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ORIGINAL ARTICLE

Evaluation and driver analysis in product family evolution

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Abstract To overcome the difficulty of dynamic evaluation and driver analysis in product family evolution (PFE), a comprehensive evaluation approach was proposed by analyzing the influences of customer needs, enterprise resources, and product data in the product family implementation process. From the perspective of time and space, the dynamic and static relation of PFE was summarized. A comprehensive evaluation model based on gray conjunction degree was established. On the basis of evaluation, the dynamic factors of PFE were analyzed. A driver analysis method based on chaotic dynamics was proposed through the chaos simulation in PFE. The sensitivity of influencing factors was also determined in this process. Finally, the effectiveness and feasibility of the method were demonstrated by evaluation and analysis of small wheel loaders.

Keywords Mass customization · Product family · Evolution evaluation · Driver analysis

1 Introduction

Manufacturing firms are now aiming to deliver products with greater quality, faster response time, more innovative designs, more customization, and lower prices [1]. At the same time, they are facing increasing challenges in designing products to accommodate new technologies that evolve faster than ever before [2]. Mass customization (MC) is a production strategy focused on the broad provision of personalized products and services [3], which permits the identification and fulfillment of different customer needs without sacrificing effectiveness, efficiency, and low cost [4]. The analysis and implementation of MC systems have received increasing consideration by researchers since the late 1980s [5]. To make MC a reality, many strategies have been developed in recent decades, such as modular design, product family, and delayed differentiation, especially the strategy of product family.

As an effective means to implement MC, product family design (PFD) has been widely recognized in academia and industry [6]. By developing products as a family, reusing a common product platform, firms can reduce the cost of developing individual product variants [7]. The product family (PF) strategy is not the same as single product development. It aims to maximize the overall performance by adjusting the balance between performance and commonality within a PF. In essence, with the target of optimizing the overall performance of PF, various trade-offs were optimized to identify the best balance point in PFD. Although the initial stage of PFD may be very good to meet market demand, some external factors tend to change, showing a dynamic and gradual nature [8], so the original prebalanced state of the trade-offs was disrupted in the implementation process of PF. Therefore, the balancing process of optimizing trade-offs in PFD is often manifested as a dynamic process over time.

PF is growing primarily to meet market demand, including: the desired level of performance, reliability, serviceability, environmental requirements (e.g., using safe materials), more fuel efficiency, effective recycling, more sensory interaction and better esthetics, and a sense of satisfaction, intimacy, and luxury. Generally, a PF is a set of related products for achieving maximum external variety and minimum internal variety [9]. The product variants in a PF might be similar in features, components, and manufacturing processes and/or process sequencing [10]. There are two

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ways in PFD [11] :(1) module-based configurable PF (e.g., product variants in PF are constructed by adding, substituting, and removing one or more functional modules from a shared platform [12]) and (2) scale-based parametric PF (e.g., the variety demands are satisfied by "stretching" or "shrinking" one or more scaling variables of a product platform in one or more dimensions [13]). PF development is of a more resilient adaptability compared with a single product development, simultaneously increasing the difficulty of assessment and control. Moreover, PFD is a highly involved, often ill-defined, complex, and iterative process [14].

The evaluation of product family evolution (PFE) is the basis for PF development. Only by establishing a reasonable evaluation system that reflects market demand fully in PFE can we develop PF effectively, reduce development costs, improve the speed and reliability of product development, and enhance the variability of business decisions [15]. Thus, the evaluation of PFE is particularly important in PFD. In this regard, Thevenot et al. [16] presented an evaluation method, comprehensive metric for commonality, for PF components. Commonality versus diversity index was introduced by Alizon et al. [17] for evaluating the commonality and diversity of PF. Zha et al. [18] proposed a knowledge-based decision-making method for the evaluation of PFE. Aiming at trade-offs between the commonality and diversity of PF, Ye et al. [19] utilized PFD graph (PFEG) to adjust the balance between commonality and diversity, so designers can easily evaluate PF through this quantization.

The above researches on PFE were the basis of PF development, also the key to PFD. What has received little attention in PFE thus far, however, is the dynamic perspective of PFE, particularly in terms of driver analysis (e.g., the sensitivity analysis among influencing factors in PFE). On the basis of the evaluation of PFE, this paper presents a new driver analysis approach to support the dynamic judgment of PFE as well as implementation of innovation strategy for business managers.

The proposed approach has a positive impact on evaluation and driver analysis in PFE. Focusing on the relationship between external factors and PFE, the proposed approach analyzed the sensitivities of external factors from the time perspective. The traditional approach obtains parameter sensitivity, with influencing factors as variables, using complex equations to seek the partial derivative of parameters. However, PFE is a nonlinear system with multiple factors that largely determine the direction of PFE. PFE is based on the existing PF but not limited to it. PFE is driven by the goal of satisfying the customization needs with uncertainty and has different directions.

In summary, having the nature of function uncertainty and design diversity, PFE has the "not running out" and "homeless" characteristic in a chaotic system. The new method proposed in this paper takes advantage of the chaotic system to analyze the sensitivities to external factors in PFE. In the same chaotic system, each PF (e.g., every PF has different customer needs and design methods) has different chaotic characteristics and evolution tendencies. Although there was a slight difference in the initial state in every PF, PFE has large variation in the same chaotic system. Therefore, the sensitivities of factors in product families are obtained in the iteration process of a chaos system.

This paper is organized as follows. In the next section, the dynamic factors in PFE are discussed in detail. Section 3 establishes an evaluation model based on gray correlation degree (GCD). In Section 4, a driver analysis method in PFE based on chaos theory is introduced. The effectiveness and feasibility of the method were demonstrated by evaluation and analysis of small wheel loaders in Section 5. Finally, Section 6 concludes the paper with a summary and further study issues.

