Hindawi
Complexity
Volume 2019, Article ID 3512142, 14 pages
https://doi.org/10.1155/2019/3512142

Research Article

Manufacturers' Green Decision Evolution Based on Multi-Agent Modeling

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Received 10 January 2019; Accepted 27 February 2019; Published 1 April 2019

Academic Editor: Dehua Shen

The development of green products is gradually becoming important due to serious ecological issues. In this study, an agent-based model is developed to visualize and analyze the evolution of green decision-making in the manufacturing industry. Based on this agent-based model, the macrobehaviors of manufacturers, consumers, and products are analyzed and simulated. Our results show that, first, the manufacturing industry emerges showing a "convergence" effect. The manufacturers may overestimate the consumers' green degree demand, but this gradually gets corrected through the mechanisms of market competition. Second, as consumer income increases, it becomes easier for manufacturers to adapt to the market's supply and demand as impacted by the products' green degrees, and it becomes unfavorable for them to form a monopoly in the market. Furthermore, the profit of manufacturers is mainly derived from the sales and gradually gets more influenced by the products' green degree when the consumer income increases.

1. Introduction

The development and promotion of green products is gradually becoming important for governments due to serious ecological issues. Green products can be defined as products that are composed of recyclable materials and are remanufactured using water and energy-saving methods to reduce waste, packaging, and the amount of toxic materials disposed [1]. The concept of green degree was developed to distinguish green products from other competitive products and highlight the degree of environmental-friendliness of green products. It reflects the general impact of different green attributes on a green product that is transparent to consumers. The firms can then evaluate the greenness of their products to consumers in a credible way, for instance, in terms of emission levels and gas-mileage of vehicles [2].

We take China's split air conditioners as an example to illustrate this concept. In practice, the green degree of split air conditioners is divided into three levels based on their energy efficiency. If the energy efficiency is valued above 3.6, it is ranked as the best. The values of energy efficiency for the other two levels are [3.4, 3.6) and [3.2, 3.4). If the energy efficiency of an air conditioner is lower than 3.2, it cannot be sold in the market. If manufacturers create products with a higher green degree, it will not only benefit the environment but also enhance their corporate social image and create new competitive advantages [3].

Manufacturers' green degree decisions concerning their products can be triggered by the green demands of consumers and markets [4]. The green purchase behavior of consumers is of great significance to the decision-making of manufacturers regarding the product's green degree [5]. However, consumers' green buying decisions are very complex. First, when consumers choose products, most tend to evaluate whether they can afford the product based on their income, which determines their purchasing power [6]. Therefore, consumer income is an important factor that affects their purchase intention and behavior concerning green products [7]. Second, an increasing number of consumers value green products because these can save more energy and are environmentally friendly, among other reasons [8]. Besides, consumers are affected by their social networks; they may choose products based on information shared with their friends and some network platforms [9]. Interactions between consumers and the influence of "word-of-mouth" significantly impact consumers' purchase decisions.

Additionally, a manufacturer's green degree decision concerning its product is also complicated. When manufacturers make decisions on this issue, they are accustomed to considering market competition feedback and results, which are determined by consumers' purchasing behaviors. Feedback includes a manufacturer's current and historical sales and profit, among others [10]. Besides, manufacturers may refer to the green decisions of other manufacturers and especially learn from the most competitive company [2]. Thus, a manufacturer's green-related decision changes dynamically and the green degrees of all products in the market evolve at different times.

Due to the complexity of the decision-making and interaction between manufacturers and consumers, the evolution mechanism of a manufacturer's green degree decision concerning its product is still unclear. Thus, we find the following problems worth investigating:

(1) How is a manufacturer's green degree decision concerning its product affected by consumer income and purchase decision?

(2) How does the green degree of products evolve due to competition within the manufacturing industry?

(3) At which level of green degree can products generate more profits given different levels of consumer income?

The market system is composed of the agents of manufacturers and consumers. It is a typical complex adaptive system in which agents are heterogeneous and behave adaptively [11]; the interactions and transactions among manufacturers and consumers change dynamically, and the system performance is complex and nonlinear.

Agent-based modeling (ABM) is a form of "bottom-up" modeling, which is well suited for studying complex adaptive systems comprising autonomous, interacting agents whose behaviors are based on the current state of their interactions with other agents and the environment [12, 13]. Therefore, ABM was adopted in this study to construct interactions among consumers and manufacturers. We used small-world networks [14] to construct interactions among consumers to model the "word-of-mouth" influence. The particle swarm optimization (PSO) algorithm [15] was applied to model dynamic decisions of manufacturers concerning their products' green degrees. Using ABM, this study was able to investigate the emerging macrobehaviors of the system from the microbehaviors of consumers and manufacturers [13]. Based on the model, we analyzed how the manufacturers' green degree decisions are derived from consumers, how the industry's green degree changes differently under varying purchasing powers of consumers, and why products of different levels of green degrees can survive in competitive markets.

The novelty and distinctive features of this study are as follows. First, unlike previous studies that paid more attention to the optimal decision-making of an individual manufacturer, this study focuses more on the evolution of decision-making concerning products' green degree and the competitive performance of products with different green degrees in the market. Second, this study constructs a multiagent model which takes into account more complex features of agents, for instance, by fully considering consumers' income; consumers' preference heterogeneity related to price and green degree; consumer interactions; and the competition, imitation, and learning among manufacturers. Third, this study presents a visual analysis of the product green degree evolution under different consumer income scenarios and an analysis of multidimensional performance indicators such as the product green degree, product sales, manufacturer profits, product concentration degree, and the matching degree of supply and market demand.

The rest of the paper is organized as follows. Section 2 presents a review and analysis of the literature on decision-making related to manufacturers' green products. Section 3 provides a systematic analysis of the agents and their interaction mechanisms and discusses the construction of the agent-based model. Section 4 presents an analysis of the decision-making process of agents and their interactions and the set-up of simulated scenarios. Section 5 discusses the simulations and their results together with managerial insights. Section 6 presents the conclusions and suggestions for future research.

2. Literature Review

The decision-making of manufacturers of green products generally can be categorized based on two dimensions: (1) market characteristics and (2) the supply chain environment.

Regarding market characteristics, Liu et al., (2012) [16] studied the effects of competition and consumers' environment consciousness on the profitability of manufacturers with different green efforts. Swami and Shah (2013) [17] showed that greening efforts lead to an increase in market demand, while the optimal greening efforts of the manufacturers and retailers are determined by their green sensitivity and green costs. Nouira et al. (2014) [18] showed that, by providing variations of products with different green degrees for ordinary and environmentally conscious consumers, enterprises can gain more profit than by providing only one product. Zhang et al. (2014) [19] studied the pricing strategy of manufacturers under a hybrid production mode where green and nongreen products compete in the market and revealed that the difference in production costs exerts an influence on the production choice of manufacturers when consumers are heterogeneous in their product evaluation. Xi and Lee (2015) [20] analyzed the pricing and investment decisions on green product innovation in the scenario where consumer demand is dependent on price and investment of green innovation. Zhu and He (2017) [2] analyzed the influence of various types of green products and market competition on the green degree decision of competing enterprises. Ülkü and Hsuan (2017) [21] investigated the pricing decisions and profits of two competing enterprises under different levels of modularity of green products and consumers' environmental sensitivity. Yenipazarli and Vakharia (2017) [22] addressed the question of to what extent a specific green product strategy can benefit the environment while simultaneously resulting in profits. Raza et al. (2018) [23] proposed an integrated revenue management framework to deal with the manufacturer's green effort, pricing, and inventory decisions in the market where consumers are heterogeneous in their willingness-to-pay.

