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Review

From Biological Gene to Functional Gene: Revolutionizing Product Innovation Design

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Abstract: The functional gene is a product of functional information expression methods inspired by biological genes. Product innovation design is essentially a process of functional problem-solving, which has an intrinsic connection with biological gene expression. The analogy of biological genes, which standardize product function information into functional genes and apply them in product innovation design, holds enormous potential. This paper provides a comprehensive analysis of relevant literature. Firstly, it elaborates on the development of functional genes from the refinement of product genes, clarifying the relationship between functional genes and product genes. Then, it discusses the theoretical foundations of functional gene research, such as the concept, characteristics, and information transmission pathways of functional genes. Moreover, it analyzes key technologies for the application of functional genes, such as functional information encoding forms, and functional gene structure, while summarizing research case studies on functional gene applications. Finally, it explores three key challenges: determining functional gene information content, protecting intellectual property rights, and identifying defects. It also proposes research entry points, aiming to provide references for the field of product innovation design.

Keywords: functional gene; biogenetic-inspired; product innovation design; advancements and prospects

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1. Introduction

Economic globalization has led to intensified market competition. In order to meet the increasingly personalized demands of the market, the efficiency of product innovation and design has become a focal point [1–3]. Over 90% of new product development in the manufacturing industry is based on the reference and innovation of existing products [4–6], which involves the reuse of knowledge from different disciplines and fields [7,8]. Products serve as carriers of functions, and functions are the core of products. Therefore, product design is a process of seeking solutions for functions [9].

Biological knowledge has significant implications for engineering design [10], such as bio-inspired fatigue-resistant design [11], lightweight design [12], design analogy to nature engine [13], multiple biological effects [14], and so on. In the field of genetics, genes are composed of nucleotide sequences that contain genetic information, and they control the development and expression of traits in organisms [15]. Biological genetic effects primarily manifest in processes such as gene replication, transcription, translation, recombination, and mutation, playing a crucial role in the growth and development of offspring. There is an inherent connection between knowledge reuse in design and the thinking and principles of biological genetic inheritance [16–18]. By extracting, genetic expression, storing, and utilizing design knowledge from existing products, the efficiency of design knowledge reuse in the product design process can be enhanced [19,20].

However, currently, the application of biological genetic thinking to product design presents a diverse range of numerous and complex trends. Scholars have proposed different types of genes based on different emphases, including functional gene [21], product form gene [22], and manufacturing gene, among others. It is important to distinguish functional gene from product gene.

Therefore, this article provides a summary of the literature on product genes and analyses the unique significance of functional genes and the current status of research. Furthermore, theoretical studies such as conceptual changes, characteristics, and informational genetic pathways of functional genes are analyzed. In addition, elaborates on applied research in coding forms of functional genes, genome structure, and engineering applications. Finally, existing problems and challenges in functional gene research are presented and insights into future research priorities and prospects are provided.

2. Origin of Functional Gene

As early as the 1990s, Professor Holland [23,24] combined the genetic inheritance mechanisms of biological evolution with product design, making the earliest attempt to apply biological genetic engineering to the field of engineering technology. Subsequently, Professor Gero [25–27] gradually combined the concept of designing genes with genetic algorithms in the field of engineering design by applying genetic engineering principles. During the same period, research into using genetic thinking to guide product design began in China. Gu et al. [28,29] proposed product concept gene models, product structure gene models, and process design gene models by analogy with biological systems to achieve hierarchical management of knowledge.

Nowadays, the concept of genetic engineering has been applied to various stages of the product lifecycle. The product lifecycle [30,31] refers to the entire process from conceptualization to retirement and maintenance of a product, typically divided into stages such as requirements analysis, conceptual design, detailed design, production manufacturing, and operation and maintenance. Correspondingly, product genes are classified into different types based on their purposes, including requirement gene, styling gene, function gene, and manufacturing gene, collectively known as product genes.

The requirement gene is used to discover the requirements of the target system, typically by analyzing historical operational data and conducting user surveys [32]. The styling gene [33], also known as the appearance gene, serves the process of product styling and appearance design. They determine the product's volume and appearance by analyzing usage scenarios and user experience, contributing to the conceptual design phase. Function gene [34] involves the standardized expression of product functions and structures, focusing on realizing the product's basic functionalities. They play a crucial role in both conceptual and detailed design phases. The manufacturing gene, also known as the quality gene [35–37], is applied in planning the production process, scheduling, and later stages of equipment operation and maintenance [38]. Analyzing the relationship between the different stages of the product lifecycle and the product genes is shown in Figure 1.