2 Dynamic factor analysis in PFE

2.1 Dynamic process in PFE

The process of PFE is accompanied by conflicts [20]. The driving force in PFE comes mainly from changes in market demand and technological progress, such as unpredictable customer demand, market uncertainty, technology advances, and highly competitive environment. Adapting to market demand, technological developments, and other external factors, the internal structure of PF needs to be adjusted, in which some new functions are added. PFE is of two kinds, mutation and gradient. When new technology, material, and craft appear, there is a big change in PFE, namely mutation. On the other hand, PF structure changes gradually to meet market demand which is called gradient. Therefore, PF structure changes constantly with time; simultaneously, it evolves with the extension and upgrade of product platform [10]. PFE is described in Fig. 1.

2.2 The analysis of dynamic and static factors in PFE

PFE not only shows the space growth in the life cycle of PF, but also evolves from one PF to another [21], namely survival of the fittest. PFE should be studied from the dynamic perspective, regardless of PFD, PF evaluation, or analysis of the other indicators in PFE. So PFE can be described from the perspective of space and time in Fig. 2.

The same PF changes in function, structure, or quality attributes with time. Simultaneously, for different customers or markets, there are a lot of product series with different configurations in PF space [12]. The change in space mainly concerns the reuse of core asset and configuration. However,

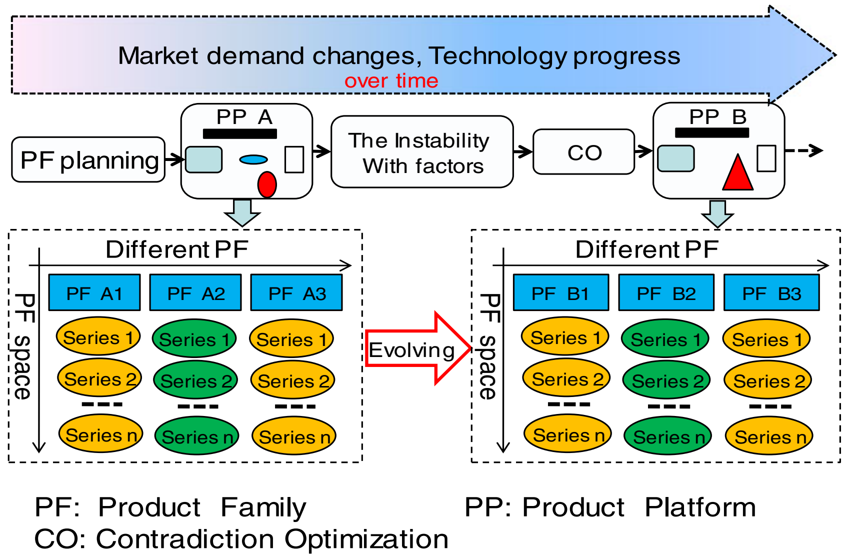

Fig. 1 The course in PFE

the problem of PFE primarily considers temporal change. The "static" analysis is basically within the same PF, but the "dynamic" analysis is mainly in different PFs. For example, platform commonality is almost static in the same PF but dynamic in different PFs. Therefore, static factors in the same PF may be dynamic in different PFs. In PDE, except few constant factors that are almost unchanged, e.g., some components or attributes in a PF that remain constant, the rest can be used as dynamic factors in the analysis.

2.3 Driver analysis in PFE

Combining with the implementation process of small wheel loaders (SWLs), we analyze dynamic factors in terms of dynamic market, the levels of design, technology and management, as well as technological advances. Table 1 summarizes dynamic factors in PFs (SWLs).

In terms of market demand, customers care only whether to purchase satisfactory products, including customization scale, function, grade, efficiency, and price. Designing a competitive product needs to consider raising the product's internal versatility and simultaneously reducing its external

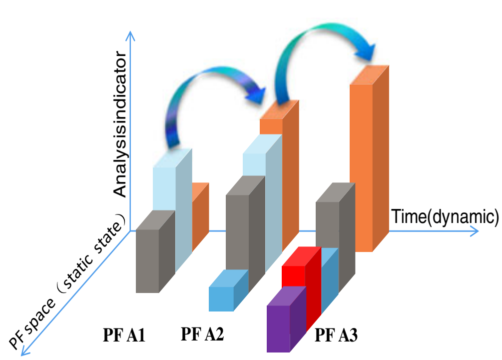

Fig. 2 Static and dynamic in PFE

versatility, minimizing design costs and shortening the development cycle in PFD. For enterprise resource, the level of technology and management is directly related to the economic efficiency and competitive power of an enterprise, which include manufacturing costs, advanced technology, and overall quality of staff. In addition, the progress of science and technology has a very important impact on PFE. Therefore, many factors affect the implementation process of PF, which has a certain dynamic and gradient property. Comprehensive evaluation model based on GCD is established for PF dynamic evaluation. At the same time, driver analysis as well as the scientific and rational evaluation is the key to PFD for MC.

3 The establishment of evaluation model

There is a complex relationship among influential factors in PFE. The strength, size, and order of the relationship among these factors can be described by GCD. The similarity index between two gray systems is characterized by GCD, according to the similarity degree of curve geometry. The biggest advantage of gray relational analysis, an objective method of data analysis, is that it does not require a large amount of data. Even with a small amount of data, it can obtain desired results. However, to achieve higher accuracy in PFE analysis, subjective judgment should be added; namely, analytic hierarchy process gives appropriate weights for each indicator in PFE.