Focusing on the related decision-making of green product manufacturers in the supply chain environment, Ghosh and Shah (2012) [24] analyzed the influence of channel structures, greening costs, and consumer sensitivity towards green apparels on greening levels, prices, and profits of the green supply chain. Zhang and Liu (2013) [25] showed that cooperative decision-making can guarantee that the supply chain and its members gain optimal profit and that supply chain members become more active in producing and promoting green products under a revenue-sharing mechanism. Ghosh and Shah (2015) [26] explored the impact of cost-sharing contracts on the green degree, price, and profit of green supply chain under circumstances where consumers are relatively sensitive to the environment. Huang et al. (2016) [27] proposed a game-theory model to study the effect of production lines, supplier selection, transportation selection, and pricing of green supply chain on the profitability and greenhouse gases emissions of the supply chain. Liu and Yi (2017) [28] took into consideration target advertising and showed that the optimal price is inversely associated with the green degree and investment of target advertising. Yang and Xiao (2017) [29] examined how price, green degree, and profit of green supply chains are affected by channel leadership and government subsidy under a fuzzy environment where production costs and consumer demands are unclear. Madani and Rasti-Barzoki (2017) [30] revealed that cooperation among supply chain members can encourage these members to produce greener products and gain more economic benefits for themselves. Xing et al. (2017) [31] found that, in competition with traditional manufacturers, green manufacturers are more likely to choose the integrated channel strategy to make rational green degree decisions and quickly make changes in response to market demands. Song and Gao (2018) [32] showed that a revenue-sharing contract is relatively effective in enhancing the green degree and profit of the whole green supply chain. Hong et al. (2018) [33] explored an effective way to optimize the service time and production selection decision of the green supply chain considering service time and emission regulations.

The existing study (on manufacturers' decision-making concerning their product's green degree) mainly focuses on the optimal decision-making of individual manufacturers under different circumstances and less on the decision of manufacturers and the industry as a whole. In actuality, in market competitions among manufacturers, there are interactions such as mutual imitation and learning, which exert influence on the products' green degree decision made by manufacturers. Moreover, the existing study describes market demand as a linear function of the product's price and green degree but ignores the interactions among consumers and consumers' learning and imitation behaviors in the process of making purchase decisions. Meanwhile the consumers' purchasing decisions are not only influenced by the multiattributes of the product (such as price and quality) but are also impacted by other consumers in the interaction network.

3. Agent-Based Modeling

3.1. Model Description and Analysis. The market includes consumer and manufacturer agents as well as green products. Manufacturers and consumers are connected via products; they interact based on product supply and demand. The relationships among agents are described in Figure 1. The agents' decision-making and interaction mechanisms are considered and shown in this model.

As shown in Figure 1, the products have different price and green degrees, which are provided by different manufacturers and diversely meet the needs of different consumers. During market transactions, the consumers make purchasing decisions, and the manufacturers make product green degree decisions. The factors influencing consumers' purchase decisions include consumer income, price and green degree expectations, and their sensitivity to the price and green degree, among others. Additionally, the "word-of-mouth" recommendation and imitation tendencies based on interactions among consumers also affect the purchase decisions of consumers. The manufacturers may adjust their green degree decisions based on feedback from product competition, including current and historical experiences. Moreover, the manufacturer may learn from other benchmark manufacturers through interactions among manufacturers. All agents' decisions may adjust dynamically, with the products' green degree changing accordingly [34]. As a result, the green degree of the manufacturing industry evolves nonlinearly.

The system's macroperformance, such as the industry's product green degree and competition performance, can be studied through the interactions of these agents in the market; and indicators including manufacturers' sales and profit, as well as the product concentration degree, constantly emerge in different curves under various scenarios.

3.2. Consumer Agents

3.2.1. Consumer Interaction Network. During the purchase and consumption process, consumers are connected through one or more formal and informal relationships, called the consumer interaction network [35]. The consumers are embedded in the interaction network; therefore, their purchase decisions are influenced by other consumers in this network [36]. Newman (2000) [37] suggested that many real-world social networks have the famous "small-world" property; therefore, "small world" is used to describe the structure of consumer interaction networks. Watts and Strogatz (1998) [38] suggested that the small-world networks are characterized by a high degree of local clustering (like regular lattices) but also possess a short diameter or vertex-to-vertex distances, which can be constructed as follows.

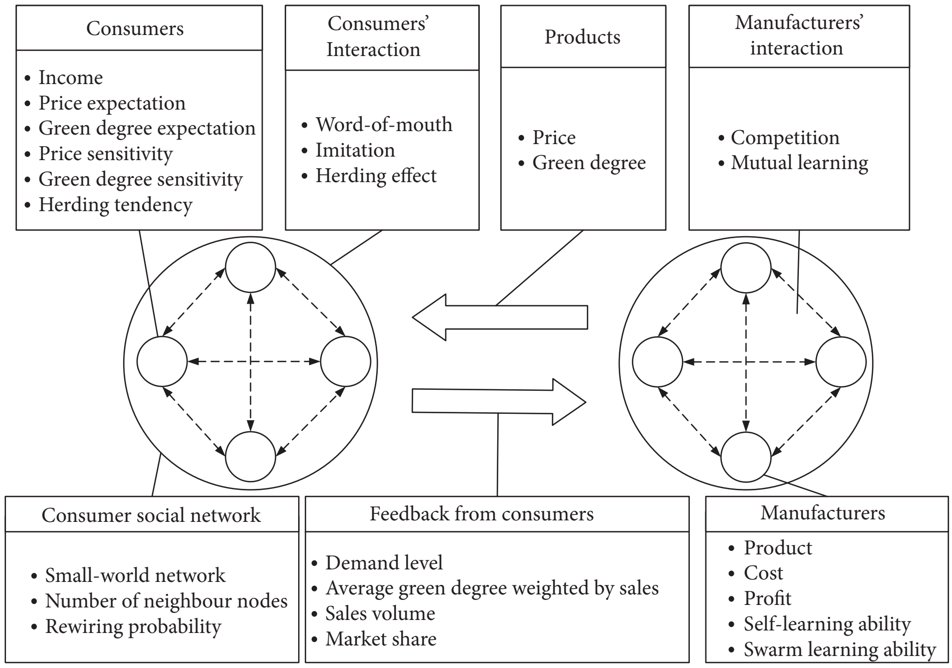


Figure 1: The system structure diagram.