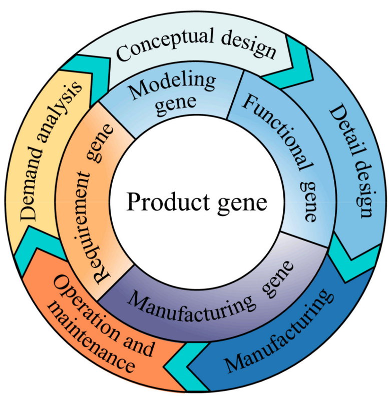

Figure 1. The relationship between product lifecycle and product gene.

According to the literature selection criteria, a preliminary search was conducted by setting keywords and field classifications. For Chinese literature, the China National Knowledge Infrastructure (CNKI) database was used, with keywords such as "product gene" (in Chinese), "design gene" (in Chinese), "design DNA" (in Chinese), or "gene expression" (in Chinese), and classification numbers set as "TH122 mechanical design" (in Chinese) or "TB472 product design" (in Chinese). For English language literature, the Web of Science Core Collection was utilized, with keywords such as "product gene", "design gene", "design DNA", or "gene expression", and research fields set as "Engineering, Mechanical" or "Engineering, Manufacturing" or "Engineering, Industrial". Additional literature was supplemented through platforms like ScienceDirect and Springer. The publication timeframe was set from January 2000 to June 2023, resulting in a total of 858 papers. Among them, there were 186 Chinese papers and 672 English language papers. Subsequently, after excluding literature in the field of biological genetic engineering, a total of 733 relevant references were selected.

Furthermore, based on the research content and respective fields of the literature, the papers were further categorized into demand gene, form gene, functional gene, manufacturing gene, and others. During the process of organizing the literature, it was found that Chinese literature focused more on research related to form genes and functional genes, while English language literature had a greater emphasis on functional genes and manufacturing genes. The percentage of each type of literature in Chinese and English language literature was plotted as shown in Figure 2.

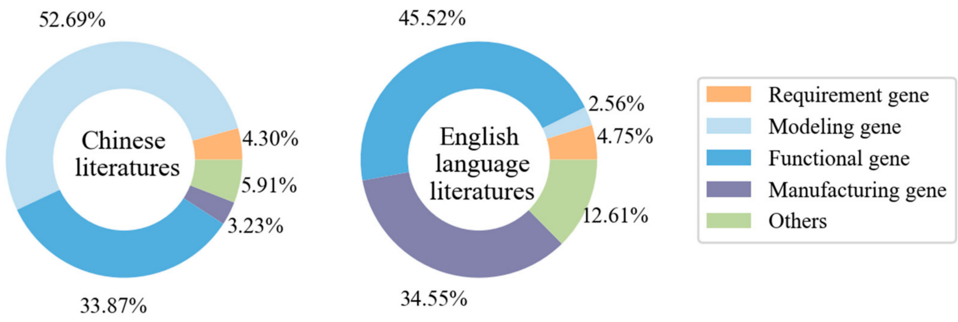

Figure 2. The ring diagram of the percentage of each type in Chinese and English language literature.

Moreover, an analysis of the growth trends for each category of literature was conducted based on year and type. Trends in the growth of various types of literature were compiled, as illustrated in Figure 3.

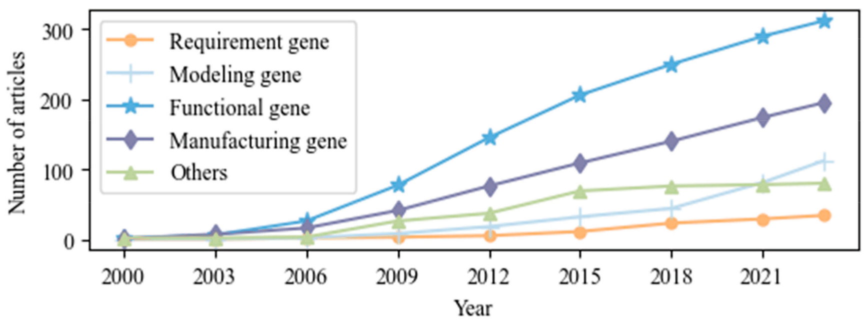

Figure 3. Trends in the growth of various types of literature.

From the above analysis, it is evident that product genes have evolved into multiple refined directions through continuous practice. Among them, the functional gene has experienced rapid development. This is mainly because product functionality forms the foundation for meeting user needs, and functional design is at the core of product design. A well-designed product functionality can enhance product competitiveness and reduce production costs. The following section will provide an overview of the theoretical research, application research, challenges, and opportunities related to functional genes.