3.1 Data normalization and determining reference series

The indicators can have different dimensions and magnitudes. In order to facilitate process analysis in PFE and ensure the reliability of the result, relative correlation analysis was

Table 1 Dynamic factor in PFE

Attribute	Dynamic factor
Dynamic market	(1) Customization scale, (2) multifunction, (3) outline dimension, (4) grade, (5) power, (6) work environment, (7) life time, (8) maintainability, (9) easy to operate degrees, (10) lead time and price, (11) safety performance, (12) speed, (13) efficiency
Design level	(1) Design costs, (2) development cycle, (3) degree of modularity (integration, parts modularity, structural similarity, parts commonality), (4) degree of automation, intellectualization, and digitization, (5) scalability, (6) maintainability
Technology level	(1) Manufacturing costs (2) parallelization level (3) Configuration level (4) design flaw (5) Defective rate (6) The utilization of new materials, equipment and technology
Management level	(1) Management costs, (2) profitability, (3) human resource (innovation capability), (4) E-commerce level, (5) overall quality of staff(work experience, proficiency, operator error rate)

utilized to compensate data deviation in absolute correlation analysis. The analysis result is only related to the sequence change rate relative to the initial point, so the raw data in PDE is processed in a standardized way. The 0–1 normalization approach was adopted in the experiment in this paper.

After the data in PFE were normalized, the reference vector x_0 is the optimal value of the corresponding dimension in the evaluated data of PFs. x_i is the data vector of PF i.

$$\begin{cases} x_0 = \{x_0(1), x_0(2), \ldots x_0(k), \ldots, x_0(n)\} \\ x_1 = \{x_1(1), x_1(2), \ldots, x_1(k), \ldots, x_1(n)\} \end{cases} \tag{1}$$

Therein, $x_i(k)$ is analysis indicator k in PF i.

3.2 Calculating the correlation degree matrix

The correlation degree matrix is the comparison of the difference between x_i and x_0, defined as follows:

$$\varepsilon_i(k) = \frac{\min_i \min_k \left| x_0(k) - x_i(k) \right| + \zeta \max_i \max_k \left| x_0(k) - x_i(k) \right|}{\left| x_0(k) - x_i(k) \right| + \zeta \max_i \max_k \left| x_0(k) - x_i(k) \right|} \tag{2}$$

where $\zeta \in [0,1]$ is a constant to lower the impact of the extreme value in the calculation; usually, the value is 0.5. Assuming that there are mPFs, the correlation degree matrix E is defined as:

$$E = \begin{bmatrix} \varepsilon_1(1) & \varepsilon_1(2) & \ldots & \varepsilon_1(n) \\ \varepsilon_2(1) & \varepsilon_2(2) & \ldots & \varepsilon_2(n) \\ \ldots & \ldots & \ldots & \ldots \\ \varepsilon_m(1) & \varepsilon_m(2) & \ldots & \varepsilon_m(n) \end{bmatrix} \tag{3}$$

3.3 AHP determining index weights

Experts' experience and knowledge in a specific field is very important when using AHP. However, experience and knowledge are qualitative and subjective. In order to solve this problem, this paper takes the following measures in the AHP analysis process.

1. Increasing appropriately the number of evaluation indexes. There are 22 underlying indicators in the case study in this paper, which can increase the objectivity of the analysis, and data reliability was further improved by checking the consistency of the judgment matrix.
2. Fuzzy theory was integrated into AHP.
3. Increasing the number of experts in the field. Experts are independent, without influencing each other, for improving the accuracy of judgment in the evaluation process.

The analysis process is as follows:

Step 1: Establishing the hierarchy model

In the process analysis of PFE, there is a three-layer structure, namely A, B, and C (the lowest hierarchy). The upper hierarchy has a dominant role over the lower one. Simultaneously, there are many influencing factors within a complex relationship.

Step 2: Building judgment matrix

Assuming that the factor A_k as a criterion layer has a dominant role to the factors B_1, B_2,…, B_n in the next layer, the pairwise comparison amongB_1, B_2,…, B_n constitutes the judgment matrix $B=(B_{ij})_{n\times n}$, in which B_{ij} denotes the importance degree in regard to A_k for B_i and B_j. And then, B is converted to the fuzzy consistent matrix B'. Generally, the elements in a matrix were scaled with the values 1–9.

Step 3: Consistency check of the judgment matrix

In order to maintain the consistency of subjective judgment, the consistency of the judgment matrix was verified to avoid obtaining conflicting results.

3.4 Calculating the evaluation results

Dynamic factor weights in PFE are calculated from top to bottom by AHP; namely, the weights of underlying factors can be calculated with respect to the importance of the highest level (target level). Assuming that the weight vector is $W=[w_1, w_2, \ldots, w_n]$, where $\sum_{i=1}^{n} w_i = 1$, the evaluation model based on GCD is established as follows:

$$R = E \times W^T = [r_1, r_2, \ldots, r_n]^T \tag{4}$$

Thus, Eq. 4 shows that with the higher value r_i, the evaluation of PF_i (product family i) is better. After product families were evaluated by the evaluation method based on GCD, the evaluation result shows overall comprehensive performance for the PFs. In addition, in order to obtain the sensitivity of influencing factors, driver analysis in PFE should be done further, i.e., the sensitivity analysis.