Starting from a ring lattice with N vertices and K edges per vertex, each edge is rewired at random with probability P_r. This construction produces graphs between regularity ($P_r = 0$) and disorder ($P_r = 1$), such that P_r in the intermediate region $0 < P_r < 1$ produces some degree of both. Specifically, it is required that $N \geq K \geq \ln N \geq 1$, where $K \geq \ln N$ guarantees that a random graph will be connected. Hence, consumers will be affected by the characteristics of the small-world network such as the number of neighbor nodes K, which can characterize the number of consumers interacting with one consumer in making purchase decisions, and the rewiring probability P_r, which represents the probability that the consumer's neighbors will change their purchase decisions.

3.2.2. Consumer Purchase Decision-Making. The manufacturers and consumers can be denoted as i and j and their numbers are M and N, respectively. U_i^j is the utility of the product i for the consumer j ($j \in (1, \cdots, N)$), which can indicate the consumers' motivation and willingness to purchase products. The consumers make purchase decisions according to the utility of the product. The motivational function proposed by Zhang and Zhang (2007) [39] is used as the decision basis for consumers to make purchase decisions. The utility U_i^j is shown in

$$U_i^j = \mu_i^j * p_i^j + \rho_i^j * g_i^j \qquad (1)$$

The utility U_i^j of the product i for the consumer j is mainly influenced by two factors: the price and quality of the product. In (1), μ_i^j represents the price sensitivity of consumer j to the product i. Price sensitivity, which shows the consumer's cognition and perception of the goods' value, including practical and emotional values, is one of the attributes of consumers and varies from consumer to consumer. The price sensitivity distribution model [40] suggests that a consumer's price sensitivity is an exponential function of the difference between the real price of a product and the expected price of the product as shown in (2), where $\lambda_j > 1$ and $p_{(e)}{}_i^j$ is the consumer j's expected price of the product i.

$$\mu_i^j = \frac{1}{1 + \lambda_j^{(P_i^j - P_{(e)}{}_i^j)}} \qquad (2)$$

On the other side, ρ_i^j is the green degree sensitivity of consumer j to the product i. In this model, the green degree of the product refers to the general impact from multiple green attributes of the product, while multiple green attributes are equivalent to qualities of the product at a certain level; therefore, the sensitivity of the consumer to the product's green degree can be regarded as the sensitivity to the product quality. The outlier avoidance consumer psychological theory [41] suggests that the more closely the quality of the product approximates the consumer's expected quality of this kind of product, the more sensitive the consumer is to the quality of the product. The quality sensitivity ρ_i^j is as shown in (3), where $0 < \beta_j < 1$ and $g_{(e)}{}_i^j$ is consumer j's expected green degree of the product i.

$$\rho_i^j = \beta_j^{|g_i^j - g_{(e)}{}_i^j|} \qquad (3)$$

In reality, consumers are embedded in the corresponding social networks; therefore, their purchase decisions for the same kind of products with similar utilities are not only influenced by the price and green degree of products but are also affected by other consumers in the network such as friends' recommendation and word of mouth, among others. Besides, when making purchase decisions, consumers show a certain degree of herd mentality [42]. Herding behavior refers to the phenomenon where an agent's decision-making in the market is influenced by what others around him are doing [43]. When consumer j interacts with other consumers, the utility of the product for himself will change correspondingly under the influence of the herd mentality. The changing rules of product utility for consumer j under the influence of herd effects are shown in formula (4) as follows:

$$HE_j = \theta_j * infl_{jl} \tag{4}$$

where HE_j refers to the herd effect on consumer j and the parameter θ_j, which is subject to uniform distribution, denotes the herd tendency of consumer j. The closer the value of θ_j is to 0, the less likely a consumer is to be influenced by the surrounding people and the weaker the herd effect is, while the larger the value of θ_j, the more likely a consumer is to be influenced by the surrounding people and the stronger the herd effect is. The parameter $infl_{jl}$, which denotes the influence of other consumers in the consumer interaction network as perceived by consumer j, can be obtained from the average utility of product i for neighboring consumers, as shown in formula (5), where h is the number of neighbors who interact with consumer j in the consumer interaction network and U_{jl}^i is the utility of product i for the neighboring consumer l $(l \in (1 \cdots h))$.

$$infl_{jl} = \frac{\sum_{l=1}^{h} U_{jl}^i}{h} \tag{5}$$

Accordingly, on the basis of formulas (1) to (5), the product's utility can be further computed as shown in

$$U_i^j = \frac{1}{1 + \lambda_j^{(p_i^j - p_{(e)}{}_i^j)}} * p_i^j + \beta_j^{|g_i^j - g_{(e)}{}_i^j|} * g_i^j + \theta_j * infl_{jl} \tag{6}$$

According to related literature [44], there is a positive correlation between consumer's expected green degrees of the product and his/her income; that is, a consumer with a higher income places more emphasis on the environmental performance of the product and his/her expected green degree of the product is much higher. Therefore, a consumer's expected green degree of the product is shown in formula (7), where $income_j$ is the income of consumer j, m is the regression coefficient between a consumer's expected green degree and his/her income and $m > 0$, a is a scaling constant indicating the fixed expectation for the green degree of the product when a consumer's income is 0, and ω_j is the stochastic disturbance drawn from a uniform distribution, indicating the deviation of a consumer's expected green degree of the product.

$$g_{(e)}{}_i^j = m * income_j + a + \omega_j \tag{7}$$

In addition, it is assumed that consumer j can estimate the expected price $p_{(e)}{}_i^j$ of product i based on his/her own expected green degree $g_{(e)}{}_i^j$, and $p_{(e)}{}_i^j$ increases with $g_{(e)}{}_i^j$. Moreover, following Eppstein et al. (2011) [45], it is also assumed that if the product price exceeds 100% of the expected price, consumers will consider the product not affordable and refuse to purchase it. Therefore, the utility function of consumers' evaluation of different products is shown in formula (8) below.

$$U_i^j = \frac{1}{1 + \lambda_j^{(p_i^j - p_{(e)}{}_i^j)}} * p_i^j + \beta_j^{|g_i^j - m * income_i - \omega_j|} * g_i^j + \theta_j * infl_{jl} \tag{8}$$

To obtain the maximum utility, consumers compare the utilities of products from all manufacturers in the market and follow the rules below to make purchase decisions: product 1 will be purchased when $U_1^j = \max\{U_1^j, U_2^j, \cdots U_M^j\}$, product 2 will be purchased when $U_2^j = \max\{U_1^j, U_2^j, \cdots U_M^j\}$, product M will be purchased when $U_M^j = \max\{U_1^j, U_2^j, \cdots U_M^j\}$, and the product is purchased randomly when $U_1^j = U_2^j = \cdots = U_M^j$.

3.3. Manufacturers' Agents

3.3.1. Manufacturers' Profits. In this study, there are M competing manufacturers in the market. It is assumed that products from different manufacturers are similar in their function and performance but differ in price and green degrees; therefore, manufacturers compete based on the price and green degrees of the products.

