Review of Contemporary Product Gene Research in Design and Modeling Areas*

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Abstract

The combination of natural process and engineering design & modeling activities has been proposed due to the demand of intelligent manufacturing and conceptual design. A product gene (PG) concept, as a combination of mechanical design and biological growth is proposed in recent years. PG is the application of genetic engineering to the mechanical-design field. In this paper, a comprehensive review is carried out on the research of PG theory and its application. The PG theory research, which focuses on the similarity and difference between biological gene and PG, is divided into three parts: concept and characteristics, data model, and operation technologies of PGs. Furthermore, to implement PG into the design and modeling area, PG research application is also discussed. Then a comparison between PG and other design & modeling methodology is conducted. Finally, the conclusion and discussion of future development of PG research are advanced.

Key words: Product Gene, Product Genetic Engineering, Mechanical Design, Growth Design, Intelligent Manufacturing

1. Introduction

Based on biological research, people define genes as the basic genetic material that can transfer genetic information to the next generation, thus make offspring possess similar generation characteristics with parents. In addition, genetic engineering is a technology that transforms genetic characteristics of a creature via specific operation on genes according to human requirements.

In recent years, many scholars have found that similar genes exist in products as well, especially in mechanical products. For instance, a product design process is similar to a creature growth. Features of each function can be regarded as genetic information, which determines the method of manufacturing and configuration. PG is extracted from the existing products, and then it can generate new products via the PG expression. Thus, PG contains the entire information needed in product design, and determines the design process. Many advantages of PG have been discovered, such as: (1) high flexibility in design knowledge expression on the basis of PG recombination; (2) clear framework for product growth design; and (3) support conceptual design(1).

Due to the above advantages, most of the recent studies on PG are focused on the field of evolutionary mechanical design. Many studies have been conducted since the concept of PG was put forward. These PG studies are divided into two parts: PG theory and PG research application(1).

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The PG theory consists of three parts: PG concept and characteristics, data model of PG, and PG operation technology. Specifically, PG concept and characteristics are the basic attributes of PG. In recent years, various definitions of PG concept and characteristics have been proposed, but standard PG concept and characteristics have not been established until now.

The Data model of PG is used to represent the PG in PG engineering. In biology, a double-helix model(2) is proposed to represent the gene, the basic unit of creature inheritance and copying, and the basic unit of a living creature. This similar structure also exists in PG and lays the foundation of PG engineering.

The operation technology of a PG is the application of methods of PG engineering, which aims to create new product via the transformation of PG. It consists of obtainment, recombination, and expression technologies. Among them, the PG obtainment is used to extract PG from products, the PG recombination transforms existing PG into new PG that satisfies the new requirements, while the PG expression is applied to control the PG growth process to real products or product schemes.

In addition, the application of PG is the ultimate purpose of PG research. Currently, most studies on PG applications are focused on PG-based manufacturing and mechanical design. PG is applied in many design types, such as conceptual, growth, and variant designs, and etc. Some advances have already been acquired in the conceptual designs.

The current paper is organized as follows: In section 2, the PG concept is defined, and the data model, coding and operation technologies of PG are described. In section 3, the applications of PG in many fields are introduced, including conceptual, automation, growth, and variant designs. In section 4, the PG method is compared with some similar design & modeling methods. Finally in section 5, the conclusions of the paper are presented, and the future research trends of PG are also analyzed and forecasted.

2. Theory of PG

2.1 Concept and characteristics of PG

During the initial stage of the general design activity, original information is required, which can gradually be detailed in the process until the design process is completed. The growing process of this original information during the design activity is essentially similar to creature growth. As shown in figure 1, through a systematic comparison, the corresponding relationship between creature growth and product design is described as follows: biological gene→PG, RNA→conceptual structure, protein→entity structure, cell→part, and living creature→mechanical product. Based on this correspondence, a conclusion can be drawn that both creature growth and product design create new entity via the synthesis of basic construction units. The genetic material of a creature is DNA. Its basic construction unit is protein, and the new entity is a living creature. Correspondingly, the genetic material of a mechanical product is PG. Its basic construction unit is part, and the new entity is a mechanical product. The process of creature evolution is inheritance and mutation, whereas the process of product design is PG decomposition and reconstruction.
In biology, gene is a nucleotide sequence in a DNA molecule that possesses some genetic effects. It is the basis of genetic information conveyance and character development. The function of a gene includes recombination, mutation, transcription and translation. As for engineering design area, similar genes can be found in mechanical products, defined as PGs.