4 Driver analysis based on chaotic system

4.1 The relationship between chaotic system and PFE

Chaos theory is a scientific description of chaotic phenomena and mechanism, which are everywhere and exist in both the material world and human society [22], such as changes in the weather, fluctuations in the stock market, evolution of the population, crust movement, and the spread of disease. The main feature of a chaotic system [23] is described as follows:

1. Sensitivity to initial state

   Tiny perturbation only results in a slight deviation in linear systems. However, a chaos system is highly sensitive to the initial values (parameters). The tiny differences of initial value may lead to completely different results in the same chaotic system. Therefore, the sensitivities of the influencing factors in PFE can be recorded in a chaotic iteration process.
2. Partial instability and overall stability

   Because of index separation of adjacent tracks in a chaotic system, chaos stretching makes slight differences in the initial state become larger and larger.
3. Existence of strange attractor

   Although the specific location of a chaotic orbit is sensitive to the initial state, the approximate location of the chaotic orbit (attractor) can be known in the iterative process, namely boundedness in a chaotic system.
4. Nonlinear systems can be well described

   Nonlinearity is a necessary condition for chaos. A nonlinear system with few freedom degrees can generate a complex chaos. Therefore, complex behaviors observed in many complex systems may result from simple origins, which can be analyzed using a simple equation.

PFE with a lot of external factors is a complex nonlinear system [24, 25]. Generally, the initial state of each PF is different, so each PF, with the influence of external factors, has different evolution directions. For example, the evolution directions of two SWLs with similar initial state are completely different: one for open-air construction but the other for underground work. Their functions are almost identical at the beginning of design except the volumes, so different volumes of the two SMLs affect turning radius, which in turn affects the performance of two SWLs. Different performance affects customer satisfaction. In turn, customer satisfaction promotes the evolution of the two SWLs. In other words, the design of the two SWLs evolves in different directions. Therefore, PFE is in line with the iterative process of the chaotic system [26]. We can take advantage of chaos analysis to determine the sensitivities of factors in PFE so as to improve and control the evolution. There is an explicit overall objective, with the evolution uncertainty, so PFE meets the essential characteristic of the chaotic system [26, 27]. The driver analysis of PFE can be done using the sensitivity and dependence principles in the chaotic system.

4.2 The establishment of chaos analysis system in PFE

4.2.1 Determining driver analysis indicators

PFE is a nonlinear system over time. Including a lot of external factors, the process of PFE is quite complicated. However, the analysis indicators of a chaotic system must meet chaotic characteristics, which maintain the interdependence and restraint relationship; namely, the change of a factor in PFE would inevitably lead to changes of its own and other factors in the next stage. In this paper, we survey and analyze the complex mechanical product family (SWLs), and the chaotic indicators in PFE are largely limited to the following three categories: customer satisfaction degree (CSD), economics, and agility and personalization (AP), which are affected and restricted with each other. In this paper, we study only the three chaotic indicators: CSD, economics, and AP. Their relationship is shown in Fig. 3.

In Fig. 3, in order to receive more commercial interests, an enterprise producing a product with a higher CSD, the economic input is usually higher (the economics is worse), so economics is inversely proportional to CSD. From the perspective of customization, the faster and more personalized an enterprise produces a product, namely, the better the AP is, the higher the CSD is. Similarly, AP is inversely proportional to economics. In addition, the application of new material and technology can simultaneously improve the relevant indicators in PFD, e.g., modularity technology can simultaneously

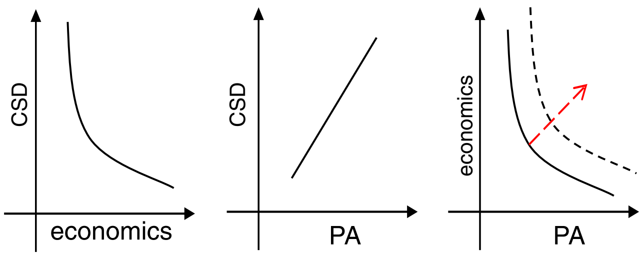

Fig. 3 Approximate relationship between the indicators

improve agility, personalization, and economics of a PF. Therefore, the inversely proportional curve, driven by new technology and material, moves toward the direction shown by the dotted line in Fig. 3.

4.2.2 Establishing chaos analysis system

After the above analysis, a chaotic system can be established to analyze the process of PDF and to determine the sensitivity of the dynamic factors in PFD, based on the following characteristics:

1. PFE is a nonlinear process. The relationship among the factors was described in Fig. 3, and the tiny change of a factor may lead to a huge change of the integrated performance in PF. Hence, the performance of a PF in the next period of time, namely the evolution trend, depends on not only the current state of the PF but also the changes of various factors. A chaotic system can simulate the process and trend of PFE by iteration of chaos.
2. Among the influencing factors of a PF, some factors have a strong impact on PFE and the others may have weak impact, so different initial values can lead to different trends in PFE. This is in line with the sensitivity characteristic in the chaotic system (the dependence on initial conditions).

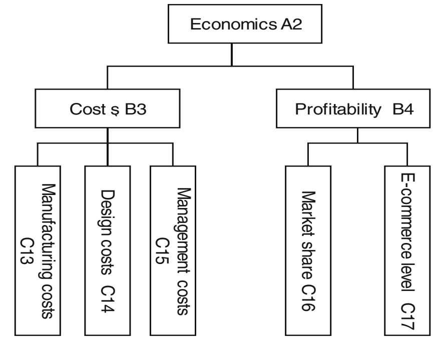

Fig. 5 The factors in economics

3. Because of the impact of the external environment, the trend of PFE is uncertain. However, a PF cannot immediately change, with certainty in a period of time. PFE cannot "jump" the range of chaotic attractor, so the center of the chaotic attractor can be utilized to evaluate the comprehensive performance of a PF.