The production process of products with higher green degrees may be more complex and require higher levels of technology; therefore, it is inevitable for the manufacturer to invest additional costs in certain aspects of the production to improve the green degree of products. The unit cost function of green products can be separated into two parts: one is the fixed regular unit production cost $\underline{c_i}$; the other is the additional margin cost c_i'. Based on relevant literature [16], the additional margin cost is a quadratic function with the product green degree; as such, $\underline{c_i}$ can be set as $c_i' = (1/2) r_i {g_i}^2$, where r_i represents the cost factor related to the green production efforts and $r_i > 0$. Therefore, the unit cost function of green products is shown in formula (9) below:

$$c_i = \underline{c_i} + \frac{1}{2} r_i {g_i}^2 \tag{9}$$

With regard to product pricing, it is assumed that the manufacturer applies the cost-plus pricing method: that is, the price of the product i is set as $p_i = (1 + o_i) c_i$, where $o_i > 0$ represents the mark-up on the product. Accordingly, the product price p_i is shown in formula (10) below:

$$p_i^j = (1 + o_i) c_i = (1 + o_i) \left(\underline{c_i} + \frac{1}{2} r_i {g_i}^2 \right) \tag{10}$$

Moreover, we set the parameter pc_i^j to indicate whether consumer j purchases the product i, and if the answer is yes, $pc_i^j = 1$; otherwise $pc_i^j = 0$; then the sales volume of product i can be calculated as in formula (11) below, where q_i is the sales volume of product i:

$$q_i = \sum_{j=1}^{N} pc_i^j \tag{11}$$

Thus, the profit of the manufacturer is shown in formula (12) below:

$$\pi_i = \left(p_i^j - c_i^j\right) q_i = \left(p_i^j - c_i^j\right) \sum_{j=1}^{N} pc_i^j \tag{12}$$

3.3.2. Manufacturers' Decision-Making. Manufacturers adjust the green degrees of their products based on their profits. To better analyze the evolution of manufacturers' product green degree decision-making, this study assumes that there are no technical barriers and production performance limitations for manufacturers, indicating manufacturers can adjust the green degree of their products based on their profits without having to bear additional costs from production conversion. Moreover, the algorithm PSO [15] is applied to simulate the manufacturers' products' green degree adjustment behavior so that the mutual imitation and learning among manufacturers can be better considered. A manufacturer learns and imitates from the "benchmark manufacturer" with the best profit in the market. Manufacturer i determines the subsequent green degree of its products based on its current product green degree ($g_i^j(t)$), the historical product green degree ($pbest_i^j$) that resulted in its best profit thus far, and the current product green degree of the "benchmark manufacturer" in the market ($gbest_i^j$). The product green degree of manufacturer i is thus updated by the following.

Step 1. Initialize the manufacturer parameters, that is, setting the number of manufacturers M and the initial product green degree $g_i^j(t)$, randomly generating velocity $v_i(t)$.

Step 2. Calculate each manufacturer's current profit $\pi_i(t)$ under its current product green degree $g_i^j(t)$.

Step 3. If the manufacturer's current profit $\pi_i(t)$ is larger than the manufacturer's previous best profit π_{ip}, then the π_{ip} is replaced with the $\pi_i(t)$ and the product green degree corresponding to the previous best profit $pbest_i^j$ is updated to the current green degree $g_i^j(t)$.

Step 4. It is assumed that the manufacturer can learn from the "benchmark manufacturer." The profit of the "benchmark manufacturer" in the current market is recorded as π_{best}, which can be shown as $\pi_{best} = \max(\pi_i(t))$, and the product green degree of the "benchmark manufacturer" is updated to $gbest_i^j$.

Step 5. The velocity and the product green degree are updated as shown in formulas (13) and (14) below:

$$\begin{aligned} v_i(t+1) = {} & c_0 v_i(t) + c_1 rand_1 \left(pbest_i^j - g_i^j(t)\right) \\ & + c_2 rand_2 \left(gbest_i^j - g_i^j(t)\right) \end{aligned} \tag{13}$$

$$g_i^j(t+1) = g_i^j(t) + v_i(t+1) \tag{14}$$

In formula (13), c_0 is the weight coefficient whose value, set in the range of $[0.9, 1.2]$ and enables the PSO algorithm to have good convergence based on relevant literature [46]; therefore, we set $c_0 = 1$. c_1 is the manufacturer's learning coefficient, which reflects its self-learning ability from its history; c_2 is the manufacturer's swarm cognition coefficient, which indicates the degree of collaboration between manufacturers and the degree of the manufacturer's acceptance of the group's common information [47]; and $rand_1$, $rand_2$ are random numbers drawn from a uniform distribution in the range (0,1).

Step 6. Return to Step 2 until all manufacturers have been looped through.

4. Simulation Scenarios Design

We collected information about manufacturers and annual sales of split air conditioners from Taobao and JD and referred to the ratio between the number of manufacturers and their annual sales. We assumed that there are 10 manufacturers and 10,000 consumers in the market, and their decision-making processes and interactions are shown in Figure 2. In the initial period of simulation, manufacturers sell their products with different prices and green degrees. The consumers calculate the utilities of all products that meet their purchasing power and make purchase decisions based on the principle of maximum utility. After consumers purchase products, manufacturers are able to obtain their own competitive performance indicators such as sales and profit, and they seek out the "benchmark manufacturer" by comparing the profit of other manufacturers. Subsequently, they adjust the products' green degree and prices in the next business cycle based on the PSO algorithm and other influencing factors.

Therefore, we keep the basic parameters of the model unchanged and change $Income_j$ in three different scenarios, as well as the parameter $Income_j$ values in three ranges, $N(400, 75)$, $N(500, 75)$, and $N(600, 75)$, correspondingly. The variances of consumer income levels are kept constant, and the means of consumer income levels are different in the three scenarios.

To reduce randomness in the simulations and improve the statistical stability and validity of simulation results, each simulation scenario is ran 10 times, and the total number of ticks per simulation scenario, Tmax, is set to 150, the average results of which is then statistically analyzed. The initial value-setting of the basic model parameters is shown in Table 1.

To analyze the manufacturers' decision-making concerning their products' green degree in a more detailed manner,