3. Theory Research on Functional Gene

Products are the carriers of functionality, and functionality is the core of products—it represents a certain need of the customer [39]. Product design is the process of transforming functionality into structure [40]. A functional gene is the product of gene expression of product design knowledge from a functional perspective. Their application in product design, combined with genetic inheritance and variation, contributes to the efficient and rapid generation of highly innovative product designs [41]. The theory of functional genes includes concepts, characteristics, and genetic transmission pathways.

3.1. The Concept of Functional Gene

Functional genes originated from the refinement direction of product gene development. Initially, the functional gene was primarily used to record product functional information, structural information, and to accumulate design knowledge and enable rapid retrieval [42,43]. As the integration between biological genes and product design deepened, the research focus gradually shifted toward how to utilize genetic inheritance and variation concepts from biology for innovative product design. Research scholars have conducted in-depth research from multiple perspectives such as the inclusion of information, expression process, expansion, and application of functional genes. This article screens some of the research at various stages based on publication time and novelty and displays some of the functional gene research scholars' viewpoints in Table 1.

Table 1. Scholars and viewpoints on functional genes.

Scholars	Time	Main Viewpoints	Inclusion Information	Expression Process	Expansion and Application
Feng et al. [44]	2001	· A feature-based information model is proposed; · Analogy of biological genetic engineering and product principle program design.	√		
Koza et al. [45]	2004	· Overturn the view that "creative invention is the flash of genius"; · Proposing that creative inventions can be discovered through automated methods.	√		
Chen et al. [46,47]	2005, 2007	·The functional characteristics include material, energy, information, etc. And, through the verb attribute pair representation function; · Gene extraction from existing products using reverse transcription technology. ·A search method for energy conversion is proposed.	√	√	
Chen et al. [48]	2006	· Function is the goal of design, and product conceptual design is the transformation from function to structure. · Put forward functional gene, structural gene, etc.	√	√	
Reich et al. [49]	2012	· Establishing an interdisciplinary engineering knowledge genome to enable multidisciplinary knowledge sharing.	√		√
Li et al. [50]	2020	· The coding method of product gene containing functions and attributes is proposed. · Innovative design was carried out by using gene manipulation techniques such as decomposition, crossover, and recombination.	√	√	√

Table 1. *Cont.*

Scholars	Time	Main Viewpoints	Inclusion Information	Expression Process	Expansion and Application
Wang et al. [34]	2022	· Extract functional information from patents, construct and digitize functional genes; · Gene retrieval and reuse by computer algorithms.	√	√	√

√: Includes this phase of research.

From Table 1, it can be seen that research on functional genes is undergoing a transition from shallow to deep, and from individual aspects to a comprehensive understanding. This has resulted in certain differences in the conceptual representation of functional genes at different stages. Analyzing from a developmental perspective, initially, scholars recorded functional genes in the form of verb attribute pairs, input–output relationships, and other forms, to achieve the reuse of design knowledge [51]. At this stage, the concept can be described as a collection of standardized records of product functional information through the functional gene.

Furthermore, scholars introduced genetic concepts into the conceptual design process and proposed functional genes, principle genes, and structural genes that corresponded to DNA, RNA, and proteins, respectively. Further, the expression process of functional genes was explained according to the central dogma of biology [52]. The concept of functional genes gradually integrated with genetic principles and transformed into a standardized collection of product functional genetic information.

As the research on gene expression processes became more refined, the focus shifted to the sources of functional genes. A single source of gene was no longer sufficient to support diverse design requirements. Instead, knowledge was obtained from interdisciplinary knowledge repositories, patents, recombinant variations, and other sources [53,54], providing cross-domain solutions and generating more innovative design options. At this point, the concept of functional genes has become relatively stable. Functional genes are considered the fundamental genetic units that determine the expression of product functions in the product design process. They represent the standardized expression of functional genetic information.

The concept has undergone two changes compared to its initial stage: (1) There is a greater emphasis on the processes of genetic inheritance, variation, and expression in product design. (2) The sources of a functional gene is no longer limited to products alone, as patents, cross-domain engineering, and other avenues have become important sources of functional genes.

3.2. Characteristics of Functional Genes

The concept of functional genes is derived from the inspiration of biological genes, and therefore, functional genes possess similar characteristics to biological genes. However, due to the differences between engineering systems and biological systems, functional genes themselves have distinct features. Biological genes exhibit heritability, determinants of trait development, and plasticity [55]. Building upon these foundations, scholars have summarized the characteristics of functional genes from the perspectives of extraction, storage, expression, variation, screening, and other aspects, as shown in Figure 4.