Based on the above reasons and the relationship between CSD (x), economics (y), and AP (z) in Fig. 3, a chaotic system of SWLs is established as follows.

$$\begin{cases} \dot{X} = \left[a\left(\dfrac{xz}{y}\right) - by\right] \cdot q \\ \dot{Y} = \left[b\left(\dfrac{y}{x+z}\right) - (a+c)\left(\dfrac{xz}{y}\right)\right] \cdot q \\ \dot{Z} = \left[c\left(\dfrac{xz}{y}\right) - by\right] \cdot q \end{cases} \tag{5}$$

where q is the chaos constant; a, b, and c (obtained by AHP in Section 3) are the weight values for CSD, economics, and AP; x, y and z represent the current CSD, economics, and AP, respectively; and $\dot{X}$, $\dot{Y}$, and $\dot{Z}$ are the new CSD, economics, and AP, which describe the evolution trend of PF. In the chaotic iteration process, PFE mainly shows that x, y and z are replaced by $\dot{X}$, $\dot{Y}$, and $\dot{Z}$ to become a new state, which

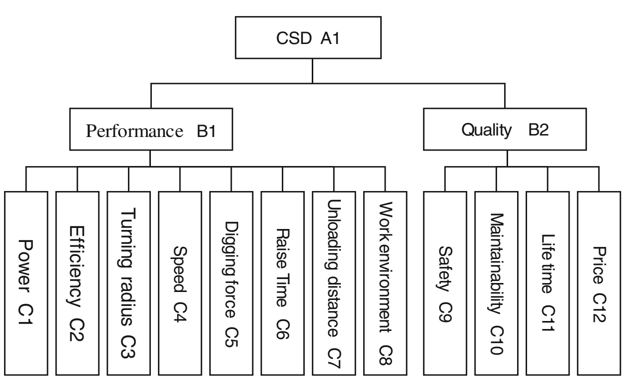

Fig. 4 The factors in CSD

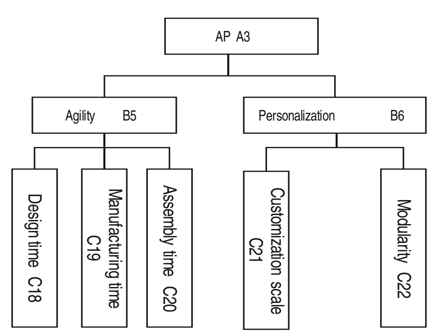

Fig. 6 The factors in AP

Table 2 The normalized data of SWLs

SWLs	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
916	0	0.0297	−0.0108	0.0104	0.0633	−0.0271	0.0093	0	0	0	0
918	0.0219	0.0025	−0.0141	0.066	0	−0.0271	0.0139	0	0	0	0
918I	0.023	0.0059	−0.0141	0.0139	0.0608	−0.0514	0.0139	0	0	0	0
918T	0.0219	0.0153	−0.007	0	0.0608	0	0	0.013	0.052	0	0
920T	0.0219	0.0059	−0.0141	0.032	0.0988	−0.0271	0.0139	0.013	0.052	0	0
SWLs	C12	C13	C14	C15	C16	C17	C18	C19	C20	C21	C22
916	0	0	−0.0207	0	0	0	−0.1131	0	0	0.0062	−0.0007
918	−0.0168	−0.0155	−0.0207	−0.001	0.0654	0.0163	−0.1131	0	0	0.033	−0.0085
918I	−0.0168	−0.0162	0	−0.0011	0.0325	0.0163	0	0	0	0	0
918T	−0.0168	−0.0207	−0.0089	−0.0014	0.0325	0.0163	−0.0283	0	0	0.008	−0.0079
920T	−0.0185	−0.0279	−0.0148	−0.0019	0.0654	0.0163	−0.0283	0	0	0.008	−0.0091

Table 3 The weights of factors in SWLs

	CSD A1=0.5396												Economics A2=01634					AP A3=0.2970				
Factor	B1=0.5000								B2=0.5000				B3=0.5000			B4=0.5000		B5=0.6667			B6=0.3333	
	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20	C21	C22
	0.087	0.11	0.052	0.049	0.366	0.19	0.097	0.049	0.193	0.16	0.23	0.237	0.7	0.254	0.047	0.8	0.2	0.571	0.286	0.143	0.667	0.333
Weights	0.023	0.03	0.014	0.013	0.099	0.051	0.014	0.013	0.052	0.092	0.12	0.019	0.057	0.021	0.004	0.065	0.016	0.113	0.057	0.028	0.066	0.033

repeats the cycle indefinitely. The chaotic evolution process shown in Eq. 5 is described as follows:

- $\dot{X}$: The new CS in PFE is represented by the expression $\frac{xz}{y}-y$ with corresponding weight coefficients; namely, the greater x and z, the higher the value of $\dot{X}$ (after the chaotic iteration) with relative stability. However, $\dot{X}$ and y are negatively correlated; namely, the better economics, the lower input costs, then the new CSD $\dot{X}$ in a PF may be worse.
- $\dot{Y}$: The new economics in PFE can also be expressed by the expression $\frac{y}{x+z}-\frac{xz}{y}$ with the combined weight coefficients. $\dot{Y}$ and the current y are positively correlated; namely, the greater is y, the higher the value of $\dot{Y}$ (after the chaotic iteration) with relative stability. Conversely, the greater the values of x and z are, the lower the new economics $\dot{Y}$ is.
- $\dot{Z}$: The new AP in PFE has the same iteration principle with the new CS $\dot{X}$.

The chaotic system can be adjusted according to the type of the study object. The CSD, economics, and AP of each product family is equivalent to the initial state of the chaotic system, so the sensitivities of CSD, economics, and AP in PFE can be obtained in chaotic iteration, which can help make some rational decisions on the implementation process of PFs.