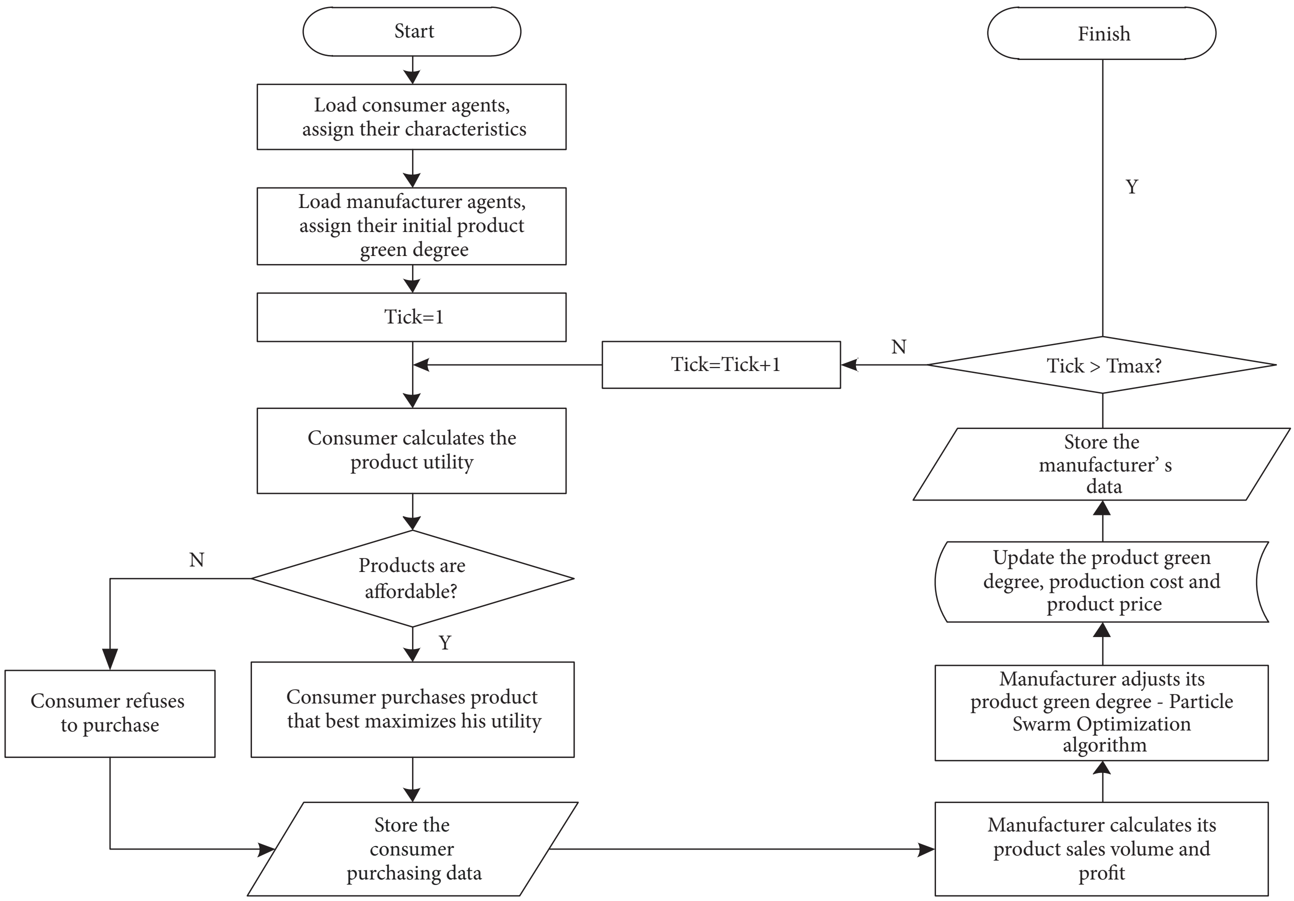


FIGURE 2: Agent interaction flow chart.

TABLE 1: The initial value-setting of the basic parameters of the model.

Parameters	Ranges of values	Distributions	References/Descriptions
N	10000	Constant	Refer to the information from Taobao and JD
M	10	Constant	Refer to the information from Taobao and JD
λ_j	U(1,20)	Uniform distribution	Zhang and Zhang (2007) [39]
β_j	U(0.4,0.6)	Uniform distribution	Zhang and Zhang (2007) [39]
m	0.067	Constant	Eppstein, et al. (2011) [45] Adepetu, et al. (2016) [44]
a	-13.54	Constant	Eppstein, et al. (2011) [45] Adepetu, et al. (2016) [44]
θ_j	U(0.0,0.1)	Uniform distribution	Zhang and Zhang (2007) [39]
P_r	0.2	Constant	McCoy and Lyons (2014) [48]
K	4	Constant	McCoy and Lyons (2014) [48]
$\underline{c_i}$	5	Constant	Refer to the manufacturers' interview results
r_i	0.02	Constant	Liu et al., (2012) [16]
o_i	0.1	Constant	Refer to the manufacturers' interview results
c_0	1	Constant	Shi and Eberhart (1998) [46]
c_1	2	Constant	Kennedy (1997) [47]
c_2	2	Constant	Kennedy (1997) [47]

Table 2: Descriptions of manufacturers' categories.

Parameters	Descriptions
M_h	Manufacturers whose initial product green degree is above 50, called the manufacturer with high initial green degree (HIGD)
m_1	Number of M_h, $m_1 < M_h$
M_m	Manufacturers whose initial product green degree is within the range of [30, 50), called the manufacturer with medium initial green degree (MIGD)
m_2	Number of M_m, $m_2 < M$
M_l	Manufacturers whose initial product green degree is within the range of [15, 30), called the manufacturer with low initial green degree (LIGD)
m_3	Number of M_l, $n_3 < M$

Table 3: Descriptions of indicators.

Indicators	Denotations	Descriptions
Green degree of HIGD	$\sum_{M_h} g_i/m_1$	The average product green degree of manufacturers with HIGD
Green degree of MIGD	$\sum_{M_m} g_i/m_2$	The average product green degree of manufacturers with MIGD
Green degree of LIGD	$\sum_{M_l} g_i/m_3$	The average product green degree of manufacturers with LIGD
Manufacturers' green supply	$\sum_M g_i/M$	The average green degree of products made by all manufacturers in the market
Consumers' green demand	$\sum_M g_i \cdot q_i/\sum_M q_i$	The average green degree of products that are actually purchased by consumers
Sales of HIGD	$\sum_{M_h} g_i/m_1$	The average product sales volume of manufacturers with HIGD
Sales of MIGD	$\sum_{M_m} q_i/m_2$	The average product sales volume of manufacturers with MIGD
Sales of LIGD	$\sum_{M_l} q_i/m_3$	The average product sales volume of manufacturers with LIGD
Highest market share	$\{q_i\}_{\max}/\sum_M q_i$	The market share of the manufacturer whose sales volume is the largest
Lowest market share	$\{q_i\}_{\min}/\sum_M q_i$	The market share of the manufacturer whose sales volume is the smallest
Profit of HIGD	$\sum_{M_h} \pi_i/m_1$	The average profit of manufacturers with HIGD
Profit of MIGD	$\sum_{M_m} \pi_i/m_2$	The average profit of manufacturers with MIGD
Profit of LIGD	$\sum_{M_l} \pi_i/m_3$	The average profit of manufacturers with LIGD
Profit of market	$\sum_M \pi_i/M$	The average profit of all manufacturers in the market

this study divided the manufacturers into three categories based on the initial green degree of their products (similar to China's split air conditioners' green degree as described in the introduction). Classifying manufacturers into different types based on their initial product green degree helps us analyze the macroevolution trends of the manufacturing industry's green degree, the competition performance of different green degrees of products, and the consumers' influences under different scenarios. The three categories of manufacturers are denoted and described in Table 2, where $M = m_1 + m_2 + m_3$.