Independence: The premise of functional gene extraction. Sun et al. [56] utilized NLP algorithms to extract patent functional information as knowledge modules for retrieval. Genes are the smallest genetic units, and the independence of functional genes implies that they can exist independently without mutual dependence. This ensures that functional genes can be extracted, stored, and called independently, making them the minimum knowledge units that can be recorded for functional genes.

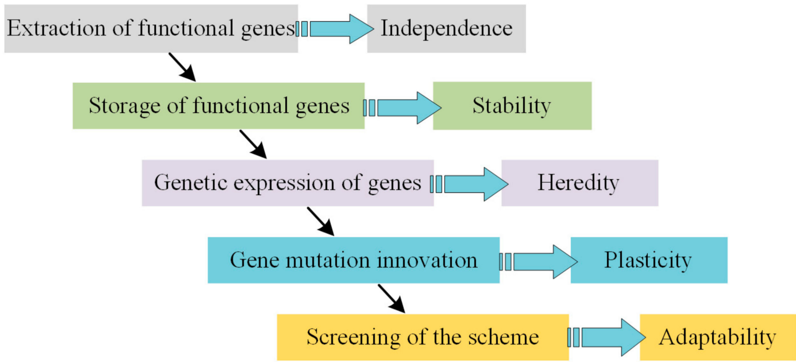

Figure 4. Process and characteristics of functional gene management.

Stability: The foundation of functional gene storage. Wang et al. [57] proposed that in order to achieve industrial digitization and improve design efficiency, design knowledge would be stored in external devices such as computers and cloud storage. As the carrier of design knowledge, functional genes need to remain unchanged despite variations in time, environment, and other factors, ensuring the stability of the stored design knowledge.

Heredity: The core of functional gene expression. Zhang et al. [58] extracted design knowledge from existing systems and documents, providing a foundation for knowledge reuse and achieving intergenerational inheritance of design knowledge. Montomoli et al. [59], using gas turbines as an example, conducted topological optimization based on existing design resources, achieving intergenerational inheritance of design features. As the carrier of design knowledge, functional genes exhibit genetic characteristics inherited from the source systems of the knowledge. This is manifested in the partial inheritance of the functionality and structure of the original system in the design of new products.

Plasticity: The guarantee of functional gene innovation. Zhang et al. [60] extracted design knowledge from a case database and made changes to physical attributes, positions, and other parameters based on the target system. In the process of reusing functional genes, directly using existing functional genes often fails to meet the predetermined design requirements of the target system. By utilizing gene manipulation techniques such as decomposition and recombination, functional genes can be transformed and optimized, leading to the generation of systems with new functionalities.

Adaptability: The selection of functional gene screening. Chen et al. [61] proposed that the trial-and-error method in design consumes a significant amount of resources, and screening design knowledge can help reduce the number of product iterations. The adaptability of functional genes is reflected in two aspects. Firstly, in the selection of functional genes, beneficial gene variations that meet user requirements will be retained, while variations that do not fulfill these requirements will be eliminated. Secondly, in the selection of functional gene sets, there is a coupling relationship between functional genes, which can result in defects in the functional gene set.

Functional gene characteristics determine their effective application in product design. Among them, independence and stability determine the feasibility of gene storage. Heredity and knowledge reuse are highly consistent, so heredity forms the foundation for addressing the issue of design knowledge reuse in the process of new product development. The plasticity and adaptability of functional genes are key to product innovation. By effectively utilizing gene recombination operations, functional genes can be transformed, leading to the generation of new solutions for functional implementation and providing theoretical support for innovative product design.

3.3. Genetic Path of Functional Information

The central dogma of molecular biology represents the flow direction and transmission laws of genetic information in living organisms [62]. The central dogma of molecular biology reveals that the transmission pathway of genetic information in biological systems is from DNA to RNA and then to proteins, completing the processes of transcription and translation of genetic information. This is consistent with the mapping relationship between functionality, behavior, and structure in the design process [63]. Based on the central dogma of molecular biology, researchers have proposed the Product Functional Gene Central Dogma applicable to functional design, which includes a three-level mapping model of functionality, principle understanding, and structure, as shown in Figure 5.

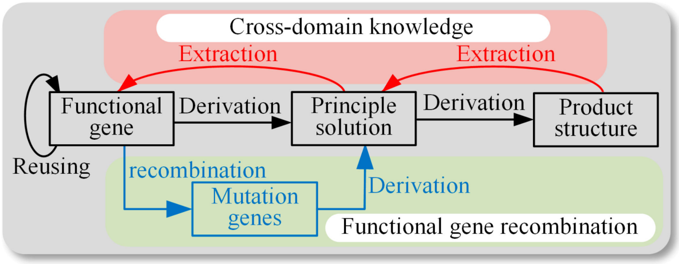

Figure 5. Functional gene central dogma. In the figure: black is the genetic path; red is the standardization path of cross-domain design knowledge; blue is the functional gene recombination mutation path.