At present, some studies are concentrated on PG concept and characteristics. However, because of different study methods and emphasis, a standard PG concept and characteristics are still not established. Outlined next are some existing definitions of the PG concept and characteristics.

Feng, Chen, Zhang, and Pan (2002) and Chen (2005) compared biological genetic engineering with the product principle scheme design. They defined PG as genetic knowledge of product function and pointed out that its realization method was consisted of processing and solving characteristics. However, they haven’t explained the difference between PG and the general sense of product information specifically.

Yang, Huang, and Shang (2007) defined PG as a collection of standardized information with genetic value that determines product life cycle. In this paper, they considered the characteristics of PG, including heredity, variability, self-organization, and self-adaptation. Among them, heredity indicated the inheritance of knowledge and technology in product design process; variability represented the ability to obtain products with new functions and new characteristics via PG mutation; self-organization and self-adaptation denoted the ability of keeping favorable mutation through the adoption of people’s different choices for product requirements.

According to analysis of the roles of PG in conceptual design, growth design, and specific product design fields, Chen, Cao, Xu, and Zhao (2009) divided PG into three types which are evolution, concept, and physical genes. Moreover, Chen, Huang, Yang, and Zhang (2005), Chen, Wu, Li, and Huang (2006), and Chen, Xu, Cao, and Huang (2009) defined PG as a recipe for a particular product, which determined the basic characteristics and the automatic growth mechanism of the product structure. In addition, Liu, and Shang (2009) considered PG as an abstraction and generalization of the general characteristics of mechanical products. They described PG as a genetic knowledge system that met the product function requirements. These definitions are similar to creature genes, but they can only apply to some sample products without complex structure and function.

Tai, and Zhong (2007) and Tai, Zhong, Miao, and Cui (2007) determined that PG was consisted of function, structure, and principle genes. Function gene (FG) was the basic information unit that described the function and characteristics of product principle solutions. Structure gene (SG) was the basic information unit that described the related structure and material characteristics of product principle solutions, and principle gene (PCG) was the basic information unit that described the physical-effect principle of the product principle solutions.

Hao, Xin, and Lou (2010) defined PG as a collection of genetic function information and the related geometrical feature information, which was consisted of a FG and geometrical characteristics.

Although the standard definition of PG is still not established, the above studies have similar views as follows:

1) PG is a collection of information. All the important information during a product life cycle, such as product function, structure, material, principle, and environmental information of the product design, is contained in PG.

2) The whole life cycle of a product is controlled by PG. In addition, the basic function, structure, and other characteristics of a product are regulated by PG, which is similar to the process of biological genes controlling creature growth.

3) PG is a collection of information created and standardized by researchers.
Based on the above studies, we propose the concept of PG as a collection of standard information that controls the growth process of products and regulates each aspect of product attributes. Meanwhile, heredity, variability, self-organization, and self-adaptation must be included in the characteristics of PG that will determine its application. Heredity allows reuse of design knowledge, which can improve the product design efficiency and shorten the product manufacturing cycle. Variability is significant because new products with new function and new structure can be obtained from PG variation. Self-organization and self-adaptation allow favorable variations applied to the environment that can be saved by PG. Thus, new products grown from PG can satisfy the requirements.

2.2 Data model

In biology, gene is expressed by a nucleotide sequence that contains specific genetic information and a DNA segment with genetic effects. A double-helix model is proposed as the structure of the gene. As a collection of standard information, PG also needs data model to support PG engineering. In recent years, many kinds of PG models have been proposed, such as PG model based on function surface (FS), product unit gene model, and etc.

Chen, and Huang (2005) put forward a PG model based on FS\((2)\), \((13)\). In their method, an object-oriented class, which included chain table PartPtrlist, PartNet, product attributes, and some process functions, was defined. Specifically, all the information of each part was saved in PartPtrlist. The relationship information among parts was saved in PartNet. In addition, product attributes described some properties, such as part number, surface number, product version, and etc. However, the weakness of this data structure is that it only focuses on the structure and assembly information, but lacks the description of function and principles.

Shang, and Huang (2007) proposed a PG model based on FS\((14)\). In their paper, a comparison between FS and PG was proposed, and a formal expression of PG was also achieved on the basis of FS. In their viewpoint, PG was a sequence which consisted of function modes and FSs based on some specific topology relationships (RP). As shown in figure 2, a hierarchical model consists of PG, function unit (FU), function mode (FM) and FS is constructed.