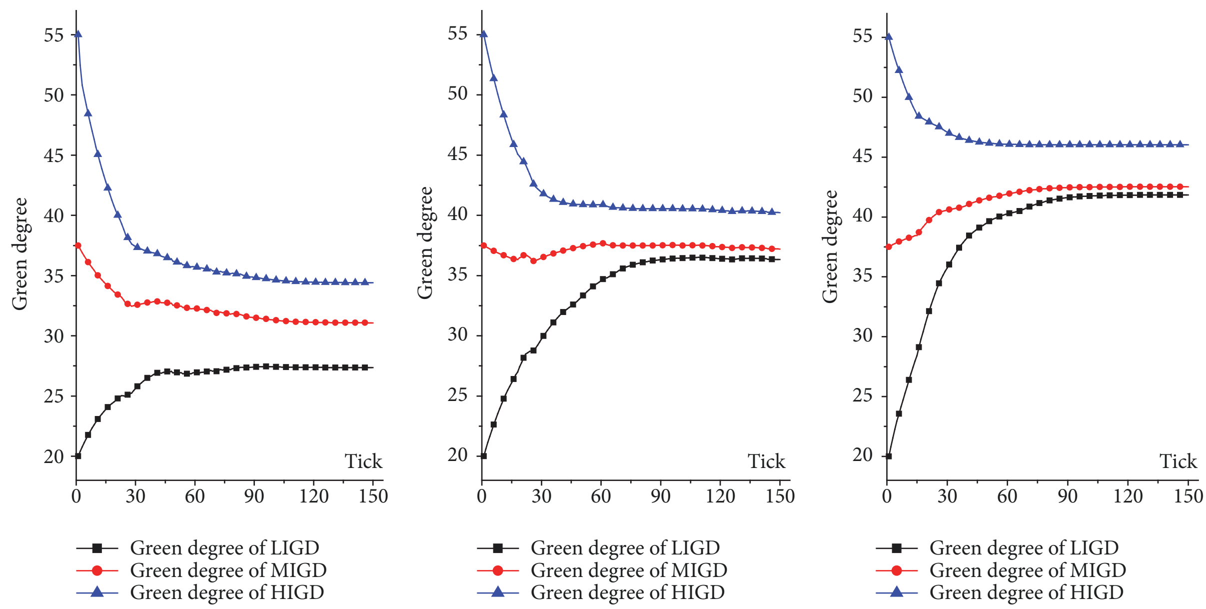
The included indicators, micro and macro, are designed to reveal consumers' consumption choices, manufacturers' green decision, and market competition performance and evolutionary trend. The green degree decision, product sales, and manufacturers' profits are analyzed in different scenarios of consumer income. All the indicators are described in Table 3, and all the indicators are studied in Section 5.

5. Results Analysis

5.1. Green Degree Decisions of Manufacturers. The green degree evolutions of the three manufacturer categories are shown in Figure 3. The consumers' income is normally distributed in N(400, 75), N(500, 75), and N(600, 75), which are shown in Figures 3(a), 3(b), and 3(c), respectively.

During market competition, the green degree of HIGD gradually reduces to a stable level, while the green degree of LIGD gradually rises to a stable level, and the differences among manufacturers narrow to a certain level. However, the green degrees of HIGD, MIGD, and LIGD remain at the highest, middle, and lowest levels, respectively. Moreover, the manufacturers' green degrees increase as the consumer income levels rise; for example, the green degree curve of HIGD is higher when consumer income level is at 600 as compared to those of other income levels.

In analyzing the green degree evolution, we make three observations. First, through imitation and learning among manufacturers, the manufacturing industry emerges showing a "convergence" effect, signifying smaller differences among manufacturers. Second, the differences always exist in the manufacturing industry since consumers' demands are diverse, and manufacturers also rely on their own experiences to make decisions to attract more consumers. Third, through market competition, manufacturers win their own consumers, and the manufacturing industry enters a stable



(a) Mean consumer income=400 (b) Mean consumer income=500 (c) Mean consumer income=600

Figure 3: Green degree evolutions of the three manufacturer categories under different scenarios.

state. Therefore, manufacturers' green degree decisions keep steady at a certain level and manufacturers produce products that fit their own consumers.

In Figure 4, we illustrate the indicators of "manufacturers' green supply" and "consumers' green demand." The "manufacturers' green supply" reflects the green degree of products that are supplied by manufacturers. The "consumers' green demand" reflects the green degree of products that are purchased by consumers.

First, by comparing Figures 4(a), 4(b), and 4(c), we observe that, at the initial stage of the system (Tick=0), consumers' green demand is higher along with higher consumer income. Second, consumers' green demand shows an upward trend in all scenarios. Third, the difference between the two indicators narrows with market competition, while the manufacturers' green supply is higher than the consumers' green demand at the final stage of the system's operation. When consumers have high income levels (mean consumer income = 600), manufacturers' green supply matches well with the consumers' green demand.

Thus, it can be seen that, during market competition, the manufacturers may overestimate the consumers' green degree demand, making the green degree of supplied products higher than that of products purchased by consumers. However, manufacturers make decisions by imitating other manufacturers and by learning from their experiences, and the supplied products' green degree gets adjusted to better match the demand's green degree so that the difference between the two indicators narrows.

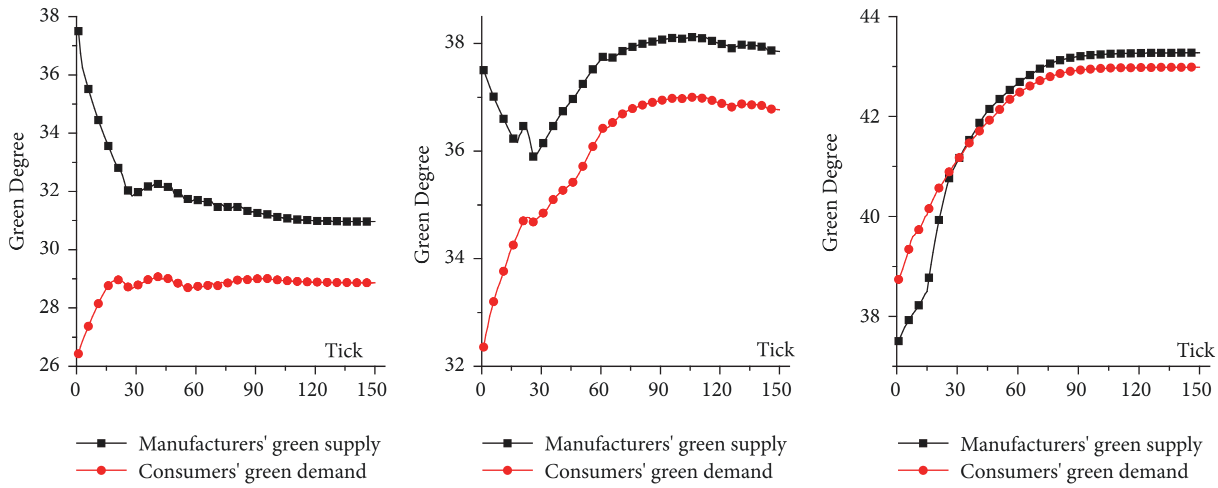
5.2. Sales of Manufacturers. Figures 5(a), 5(b), and 5(c) show the sales evolutions of the three manufacturer categories. Consumer incomes are normally distributed in N(400, 75), N(500, 75), and N(600, 75), respectively. As can be seen in Figure 5, when the consumer income level is higher, they display higher expectations of green degree, which lead to increasing product sales for MIGD and HIGD in the three scenarios. Higher consumer income favors green production; consequently, manufacturers with higher green degrees become more competitive.