In terms of genetics, Feng et al. [64] compared product principle scheme design with biological gene engineering and mapped them to the functional element–effect solution–principle understanding category and the central dogma of molecular biology. The process of functional element solution corresponds to the transcription and translation of genes. Based on this, Chen et al. [46] optimized the process of extracting verbs and key attributes as product functional genes. The key to product design is to transform expected functionality into structure. Li et al. [65] compared the product gene-functional principle-structure scheme with the DNA–RNA–protein process in the central dogma of molecular biology, explaining the process from functionality to functional principle and then to structure scheme. Currently, research is focused on conceptual design, and the result of gene translation is either product structure or structural principles. Wang et al. [66], on the other hand, pay more attention to product structure. They believe that the feature information of the component's functional surface serves as the product gene. By transcribing and translating the product gene, all product information is generated, and an information transmission model is established between the functional surface, component, and product. In summary of the above theories, the process of biological gene expression is combined with the product design process to provide theoretical support for the product design process. Furthermore, reverse transcription of cross-domain knowledge to obtain functional genes and then construct a design knowledge database can help reuse design knowledge to improve the efficiency of product design.

Merely reusing existing functional information is not sufficient to meet the complex and diverse design requirements. In order to enhance the innovativeness of system solutions, gene recombination and mutation play a crucial role. Li et al. [46] decomposed existing genes at random positions within the coding region and recombined the fragmented genes through base pairing, resulting in the generation of numerous new genes. These newly generated gene combinations were then screened based on design requirements and evaluation criteria. In addition to expanding existing knowledge, some scholars acquire functional genes from cross-disciplinary knowledge through reverse transcription. For example, Wang et al. [34] extracted design knowledge from patent databases, and Reich et al. [49] extracted information from multi-disciplinary engineering systems. The recombination and mutation of functional genes provide support for design innovation, ensuring the novelty of the design. Furthermore, standardizing cross-disciplinary knowledge into functional genes can provide cross-disciplinary knowledge for product design, leading to new solutions that may not be obtained due to the limitations of the designer's knowledge. This guarantees the innovativeness of design solutions.

Genetic inheritance contributes to improving the efficiency of product design, while genetic variation provides diverse solutions for product requirements. Current research on functional genes has evolved from the simple reuse of gene information to the study of genetic inheritance and variation mechanisms. With the thriving development of genetics, more biological genetic and variation processes and mechanisms are gradually becoming clear. The intersectional research between this field and product design will also be further developed.

4. Research on the Application of Functional Gene

Standard expression of product functional information helps to efficiently utilize design knowledge during the product design process. Faced with massive amounts of design knowledge, the expression, storage, and utilization of knowledge are the core aspects of researching functional genes. The following will compare and analyze the encoding forms, storage structures, and current application examples of functional genes based on biological genes.

4.1. Functional Gene Coding Forms

The effective genetic information of biological genes are determined by the arrangement order of the bases. In the DNA molecule, the arrangement order of the four bases, adenine (A), guanine (G), thymine (T), and cytosine (C), constitutes genetic information [67]. The genetic system based on DNA base sequence provides a stable way to store genetic traits [68]. Compared with traditional storage methods, using DNA as an information carrier has advantages such as high storage density [69] and low maintenance cost [70]. By imitating the form of biological DNA bases and storing data in synthetic DNA molecules, it is possible to meet the storage needs of massive amounts of data [71,72]. The idea of encoding biological genes has also been widely used in computer data storage [73], information encryption [74], quality inspection [75], manufacturing system scheduling [76], intelligent algorithm optimization [77], and other fields.

The complex and voluminous content of design knowledge poses significant challenges to traditional data storage methods. Scholars have drawn inspiration from the encoding ideas of biological genes to encode product functional information, enabling the storage of design knowledge for subsequent design use. The core of functional gene encoding is the standardized expression of functional information, which can be classified into three main categories based on different emphases: (1) expression through functional features [78]; (2) expression through functional constraints; (3) expression through input–output transformation [79].