5 Case study

5.1 Factor analysis in SWLs

In this paper, the five types of SWLs (PFs) produced by an enterprise were evaluated by AHP and the chaotic system, and then the sensitivities of dynamic factors in SWLs were analyzed by chaos analysis. Table 1 presents some dynamic factors in SWLs. The evolution of SWLs was evaluated from three main aspects, namely CSD (A1), economics (A2), and AP (A3). For CSD, there is only one standard in SWLs (e.g., the shorter the upgrading time is, the better the performance is in SWLs). In addition, the inheritance in each SWL is considered in economics and AP, e.g., the design, manufacturing time, and costs are decreased significantly for each SWL from one generation to another. The evaluation system for SWLS is divided into three layers, and there are 22 indicators (C1~C22) at the lowest level. The evaluation indicators are described in Figs. 4, 5, and 6.

Table 4 The CSD, economics, and AP in SWLs

SWLs	CSD	Economics	AP
916	0.0748	−0.0207	−0.1076
918	0.0463	0.0445	−0.0886
918I	0.0356	0.0315	0
918 T	0.1393	0.0178	−0.0279
920 T	0.1779	0.0371	−0.0291

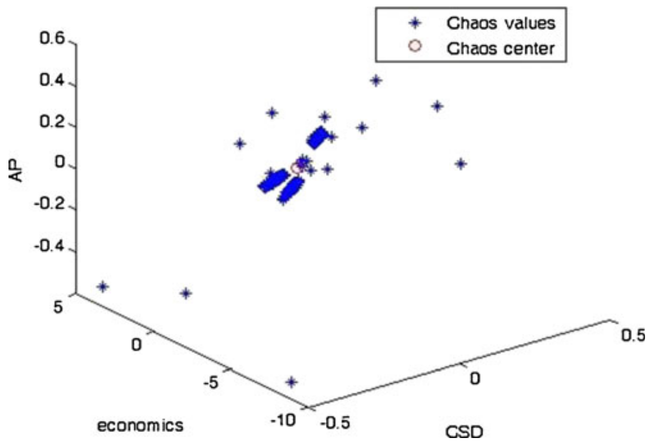

Fig. 7 Chaos graphic in 916

5.2 Evolution evaluation of SWLs

5.2.1 Data preprocessing

Through the investigation of the five SWLs: 916, 918, 918I, 918T, and 920T, the raw data of the above 22 factors are normalized. According to the actual situation, the results, added the signs of positive and negative, are shown in Table 2.

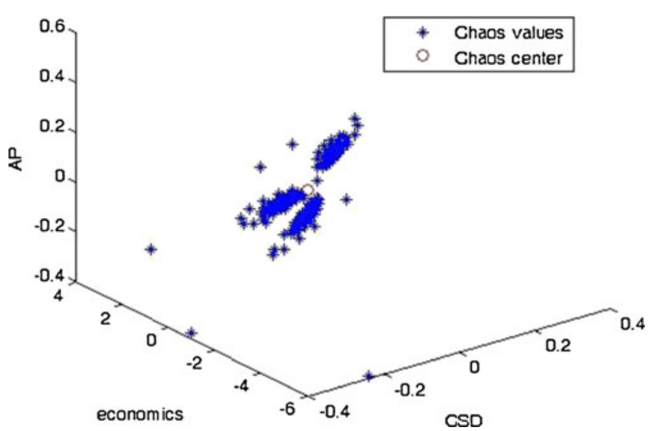

Fig. 8 Chaos graphic in 918

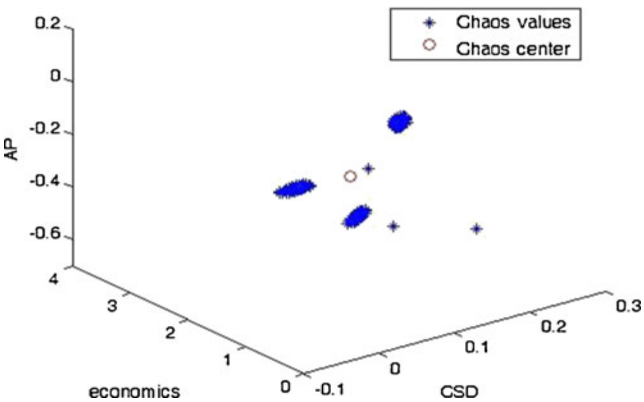

Fig. 9 Chaos graphic in 918I

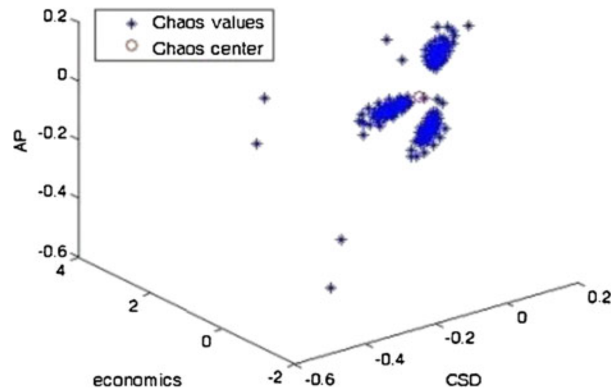

Fig. 11 Chaos graphic in 920T

We can select the optimal values of indicators in Table 2 as the reference, so the reference vector is: $\boldsymbol{X}_0$=[0.023, 0.0297, −0.007, 0.0139, 0.0988, 0, 0.0139, 0.013, 0.052, 0, 0, 0.0, 0, 0, 0.0654, 0.0163, 0, 0, 0, 0.008, 0].