In the initial stage of product competition (Tick: 0-30), combined with the analysis on Figure 3, we observe that even though HIGDs reduce the green degree of their products, they still maintain the competitiveness of their products' green degree and, simultaneously, their product prices also become increasingly competitive, leading to an increase in their sales as shown in Figure 5.

During competition, we can see from Figure 3 that LIGDs keep improving the green degree of their products such that the difference in their products' green degree against that of HIGDs and MIGDs continuously decreases, thus increasing the competitiveness of LIGDs while simultaneously maintaining the attractiveness of their products' prices. As a result, we can see that LIGDs can achieve the highest sales in Figure 5(a) and their sales continue to rise as shown in Figures 5(b) and 5(c).

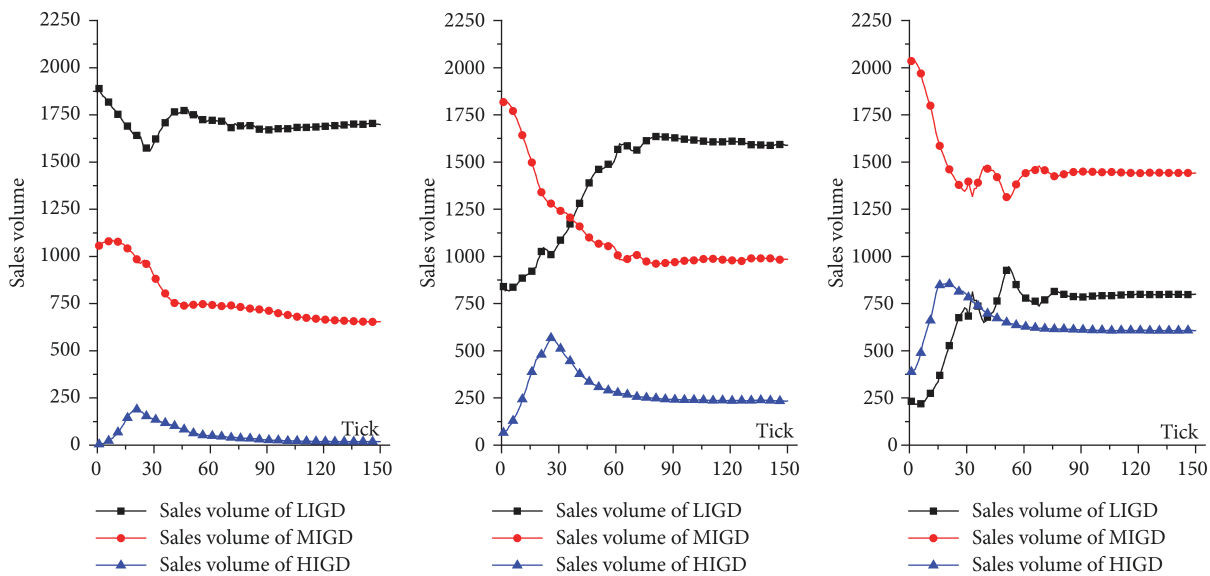
MIGDs change their products' green degree slightly as shown in Figure 3, but HIGDs and LIGDs become increasingly competitive. Moreover, consumers constantly evaluate products in the market and make their best purchasing decisions, leading to some of MIGD's market share being seized by LIGD and HIGD; therefore, the product sales of MIGDs show a downward trend in Figure 5. The sales of MIGDs become steady when the green degrees of MIGDs enter a stable state (after tick 30).

The product market concentration is signified by indicators "highest market share" and "lowest market share."



(a) Mean consumer income=400 (b) Mean consumer income=500 (c) Mean consumer income=600

FIGURE 4: Green degree of manufacturers' supply and consumers' demand under different scenarios.



(a) Mean consumer income=400 (b) Mean consumer income=500 (c) Means of consumer income=600

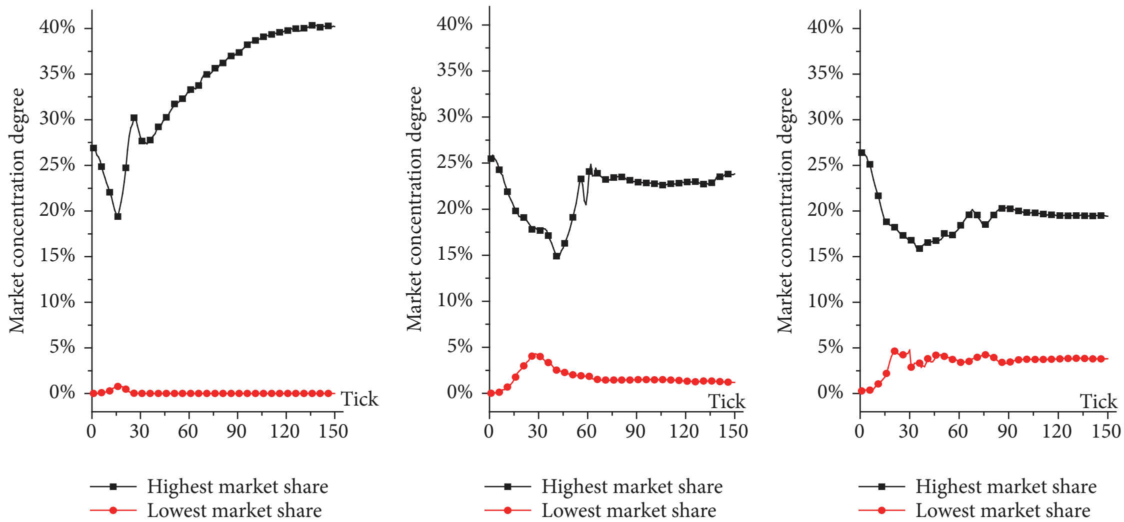
FIGURE 5: Sales evolution of three manufacturer categories under different scenarios.

The manufacturers' competition results (whether the market is evenly distributed or dominated) can be analyzed under different scenarios. The consumer incomes are normally distributed in N(400, 75), N(500, 75), and N(600, 75) as shown in Figures 6(a), 6(b), and 6(c), respectively.

The product concentration degree reflects the difference in competitiveness among manufacturers in the market. As can be seen in Figure 6, when the mean consumer income is 400, the highest market share increases to more than 40%, while the lowest market share is minimal, indicating that the market is gradually dominated by the manufacturer with higher sales, whose competitive advantage is constantly being enhanced. When the mean consumer income is 500, the highest market share gradually stabilizes at around 25%, while the lowest market share gradually reduces to about 2%. When the mean consumer income is 600, the highest market share gradually stabilizes at around 18%, while the lowest market share gradually increases to about 4%.