![Figure 2 PG hierarchical model](image)

Liu and Shang (2009) regarded PG as a hereditary knowledge system based on product requirements\((9)\). This kind of system, which included F (product function), S (structure), C (control), and L (sequence), was an abstraction and summary of the general characteristics of mechanical products. In addition, PG could be divided into FGs, SGs, and control genes (CGs). Specifically, FG indicated product function requirements, SG represented structure information, whereas CG was the operation mechanism of the conceptual design process whose essence was the decomposition–reconstruction method based on knowledge. However, the work process of FGs, SGs, and CGs has not been illustrated in details, and the difference between PG and product information cannot be found in that paper.

Li, Tong, and Shi (2010) proposed a process gene model which consisted of four bases\((15)\), such as activity, object, team/member, and resource bases. And these four bases were categorized into two types which were administration and technological types. Considering the administration type, which included team/member and resource bases, it was the distinction between this model and the other PG model. In this type, the responsibility of managers and team members were included in the team/member base, whereas the data and
tools used in the design process were included in the resource base. Finally, the design process was expressed by the connection of the administration and technology bases to show all the information involved in the design process. This is a good method to express the design process, but it has not been proved effectively as it is lacking of case studies.

Wang, Wu, and Zhe (2007) proposed a PG model represented by a triangle. Specifically, $PGM = (K, G, R)$, where $K$ (knowledge) represented design knowledge, which included experience of the designer and computational formula; $G$ (gene) indicated PG, which was divided into “DNA” and “histone”; and $R$ (rule) stood for the variant rules. Moreover, Li, and Xiao (2003) studied the formal and digital description of requirements, as well as a united expression method of PG based on a function matrix. In their paper, a PG evolution model design was established via adopting a specific modeling protocol.

2.3 Operation technology of a PG

2.3.1 A framework of PG operation

Based on data models, PG engineering can be implemented via the operation technology. These operation technologies include the following ones: 1) PG obtainment technology, which extracts PG from existing products, constructs PG database, and then achieves purpose genes; 2) PG recombination technology, which modifies PG via PG separation and connection to recombine PG based on recombination rules; 3) PG expression technology, which transforms PG into a product through control and growth mechanisms. As shown in figure 3, the main framework of PG engineering consists of the operation technologies.

2.3.2 PG obtainment

PG obtainment, the first stage of PG operation (as shown in figure 4), represents the method that extracts PG from products. The PG obtainment process can be divided into the following two steps: 1) product solutions are extracted from existing products; 2) PG is obtained via the analysis and abstraction of product solutions.

Chen, and Huang (2005) proposed a method of PG obtainment based on FS, which divided a PG into FGs, SGs, and CGs. The extraction methods of these genes were discussed in that paper as well.

Tai, and Zhong (2007) and Tai, Zhong, Miao, and Cui (2007) raised a method of PG obtainment through the analysis and abstraction of design cases. In these papers, PG acted as the minimal information unit of a product’s function, principle, and structure information. After the information was obtained through analysis and abstraction of design cases, PG could be obtained through the transformation of the information.
2.3.3 PG recombination

After the PG of an existing product is extracted, the next step of PG engineering is PG recombination. Firstly, undesirable PG segment is separated and PG searching for purpose genes is conducted in the PG database. Then, PG recombination is implemented according to the recombination rule. Finally, the recombined gene is evaluated and transmitted to the PG growth system. As shown in figure 5, similar to biological recombination, the PG recombination process is conducted to obtain a new PG by matching of existing and purpose genes.

Chen, and Huang (2005) firstly discussed four basic processes of recombination\(^\text{(2)}\). Then, they focused on the design process based on PG recombination. In the process, undesirable genes were discovered by the determination of conflicting solutions of a product design, and new PGs were obtained through the matching principle of PG recombination.

Zhao, and Wei (2004, 2005, &2010) analyzed the process of PG recombination as well\(^\text{(19)-(21)}\). The process included breaking, replacement, combination, crossing, and variation stages. The first three are primary stages, while the latter two are advanced stages, realized by the combination of the primary processes.

