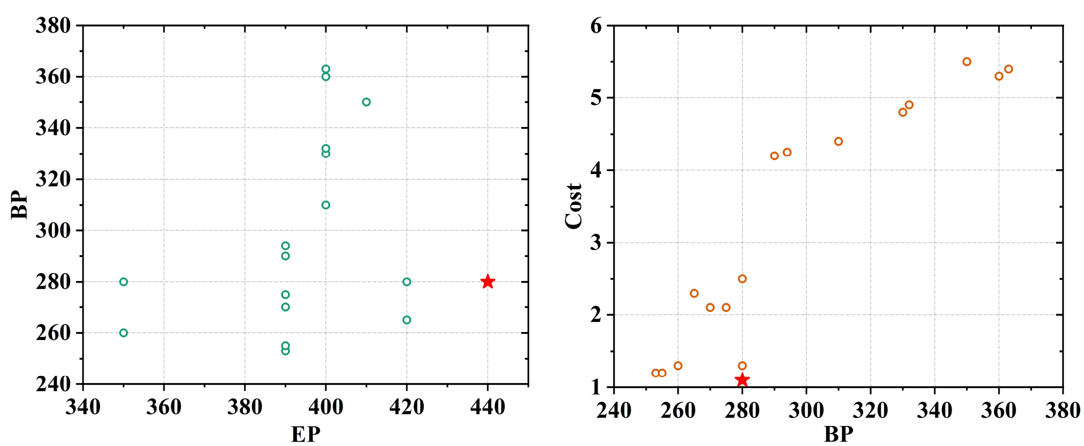
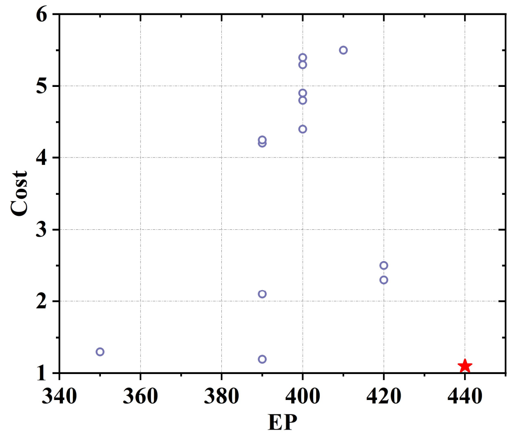


Figure 5: Pareto solution set



(a) EP and BP

(b) BP and Cost



(c) EP and Cost

Figure 6: Evaluation indicator relationship

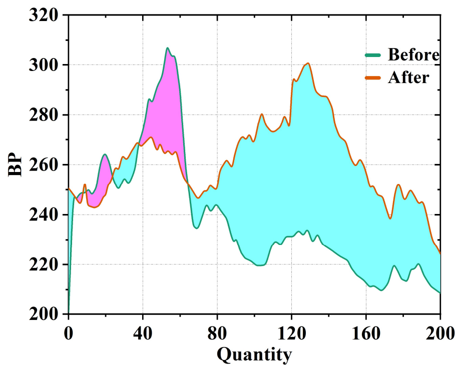
In order to further explore the influence of different materials on green packaging design under the model constraints in this paper, four different materials are randomly paired to generate multiple design options for the most initial population, and the results obtained by using the improved distributed genetic algorithm for solving are shown in Table 5. The table lists 10 design options in the order of environmental performance from high to low, cushioning performance and cost from low to high. It can be seen from the table that when Honeycomb is selected as the material for green packaging design, the highest value of fitness function is obtained, which reaches 319.05. Among the first ten design options, the lowest value of fitness function is 307.96 for the option that all the design materials are made of EVA, which is due to the fact that even though EVA has the optimal cushioning performance among the four cushioning materials selected, its environmental performance is lower compared with that of Honeycomb, which is the best cushioning material for the green packaging design. Honeycomb, it is less environmentally friendly and more costly compared to Honeycomb, which does not meet the needs of the model in this paper.