The core of functional gene research is to facilitate the reuse of design knowledge. In order to comprehensively record functional features, components' behavioral information and structural geometric features are recorded. Hao et al. [80] expressed component behavior through geometric features and expressed functions through component behavior. The functional gene is represented as $F = f(G_1, G_2, \ldots, G_m)$, where G_m represents the specific component behavior for that function, $G_m = \{[b_i, U_c(b_i)]\}$, and $U_c(b_i)$ represents the geometric features affected by the behavior. Li et al. [81] defined the standardized form of genes as action verbs and key attributes. Based on recording functional information through physical attributes (PA), behavior (B), geometric attributes (GA), etc., they defined address (N), promoter (Start), and terminator (End), forming the gene encoding form {Start, N, PA, B, GA, End}.

The reuse of design knowledge is not a simple accumulation. The implementation of functions needs to consider the influencing conditions during the process. Huang et al. [82] proposed that the functional feature model N consists of action process features (T), action object features (P), and action condition features (C). They described the functional feature gene model of a product using the triplet N = (T, P, C). Similarly, Zhang [83] encoded functional genes as {V, O, P, EF, RP}, using "verb, object, property" to represent functional information, and enabling factors (EF) to represent constraint conditions, status features, and technical requirements.

Functionality is the understanding of a design system from a technical implementation perspective. It is an abstract description of the system's input–output parameters or state changes. To facilitate computer processing of functional genes and achieve the autonomous generation of solutions through the relationship among functional gene flows, Liu et al. [84] represented product genes using data such as input–output physical quantities and technical implementation constraints, encoding functions as {N, IPU, OPU, NP, RP, EF}. Here, N is the address, IPU and OPU represent the inputs and outputs of the function, NP represents the address of the next gene, RP represents the principle of input–output transformation, and EF represents the constraints of technical implementation. Representative forms of functional gene encoding in existing studies are summarized in Table 2.

Table 2. Functional gene coding form.

Coding Form	Coding Introduces	Feature	Constraint	Flow Transformation
$F = f(G_1, G_2, \ldots, G_m)$ $G_m = \{[b_i, U_c(b_i)]\}$ Hao et al. [80]	F: Set of functional information; G: Behavioral action features of components; $U_c(b_i)$: Geometric features affected by the behavioral action.	●	○	○
$\{Start, N, PA, B, GA, End\}$ Li et al. [81]	Start, End: Start and end codons; N: Gene address; PA, GA: Physical attribute, geometric attribute; B: Behavior.	●	○	○
$\{V, O, P, EF, RP\}$ Zhang [83]	V, O, P: Standardized expression of functional processes; EF: Enabling factor, recording constraint conditions; RP: Transcription factor, representing transcriptional status.	○	●	○
$N = (T, P, C)$ Huang et al. [82]	N: Set of functional information; T, P, C: Action object, process, condition.	○	●	●
$\{N, IPU, OPU, NP, RP, EF\}$ Liu et al. [84]	N, NP: Gene number and logical address; IPU, OPU: Input, output physical quantities; RP: Transcription factor, principle of functional implementation; EF: Enabling factor, technical implementation constraint.	○	○	●

●: Consideration; ○: Not considered.

The construction of design knowledge data is an important part of future design work. However, design knowledge suffers from defects such as abstraction and complexity, making it difficult to record and store. Constructing product functional genes by analogy with biogenetic information enables the storage of design knowledge and improves the utilization of existing product design knowledge by designers. However, as mentioned above, there is still no unified form and content for functional gene encoding, mainly due to the different research perspectives and objectives of scholars. Understanding the underlying connotation of functionality and extracting the core components of functional information still presents significant challenges.

4.2. Functional Genome Structures

The entire set of functional genes of a product system constitutes the system's functional gene structure. There are currently two forms of functional gene structure: (1) a chain-like structure based on the double-stranded DNA of biological organisms; and (2) a network-like structure based on gene regulatory networks.

Biological genetic information is stored in double-stranded DNA, which has good stability [85]. Researchers have introduced the structure of biological DNA into the field of product design, forming functional gene models with a chain-like structure. Li [86] used the correspondence between function-principle-behavior-structure and four types of nucleotides to construct a complete gene information model by recording the product's functionality, working principles, physical states, and structural parameters, forming a structurally compact double helix information model. In a simpler approach, Li [50] mapped the relationship between functional behavior and key attributes as hydrogen bonds to achieve a more fitting expression in the DNA double helix structure. Through the analysis of gene structure, the optimization of standardized structure for functional gene information can be promoted, thereby increasing the storage density of design knowledge and reducing data storage pressure. The various functional genes are connected end to end to form a functional gene chain based on gene addresses, as shown in Figure 6a.