Tai, and Zhong (2008) proposed a recombination method based on the genetic algorithm\(^\text{(22)}\). Specifically, a tree coding method was adopted to express the PG. And then the selection operator and crossover operator were designed based on the tree code. After this, the recombination process could be conducted to achieve new PGs. This method is well established to generate new products from existing product cases. However, the detail of fitness function and tree code haven’t been discussed in their paper.

2.3.4 PG expression technology

In biology, expression of a gene is divided into two phases: transcription and translation. Transcription is the process that generates mRNA based on DNA, whereas translation is the process that generates protein based on mRNA. Similar to the biological gene shown in figure 6, the PG expression is divided into transcription and translation as well. PG is transcribed to the specific conceptual structure firstly, and then the conceptual structure is translated to specific entity structure based on the matching-rule and evolution-knowledge databases.
Feng, Chen, Zhang, and Pan (2002) raised the central dogma of PG. Based on the relationship between PG and the effect solutions, specific effect solutions could be obtained from the transcription of PG, and then these effect solutions generated specific principle solutions via the translation. Chen, and Huang (2005) put forward the central dogma of PG. In their paper, PG was divided into FGs, SGs, and CGs. Under the regulation of CGs, FGs were transcribed to product prototypes, while SGs were transcribed to different types of structures. Then the product conceptual structure was formed, which consisted of product prototypes and structures. In addition, two technologies were applied in the PG translation, which were entity-matching technology based on the cases and entity-evolution technology based on the part class. Based on these technologies, the entity structure could be obtained. These papers have not discussed the specific attributes of PG, as well as the detailed translation and transcribe process. The notion of CG is useful, but the control process of CG hasn’t been discussed in this paper.

Tai, and Zhong (2007) and Tai, Zhong, Miao, and Cui (2007) proposed a different expression method. In their method, different PG types were divided into FGs, PCGs, and SGs, which possessed different expression information. Compared with former researches, this process contained the expression of principle as the complementary of function and structure information.

3. Research of PG application

PG application is the ultimate target of PG research. PG is appropriately applied in the mechanical design and manufacturing processes because of its unique characteristics. In recent years, design based on PG becomes a very hot research area. Some design methods, such as conceptual, automation, growth, and variant designs are studied based on PG.

3.1 Conceptual design

Conceptual design was first proposed in 1985. French (1985) regarded the conceptual design as a design key, but a specific definition of conceptual design was not proposed. Pahl, and Beitz (1994) put forward a definition of conceptual design. In their paper, prerequisites, process steps, and result of conceptual design were specifically defined.

The process of conceptual design based on a PG is shown in figure 7. Specifically, step 1 is function decomposition that decomposes function requirements into some sub-functions. Step 2 is searching PG in the database according to the sub-functions. Step 3 is obtainment of design principles via the transcription and translation of PG. Step 4 is the assessment and selection of the design principles. After these steps, a principle solution for physical design is obtained.

Feng, Chen, Zhang, and Pan (2002) proposed a conceptual design method based on PG. Based on the comparison between biological genetic engineering and design scheme of
product principle, the mechanism of transcription, translation, copying, and reverse transcription was raised. In addition, Chen, Feng, and Lin (2005) raised a genetics-based approach for the conceptual design\(^{(29)}\). In their paper, PG was employed to index product solutions to facilitate the mapping between functions and product solutions. Furthermore, the specific process of conceptual design based on PG was also discussed. Then, a genetics-based principle conceptual design platform (GPCDP), which could effectively support principle conceptual design in retrieving possible product solutions to requirements without any prejudice, was designed. Finally, a coin-sorting device used in non-conductor bus was developed as the case study of GPCDP. However, although the process from requirement to product solutions has been discussed, the specific process to retrieving PGs from requirements has not been described.

In Shandong University of China, many scholars carried out their researches on this area. Chen, and Huang (2005) carried out further research on the conceptual design method based on PG\(^{(2)}; (13); (35}\). In these papers, the object-oriented technology was employed to build the PG model. In addition, Shang, and Huang (2007) conducted a study on conceptual design as well\(^{(14)}\). In their paper, a modeling method of conceptual design based on PG was raised, and the automatic method of product conceptual design was discussed based on the modeling method. Finally, a CAD system named DARFAD that supported the conceptual design was designed based on this PG model. This system was built on the basis of function modeling, and provided a product evolution mode for each type of design requirements. Now it is an effective tool to aid both professional and amateurish designers conducting mechanical design work.