5.2.2 The evaluation of SWLs

From Eq. 2, the relational coefficient $\varepsilon_i(k)$ is calculated, so the gray incidence matrix E, in SWLs is:

$$E = \begin{bmatrix} 0.707 & 1 & 0.937 & 0.942 & 0.635 & 0.676 & 0.925 & 0.812 & 0.521 & 1 & 1 & 1 & 1 & 0.732 & 1 & 0.463 & 0.776 & 0.333 & 1 & 1 & 0.964 & 0.988 \\ 0.333 & 0.782 & 0.932 & 0.652 & 0.497 & 0.783 & 1 & 0.882 & 0.653 & 1 & 1 & 0.853 & 0.863 & 0.825 & 0.99 & 1 & 1 & 0.464 & 1 & 1 & 0.798 & 0.92 \\ 1 & 0.522 & 0.785 & 1 & 0.406 & 0.336 & 1 & 0.665 & 0.333 & 1 & 1 & 0.607 & 0.616 & 1 & 0.959 & 0.441 & 1 & 1 & 1 & 1 & 0.758 & 1 \\ 0.927 & 0.569 & 1 & 0.578 & 0.333 & 1 & 0.577 & 1 & 1 & 1 & 1 & 0.53 & 0.478 & 0.681 & 0.931 & 0.366 & 1 & 0.402 & 1 & 1 & 1 & 0.706 \\ 0.904 & 0.372 & 0.666 & 0.439 & 1 & 0.343 & 1 & 1 & 1 & 1 & 1 & 0.433 & 0.337 & 0.478 & 0.882 & 1 & 1 & 0.333 & 1 & 1 & 1 & 0.607 \end{bmatrix}$$

According to the steps of AHP described in Section 3.3, after the consistency of the judgment matrix obtained from experts in the field is checked, the weights of factors in SWLs are shown in Table 3.

So the weight vector in WSLs is: $\boldsymbol{W}$={0.023, 0.03, 0.014, 0.013, 0.099, 0.051, 0.014, 0.013, 0.052, 0.092, 0.12, 0.019, 0.057, 0.021, 0.004, 0.065, 0.016, 0.113, 0.057, 0.028, 0.066, 0.033}.

Combining the value $\boldsymbol{W}$ into Eq. 4, the comprehensive evaluation of WSLs is obtained. The evaluation vector is:

$$R = E \times W^T = [r_1, r_2, r_3, r_4, r_5]^T = [0.7878, 0.8011, 0.7688, 0.7438, 0.7853]^T$$

The result, in the evaluation vector $\boldsymbol{R}$, is:$r_2 > r_1 > r_5 > r_3 > r_4$. That is, the evaluation result in PFE (SWLs) is: 918>916>920T>918I>918T. However, in order to correct control and decision making in PFE, the dynamic factor sensitivities of SWLs should be analyzed.

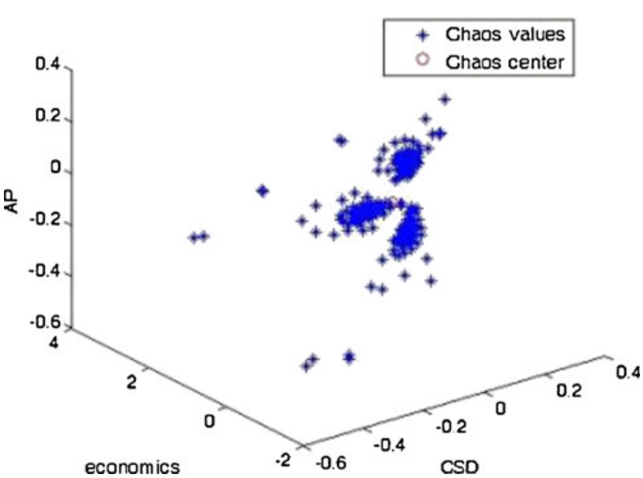

Fig. 10 Chaos graphic in 918T

Table 5 The chaos center and sum

	The chaos center			Sum	
SWLs	x	y	z	$x+y+z$	Rank
916	−0.0195	0.1619	−0.0021	0.1214	2
918	−0.0232	0.1791	−0.0239	0.132	1
918I	−0.0372	0.1846	−0.0246	0.1128	4
918 T	−0.0447	0.191	−0.0258	0.1117	5
920 T	−0.0387	0.184	−0.0248	0.1205	3

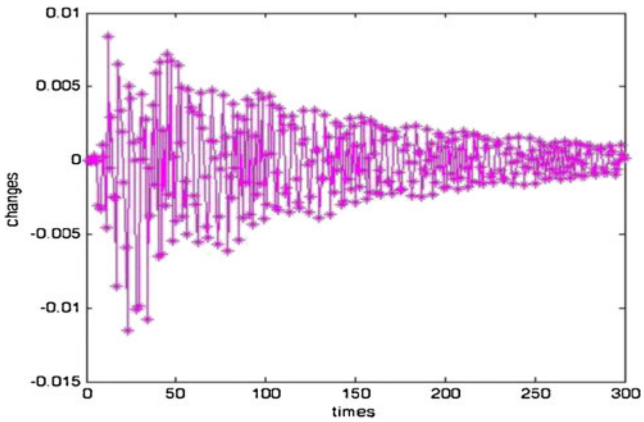

Fig. 12 The sensitivity of CSD in 918

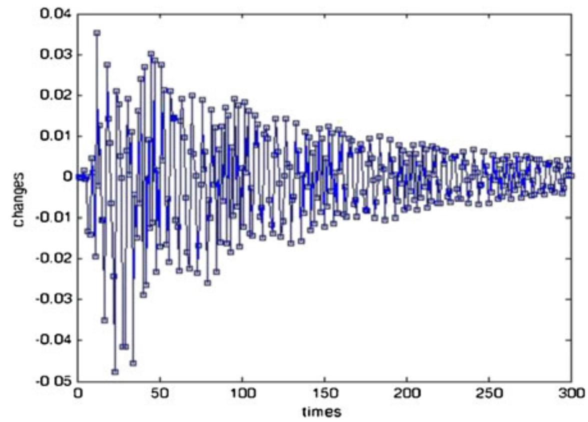

Fig. 14 The sensitivity of AP in 918

5.3 Chaos analysis system in SWLs

According to the chaotic system established in 4.2 and the wrights of CSD, economics, and AP in Table 3, the values of a, b, and c are 0.5396, 0.1634, and 0.2970, respectively. In addition, let the value q be 0.85 (the best chaos parameter in several experiments). According to the main analysis indicators in Table 3, the values in SWLs, x, y, and z, are shown in Table 4.