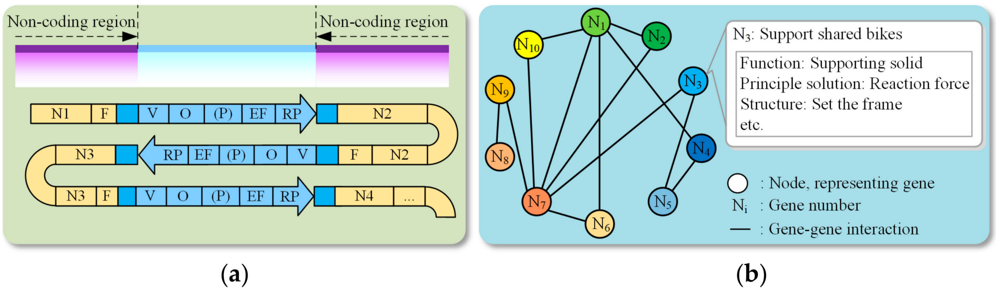

Figure 6. (**a**) Functional gene chain structure; (**b**) Functional gene network structure.

Gene regulatory networks display the relationships between genes on chromosomes [87]. Drawing inspiration from biology, some scholars construct product gene relationship networks to generate virtual product chromosomes. Taking a shared bicycle parking device as an example, the functional gene relationship network is shown in Figure 6b, with each node containing information such as behavioral attributes and structural characteristics. For acquiring node information, Chen [88,89] records parts and component lists, shapes, sizes, materials, technical specifications, etc., as nodes at different levels. Various types of nodes form a hierarchical tree-like structure, and the data or information in higher-level parent nodes are detailed by data or information in lower-level child nodes until all necessary details are provided in the last node at the lowest level. The dependency of nodes on other node information is analyzed to draw the gene relationship network. Similarly, Sun [90] constructed a complex network model for product morphology. Based on the existing network, designers selectively combine node types and groups based on requirements to complete the design process.

As mentioned above, the functional gene structure can exist in two forms: chain-like structure and network-like structure. Product functionality is not random and chaotic; the implementation of product functionality follows an execution sequence. Expressing functional groups through a chain-like structure provides a clearer demonstration of the order among functions. Additionally, according to axiomatic design theory, there are coupling relationships between functions, and the implementation of a function can be influenced by coupled functions. From the perspective of illustrating the relationships between functions, the functional gene network structure holds significant importance.

4.3. Application of Functional Genes

Functional genes are widely used in product design and can effectively improve the efficiency of knowledge reuse in the design process. Combining with gene manipulation techniques such as biological gene recombination can help generate innovative and high-quality solutions.

The efficiency of new product design plays a crucial role in the survival of enterprises [91,92]. The application of functional genes in product design can overcome the difficulties of knowledge reuse and improve product design efficiency. Wang et al. [21] proposed a product innovation process model based on functional gene extraction and construction. They used a functional similarity algorithm to retrieve product functional genes, spliced them together using flow relations, and transcribed and translated them to obtain design solutions. Zhang [83] believed that constructing a method for selecting and transcribing functional genes can clarify relevant information during the design stage, reduce blindness in the design process, shorten the product design cycle, and improve the efficiency of product design. This was validated through the design of a shared bicycle parking device, as shown in Figure 7a. Ai et al. [43] took the design of a sports water bottle as an example and standardized the functional, principle, and structural information in a design resource database. By searching for similar designs in the resource database to recombine functions, they improved the efficiency of customized product design, and achieved rapid development of customized products, as shown in Figure 7b.

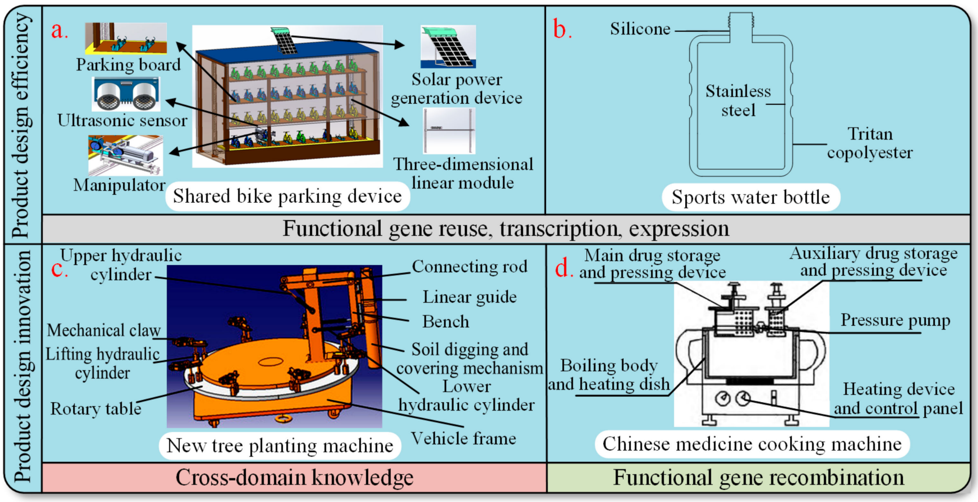

Figure 7. Examples of functional gene applications. In the figure: (**a**) is a shared bike parking device; (**b**) is a sports water bottle; (**c**) is a new tree planting machine; (**d**) is a Chinese medicine cooking machine.