![Figure 7 Conceptual design based on PG](image)

**3.2 Growth design**

Growth design is the process of imitating the creature growth mechanism for product design. During the growth design process, automatic and intelligent design mode is achieved via the control of product evolution rules. The growth design of a product includes two steps: 1) product information collection is obtained through analysis of the function requirements, and 2) product information grows under the control of evolution rules until an entity product is achieved. Through these steps, a detailed design of a product is achieved.

Chen, Huang, Yang, and Zhang\((5)\); Chen, Wu, Li, and Huang\((6)\); Chen, Wang, and Cui \((7)\) and Chen, Cao, Xu, and Zhao \((9)\) proposed a design method that applied PG into growth design\(^{(5)}; (7)\). Specifically, based on PG, a theory of growth design, which defined that mechanical product design process similar to creature growth was proposed. In that theory, the design process could be divided into two steps: transcription and translation. As shown in figure 8, during transcription, FGs are obtained from FG database via the analysis of function requirement. Then a product prototype consisting of FSs is transformed from FGs, thus a conceptual structure can be achieved. In the process of PG translation,
entity-matching technology based on cases is applied. Conceptual structures in the conceptual scheme are replaced by entity structure storage in the parts database, thus a conceptual design scheme evolves to a detailed design scheme. In Shandong university of China, a CAD system named DARFAD was constructed which could support growth design and provide some case studies. That method was in accordance with the requirements of creative and automatic designs, but it could hardly be applied to the design of complex products due to the lack of PG quantities and attributes.

![Figure 8 PG growth design-process model](image)

3.3 Creative design based on product cases

The product scheme design is the most creative phase in the whole design process, but it is still a bottleneck needed to be broken in future because it is very difficult to obtain knowledge by using traditional design method. Through contrasting the heredity and evolution of living creatures, Tai (2007) proposed the concept of population of product cases. The population of product cases was the products in the same species that had similar functions, characteristics, and structures \(^{(11)}\). Based on that concept, a model of PG consisted of function base (FB), principle base (PB), structure base (SB), and material base (MB) was proposed.

After the concepts of population of products and PG were proposed, Tai (2008) suggested a creative design method based on them \(^{(22)}\). The method got PG from the analysis and abstraction of product cases first, and then transformed PG into product solutions. The difficulty in traditional design method to obtain the product solutions was avoided in this method.

After PGs were obtained from the product cases, an evolution algorithm was proposed to design new products automatically. In this algorithm, the product design activity is regarded as the process that recombination and mutation in the existing population. And the fitness functions of the PGs are designed as well.

Finally, an intelligent creative design prototype system (ECDS) was designed to verify the validity of the creative design based on product cases and PGs. In the case studies, design solutions of scissor and elevator design are obtained effectively in this system.

This creative design can get new product solutions automatically and quickly. It can avoid the difficulty to obtain the product solutions through the application of PG. However, some disadvantages can be found as well. The creative types only including function, principle and structure innovation, are still simple. Other factors in creative design, such as
product appearance, cost, and lay-out are not included in his method. In addition, the evaluation method in the evolution algorithm is still not quantified, which cannot evaluate the product pollutions accurately.

### 3.4 Variant design

Variant design is a special design action, which aims at effectively shortening the product manufacturing cycle, ensuring the product quality, and improving the overall customer satisfaction. It is a technique for facilitating efficient and cost-effective product variety development, and its basic principle is to modify existing mature product designs or instances to meet a new design requirement[28].

Zhao, Zhao, and Wei (2008) proposed a method that applied PG into variant design[28]. In that paper, a model for variant design based on PG and an effective math-optimized model were proposed. Based on these two models, an improved artificial immune algorithm adapted to the optimum model of PGM was presented, which utilized the antibody protein polypeptide structure, the concentration regulation of the artificial immune system, and the clone-selection mechanism.

Wang, Wu, and Zhe (2007) put forward a modeling method to support variant design[29] as well. In that paper, PG conception and PG operation in variant design were defined, and a PG model that included design knowledge, PG, and variant rules was proposed. Through some manipulations, such as separation, copying, replacement, mutation, and combination, the dynamic transmission of variant information was finally realized.