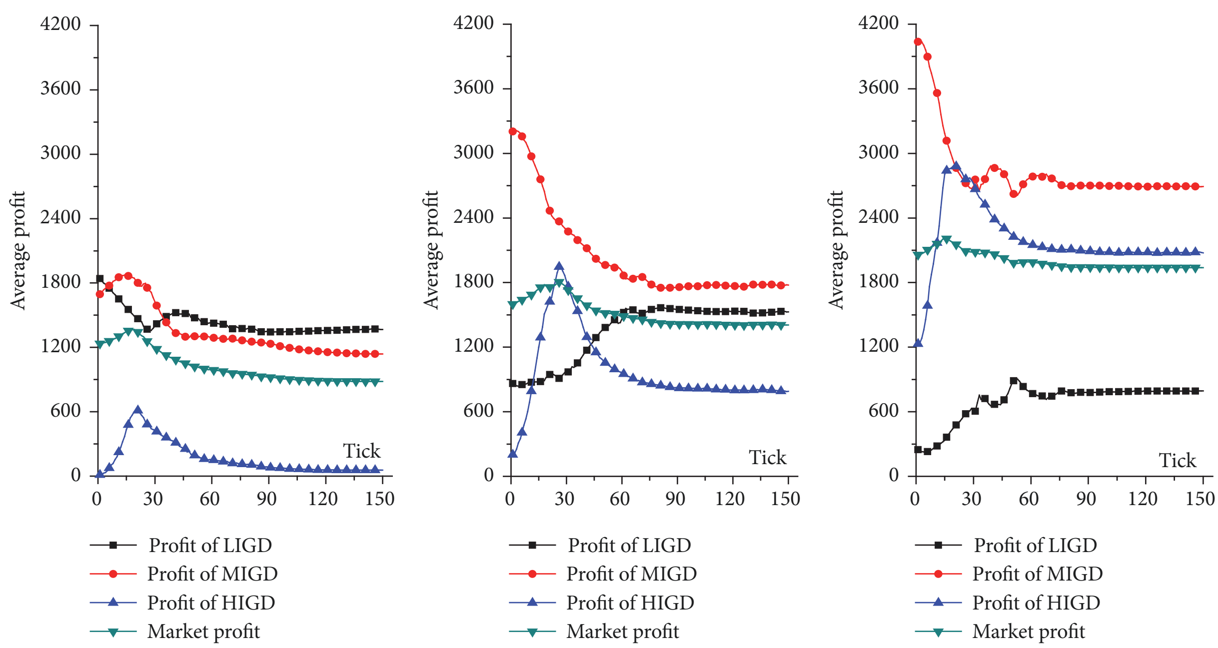
Therefore, it can be concluded that it is much harder for manufacturers to gain monopolistic advantage in a market where consumers have higher income. As the purchasing power of consumers constantly increases, the sales of manufacturers become more easily balanced such that the market share is evenly distributed instead of being a monopoly.

5.3. Profits of Manufacturers. The profit evolutions of the three categories of manufacturers are shown in Figure 7; the consumers income are normally distributed in N(400, 75),



(a) Mean consumer income=400 (b) Mean consumer income=500 (c) Means of consumer income=600

Figure 6: Highest and lowest market shares under different scenarios.



(a) Mean consumer income=400 (b) Mean consumer income=500 (c) Mean consumer income=600

Figure 7: Profit evolution of manufacturers under different scenarios.

N(500, 75), and N(600, 75), as shown in Figures 7(a), 7(b), and 7(c), respectively.

The manufacturers' profits are influenced by the products' sales and green degrees. From Figures 3, 5, and 7, we observe that the profits evolution of the three categories of manufacturers is similar to the sales evolution in Figure 5 under the same scenario. However, the difference in profits is not the same as the difference in sales among the three categories.

As can be seen from Figure 7(b), similar to the product sales of the three categories, the profit of HIGD initially rises and then decreases. The profit of MIGD initially decreases and then stabilizes, while the profit of LIGD initially rises and then stabilizes. During market competition, the profit of MIGD is slightly higher than that of LIGD, and the profits of both are higher than the average market profit, indicating that although the sales of MIGD are lower than that of LIGD, MIGD can still achieve higher profits due to the higher product price. As can be seen from Figure 7(c), even if the product sale of LIGD exceeds that of HIGD, the profit of LIGD is far lower than that of HIGD and MIGD. Moreover, while the product sale of MIGD is much higher than that of HIGD, the profit of HIGD can surpass that of MIGD in some periods of the market competition. Furthermore, a comparison of Figures 7(a), 7(b), and 7(c) shows that as the income and purchasing power of consumers increase, the profits of MIGD and HIGD also increase. The profit of LIGD is the lowest when the mean consumer income is 600.

The above analysis indicates that when consumer income is low, the profit of manufacturers is mainly obtained from the product sales. With an increase in consumer income, the profit of manufacturers gradually gets influenced by the products' green degree. The higher the green degree of a product, the higher the unit profit brought by the product, thus contributing a larger profit margin for the manufacturer. In summary, the income of consumers is one of the most significant factors influencing the profits of different categories of manufacturers. Therefore, manufacturers should take measures to get information about the actual income and green preferences of consumers in the market before making product green degree decisions.

6. Conclusions

To help manufacturers make reasonable green decisions and gain competitive advantage, it is important to clarify the evolution of products' green degrees and its impact on the competitive performance of manufacturers under different consumer income scenarios. In this light, this study built an agent-based model, considered complex characteristics of agents, and used the swarm intelligence algorithm to describe the decision-making behavior of manufacturers concerning the green degree of their products. By fully considering the interactions among consumers and manufacturers, this study presented a visual analysis of the evolution of manufacturers' decision-making on their products' green degree based on different categories of manufacturers. This study also analyzed the macrobehaviors of manufacturers, consumers, and products based on multi-dimensional performance indicators, and revealed the micromechanisms affecting the macroemergence of markets.

The results show that first, through imitation and learning among manufacturers, the manufacturing industry emerges showing a "convergence" effect, such that the differences in manufacturers' products' green degrees become smaller but always exist. Moreover, the manufacturers may overestimate the consumers' green degree demand, making the green degree of supplied products higher than that of products purchased by consumers, but this gradually gets corrected through the mechanisms of market competition. In addition, as consumer income increases, it becomes easier for manufacturers to adapt to the market's supply and demand as impacted by the products' green degrees, and it becomes unfavorable for them to form a monopoly in the market. Furthermore, when consumer income is low, the profits of manufacturers mainly come from the sales; however, with an increase in consumer income, the profits of manufacturers are gradually influenced by the products' green degree.

Data Availability

Data used in the current study is available to other researchers in order to advance the science and profession. Data generated or analyzed during the study are available from the corresponding author by request.

Conflicts of Interest

No potential conflicts of interest were reported by the authors.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (Nos. 71671078, 71501084); The Key Project of Philosophy and Social Science Research in Colleges and Universities in Jiangsu Province (2018SJZDI052); sponsored by Qing Lan Project of Jiangsu Province; Youth Backbone Teacher Training Project of Jiangsu University; The National Social Science Fund of China (18VSJ038; 17AGL010); Humanities and Social Sciences by the Ministry of Education of China (16YJC630133).

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