Table 5: Solution results

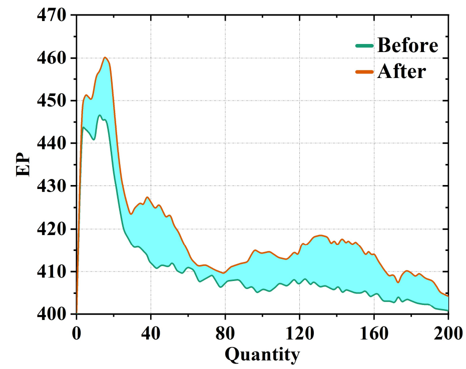
Scheme	BP	EP	Cost	Fitness function
1-1-1-1	326.77	447.81	1.76	319.05
1-4-2-1	327.53	445.84	2.14	318.98
1-3-4-2	329.21	434.53	2.26	318.81
2-3-1-1	329.97	424.73	2.92	316.77
1-3-2-1	330.29	408.09	3.64	316.22
1-1-4-2	336.73	400.77	3.86	313.6
4-3-1-2	338.34	399.24	4.19	310.37
4-4-1-2	343.62	370.62	5.35	309.81
4-1-1-1	344.27	353.05	5.36	309.57
3-3-3-3	348.11	331.08	5.96	307.96

(2) Optimization results

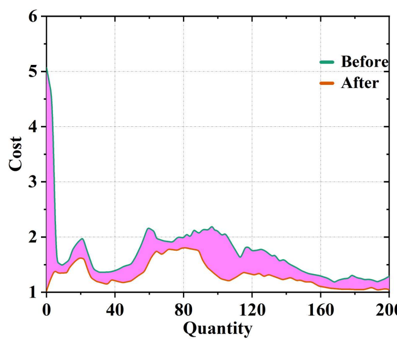
In order to more intuitively reflect the effect of green packaging design after the optimization of this paper's model, the design scheme with the highest value of the adaptability function is selected for analysis. The cushioning performance, environmental performance and cost of green packaging design before and after the production of 200 pieces of a production line using the model of this paper are selected for comparison, and the user satisfaction of green packaging produced before and after the use of the model is statistically calculated, and the results are shown in Fig. 7, with (a)-(d) denoting the cushioning performance (BP), the environmental protection performance (EP), the cost and the satisfaction (Satisfaction) respectively.). From the figure, it can be seen that the environmental performance and user satisfaction of the optimized green packaging design have increased, in which the increase of user satisfaction is the most obvious, and the average value of satisfaction of the 200 designed packages has increased from 46.45 to 90.16, with an increase of 94.10%. And the cost of the 200 designed packages also produces a significant reduction after optimization, with a range of about 22.81%. Although the cushioning performance of green packaging design is still lower than that before optimization after optimization, overall, the cushioning performance of green packaging after optimization of this paper's model also increases compared with that before optimization. The optimization results indicate that the dual optimization model of green packaging design constructed under the main constraints of environmental performance and cost in this paper has significant effectiveness.



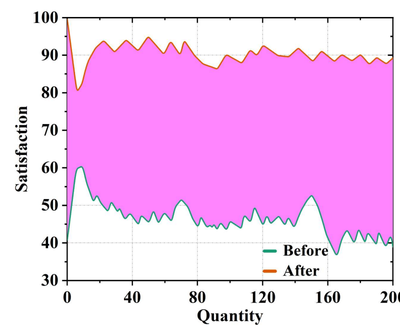
(a) BP



(b) EP



(c) Cost



(d) Satisfaction

Figure 7: Optimized result

IV. Conclusion

In this paper, a dual optimization model for green packaging design with environmental protection and cost as the main constraints is proposed, and an improved distributed genetic algorithm is used to solve it. The results show that the model in this paper successfully solves the green packaging design scheme containing the highest environmental performance (440), the lowest cost (1.1) and the medium level of cushioning performance (280) under the constraints of environmental performance, cost and cushioning performance. It is shown that the model in this paper has obvious validity and can provide useful reference for the research in the field of green packaging design.

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