### 3.5 Product information inheritance

Wang, and Ai (2011) proposed a product information inheritance method based on PG[30]. In that paper, an FS→parts→products configuration system was established, and the object-oriented technology was adopted to realize product information inheritance. As shown in figure 9, FS is divided into several levels, and low-level FSs are inherited from high-level ones. Specifically, the first level of FS is the basic surface. And the second level of FS includes those very common surfaces, such as plane, cylinder, cone, etc. The third level of FS includes those complex surfaces inherited from the second-level surfaces, such as polygon and elliptic cone surfaces, and so on. Finally, the object-oriented classes are defined to represent these FSs. The theory in that paper is successfully applied to the whole and part design of products. The advantages of object-oriented technology are fully utilized to reduce repetitive works, improve design efficiency, decrease design error rate, and realize the maximum product design optimization.
3.6 Other applications

Researches on PG applications in other fields have also been proposed by scholars. Zhao, Feng, and Pan (2000, 2003) applied PG into the research of product cost modeling\(^{(31)-(32)}\). Based on the manipulations of PG copying, PG transcription and translation, a new method to conveying, transforming and expressing information was put forward. Then a product cost gene modeling platform was designed to build the cost model and analyze knowledge and data.

Luo, Zhu, Ying, and He (2009) proposed a method that applied PG into a design of a product family\(^{(33)}\). In this method, brand identity factors were divided into dominance and recessiveness factors to reflect the characteristics of brands in the design process. Then the concept of emotion, action, and vision design genes were put forward. Finally, genomes of product family design on the basis of emotion, action and vision were proposed. In addition, Miu, and Yang (2008) discussed the design of product family\(^{(34)}\). That paper mainly concentrated on designation of brand style and construction of product culture, and constructed an analysis model for companies brand style.

The above PG studies contain most fields of mechanical design, as well as some design studies in other fields. These works show the universality of PG application and indicate the significant research value and practical applicability of PG. However, studies on PG applications are still at its initial stage, with most research still in the exploratory phase and not being implemented to the practical engineering applications. The improvement and perfection are still required to promote the research in this area.

4. PG versus other design & modeling methodology

4.1 PG versus adaptable design

Adaptable design\(^{(40)}\) is a new design approach that aims at creating designs and products easily adapted for different and changing requirements. When design requirements are modified due to changes in customer requirements, the operating environment of products or advances of technology, either the existing design needs to be adapted to create a new design or the existing product needs to be. To reduce the efforts of design and product adaptation, both design and product adaptability should be considered at the design stage. Adaptable design is a methodology for ease of adaptation of design or product considering changes in requirements.

The benefits of adaptable design include economical benefits and environmental benefits\(^{(41)}\). Specifically, its economical benefits include that a new design and product can be easier produced by modifying the existing product, and a customized product based on specific requirements of individual customers can be achieved in a lower costs. In addition, its environmental benefits contain prolonging the products’ life and facilitating remanufacture and recycle process.

Similarly, the PG method adopts some advantages of the adaptable design. Specifically, most PG definitions highlight the self-organization and self-adaptation in PG's characteristics as well, so that the PG can response to the environment changes effectively. In addition, the basic unit of PG method is a specific gene structure, which is different from the basic unit of adaptable design, thus makes the storage of knowledge easier and adapts design process more effectively.

4.2 PG versus bionic manufacturing system

The bionic manufacturing system (BMS, also known as biological manufacturing system)\(^{(42-46)}\) considers manufacturing systems as organs and the equipment or components in the system as cells with a biological viewpoint. In BMS, the parallels of manufacturing units and biological cells have been adopted to put forward modeling concepts and
applications. In addition, all system elements in BMS such as work materials, machine tools, transporters, robots are comparable to autonomous organisms.

The original idea of PG and BMS is similar. Both of them apply the biological ideas into product design and modeling area, and compare the design process to the growth process of creatures. However, there are some differences between their design processes. Specifically, in BMS, the design process is realized via the imitation of creature growth, especially the ability to adapt to the environmental changes and sustain their own life. As for PG, the process of product design is achieved through PG engineering which includes the obtainment, recombination and expression of PGs, thus makes the design process more effectively. In conclusion, although their original ideas and final purpose are similar, their implementing methods are different.

4.3 PG versus fractal manufacturing system

The fractal manufacturing system (FrMS) is a concept derived from the fractal factory introduced by Warnecke(47). The architectural model of fractals represents a hierarchical structure built out of the elements of a basic function unit (BFU), and the design of a basic unit incorporating a set of pertinent attributes that can fully represent any level in the hierarchy. In other words, the term “fractal” can represent an entire manufacturing shop at the highest level or a physical machine at the lowest level. Each BFU provides services with an individual goal and acts independently. To function as a coherent whole, however, goal consistency is maintained through a goal-formation process, which is supported by an inheritance mechanism. In addition, self-organization, self-optimization, goal-orientation, self-similarity, and dynamics are described as the main characteristics of fractals(48).