Combining Table 4 into the chaotic system in Section 4.2, the chaos graphics were obtained as shown in Figs. 7, 8, 9, 10, and 11. From Figs. 7, 8, 9, 10, and 11 the center of each graphic iterated 300 times is calculated in Table 5.

The rank shown in Table 5 is entirely in line with the evaluation result based on GCD in Section 5.2, namely, 918 >916>920T>918I>918T. Therefore, the chaotic system established in Section 4.2 can accurately reflect the changes in the PFE (SWLs) over time.

In order to analyze the sensitivities of the three factors in SWLs, the normalized data are calculated in dimensionless form. Take the case of 918; in the same chaotic system, the initial value (x, y, and z) is added, respectively, by10^{-6}, e.g., when the initial value of the chaotic system changes from $x=-0.0232$, $y=0.1791$, and $z=-0.0239$ to $x=-0.0232+10^{-6}$, $y=0.1791$, and $z=-0.0239$, we can calculate the sensitivity of x by the difference sum of each generation in 300 iterations, so the sensitivities of the three factors were shown in Figs. 12, 13, and 14.

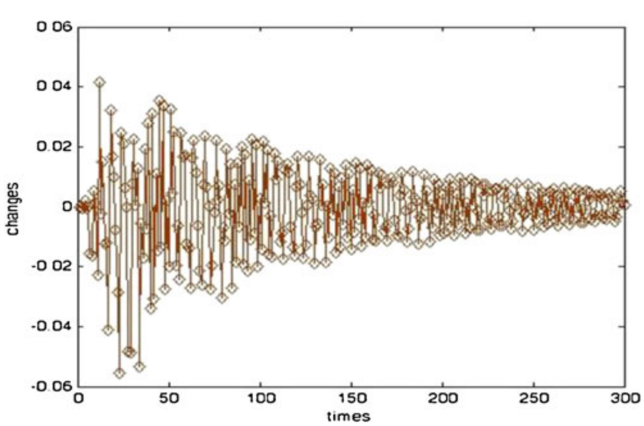

Fig. 13 The sensitivity of economics in 918

Although the changes in Figs. 12, 13, and 14 are broadly similar in shape, the values are significantly different. The economic influence in 918 is greater than the AP, simultaneously minimal impact on CSD, namely, economics>AP>CSD. Therefore, for 918, we should focus on improving the economics to maintain its advantage in PF competition. The other SWLs can also be analyzed to make decisions using the same method. The results are shown in Table 6.

According to the investigation in SWL evolution, the different results shown in Table 6 are correct and objective for the following reasons:

In 916 evolution, the launch date is the earliest, and the technology aspect is immature, so the design, manufacture, and assembly time is longer, namely serious shortage of AP (its sensitivity is the strongest). However, lower costs, higher market share, and good economic benefit are obtained in competition (the economics sensitivity is the weakest). In terms of performance and quality of 916, the CSD is moderate.

For SWL 918, because of more investment and higher costs in the design and manufacturing, the economics is

Table 6 The sensitivities of five SWLs

SWLs	Evaluation (rank)	Sensitivity
916	2	AP>CSD>Economics
918	1	Economics>AP>CSD
918I	4	CSD>Economics>AP
918 T	5	AP>Economics>CSD
920 T	3	Economics>AP>CSD

poor. Simultaneously, it has a higher CSD with small turning radius, strong breakout force, and high speed, which are safe and reliable features. In addition, the AP is improved.

In 918I, the CSD is affected by a large turning radius and the serious shortage in unloading distance. On the other hand, the AP of 916 based on 918, for a shorter design time and outstanding personalization, is better.

Targeting underground work, 918T and 920T are designed with a good security and smaller turning radius, so the two CSDs are higher. The difference between them is that 920T is an entirely new design with poor economics.

6 Conclusions

1. PFE is a dynamic rather than static process. The design, evaluation, and process study in PFE should be analyzed from the two perspectives of time and space. Affected by many factors, a product family evolves gradually in aspects of function, structure, and quality. The chaos between uncertain customer needs and product diversity designs was analyzed.
2. From the aspects of customer needs, product data, resources, and technological progress, the main factors were summarized in the design process of SWLs. In addition, the evaluation model based on GCD and AHP was established for SWL evolution evaluation, in which the objectivity of AHP is strengthened by adding fuzzy theory.
3. Utilizing the indicators of CSD, economics, and AP in SWLs, the driver analysis system based on chaos was constructed. After analyzing the chaotic characteristics of PFE, the sensitivities of three main factors in the evolution of SWLs were obtained by chaos iteration. Simultaneously, the chaotic center can also evaluate the process of PFE, and the evaluation result based on GCD is fully in line with the ranking of chaotic centers in SWLs, demonstrating the validity and correctness of the chaotic system. The designer can make a correct decision in PF design by using the method of evaluation and driver analysis in this paper.
4. In the process of PFE, this paper establishes the chaotic system of PFs only from the three macroscopic aspects. However, there are many external factors; how to choose the evaluation factors to reflect the objective law of PFE and how to establish a chaotic system more precisely to obtain the sensitivities of influencing factors in PFE are issues worthy of further research.

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