In PG method, its basic design unit PG is similar to the BFU in their autonomy and flexibility. They have similar characteristics such as self-organization. However, there are some differences between the content and application of PG and BFU. PG contains more information than the BFU. Specifically, the information of products’ function, design principle, structure and material are contained in the PG, which may be more comprehensive than BFU.

4.4 PG versus general design theory

General Design Theory (GDT) is a theory of design knowledge based on axiomatic set theory, which was proposed by Yoshikawa in 1980(49). GDT’s major achievement is a mathematical formulation of design processes. It deals with concepts that only exist in our mental recognition. GDT regards a design process as a mapping from the function space to the attribute space, both of which are defined over the entity concept set. Based on axiomatic set theory, we can mathematically derive interesting theorems that can well explain a design process.

GDT defines the general process of design activities, so it can be viewed as the basis of PG method as well. In PG method, it defines a more specific process of the design process, which can be viewed as a mapping from the requirements to the PGs. In addition, the PGs can be viewed as the entity in general design, and the different information in the PGs can be viewed as the attributes. These PGs and attributes comply with the axioms in GDT as well.

5. Conclusions

In summary, PG can be applied as the basis of many designs & modeling methods, such as conceptual design, case based reasoning design, variant design, etc. In addition, based on PG, a specific design method has been proposed by Chen, Huang, Yang, and Zhang (2005), which is known as growth design(6). In this design method, design target can be achieved through the transcription and translation of PGs, which is similar to the growth process of creature.
Compared with other design & modeling methods, PG method has its specific advantages and application areas. Firstly, PG consists of several genes, such as FG, PCG, SG, CG, thus contains comprehensive information of a product's design process and its whole life-cycle. Secondly, in the method of PG, the basic design unit PG can be easily obtained through the obtainment technology. Finally, the PG engineering makes the design activities being a systematic and effective process.

However, although some studies on PG theory and its application already exist, these works are still at its infancy stage. PG concepts applicable to diverse fields differ and lead to difficulty in establishing a standard definition of PG. In addition, some shortcomings can also be found in the operation technology and application of PG. So the authors believe that advanced research should be conducted covering the following aspects:

1) Establishment of an integrated framework of PG theory. A standard definition of the PG concept, characteristics, and formal expression technology should be raised and accepted. In addition, many cases are needed to demonstrate the applicability of the theory.

2) Application of PG in intelligent design. Design intelligence is always a focus of research. The introduction of PG into intelligent design, which controls the process of product growth under the restriction of PG and the environment, needs to be studied.

3) Application of PG in total life cycle design. The concept of total life cycle design is developed from the idea of concurrent design confronting the process of product total life cycle. Total life cycle design demands a consideration of each stage in a product life cycle. As a collection of product information, most of the contemporary researches on PG merely focus on the design of the product itself without considering total life cycle idea. PG should be a collection of the entire important information of product life cycle to be implemented in future research. A method transforming product total life cycle design into PG design should be proposed so that concurrent design of product total life cycle and integrated planning of design resource can be realized.

4) Construct of knowledge structure model. As the design and manufacturing of those multidisciplinary products are more complex, the multi-domain criteria need to be analyzed and evaluated. For PG can represent the design principles in the design process, it is suitable to develop a multi-domain PG database to save the design knowledge, improve the product design process and shorten design times.

5) Combination of PG and information technology. At present, the multidisciplinary research combines information technology with other disciplines is a study hotspot. In design & modeling area, the combination of PG and information technology should be proposed. For example, the inheritance of PG can be realized through the heredity of object-oriented technology and the saving and searching methods of PG in the database should also be studied for advantage in the automatic design of PG.

6) Establishment and management of PG database. As a saving method of PG, searching of PG unit should be the first step during the PG-based design process. If PGs meeting the requirements can be found, they should be expressed into a whole product or product part. If no PG can satisfy the requirements, a PG with the highest matching score is found, recombination operation should be implemented to this PG to obtain a new PG meeting the requirements and save this PG into the PG database to support prospective search. Repetitive work in creative design can be reduced and the design efficiency can be enhanced.

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