Product innovation helps companies quickly occupy technological high ground [93,94]. Combined with gene recombination technology based on functional genes, a wider range of problem-solving approaches have been developed [95]. Liu et al. [96] introduced the concept of product function hybridization and used TRIZ tools to solve the problems encountered in the hybridization process. They verified the feasibility of the model by using a new type of tree-planting machine, as shown in Figure 7c. Applying hybrid design theory to product design from the perspective of function is conducive to accelerating the integration of enterprise product resources and improving market competitiveness [97]. Liu [84] used physical description gene reasoning to construct a product technology system and combined it with biological gene variation to carry out variant designs of products, taking the home-use Chinese medicine cooking machine as an example. Compared with traditional variant design, introducing the gene thinking approach demonstrated greater systematic and improved product innovation level, as shown in Figure 7d. Li et al. [50] took the unmanned planetary exploration vehicle in the aerospace field as an example, and copied, broke, crossed, and connected the genes through recombination to expand the gene set. They then evaluated and selected multiple design solutions transcribed and translated from these genes, showing that gene crossbreeding increases product innovation.

In summary, the application of functional genes mainly focuses on two aspects. Firstly, by using existing functional genes to construct a complete functional gene set, and then transcribing and expressing them to obtain design solutions to improve product design efficiency. Secondly, by using cross-domain design knowledge and gene manipulation techniques such as gene cutting and recombination, the diversity of functional gene information can be expanded to enhance product design innovation.

5. Challenges and Prospects

Although functional genes have been widely researched and applied in the process of product design, there are still many challenges in the current research related to functional genes. In the following, the current problems of functional genes and the future research outlook are described.

5.1. Genetic Information Content

In existing research, various forms of functional gene encoding have been derived for different application scenarios, resulting in different recorded information. This leads to relative fragmentation and complexity in the encoding of information. Gene information serves as the fundamental genetic information, while the product structure should be the result of transcription and translation of functional genes. Recording structural and other features in functional genes increases the integrity of stored information but reduces the diversity of functional expression results and increases the volume of information storage. In the era of data explosion [98], distinguishing gene storage information and balancing the relationship between information content and storage capacity requires in-depth research on genetic mechanisms.

In the study of encoding forms, there are two key entry points: (1) Balancing the simplicity of encoding structure and the difficulty of storing a large amount of information. Biological gene structures are simple, but they can express complex structural information through transcription and translation processes. Analyzing the essential information of functional genes should involve extracting the information obtained during the expression process to reduce the volume of gene information storage. (2) Dealing with the diversity and fragmentation of encoding forms. Based on different design requirements, it is usually reasonable to choose different encoding forms. In this case, establishing the conversion relationships between encodings can better connect different encoding forms and facilitate decentralized storage through blockchain technology [99]. Furthermore, establishing the connections between encoding forms at different stages of requirements, appearance, functionality, and manufacturing can better assist in achieving the entire product lifecycle.

Overall, further research is needed to address the challenges of functional gene encoding and explore ways to effectively store and utilize information while considering the simplicity, storage capacity, and interconnectivity of encoding forms.

5.2. Intellectual Property Protection

Extracting functional genes solely from internal product systems within a company cannot meet the design requirements. Gradually, obtaining design knowledge from various channels such as patents, interdisciplinary engineering, and resource sharing has become a solution. However, accompanying this is the issue of intellectual property rights. Protecting intellectual property rights is crucial for innovation and creativity [100] as it helps maintain fair competition and promote economic development. Infringement of intellectual property not only damages the interests of the owners but also leads to corresponding punishments for the infringers. Balancing knowledge sharing while protecting core technologies from theft remains a challenge.

To address the above-mentioned issues, a two-fold analysis can be conducted from the perspectives of being infringed upon and infringing upon others: (1) To prevent infringement by others, when storing and sharing knowledge within the enterprise, it is necessary to differentiate design knowledge. General designs can be left untreated, while key technologies that require protection can be encoded using an encoder to generate protective codes [101] to prevent unauthorized use. During the knowledge retrieval process, a decoder can be used to decode and access the protected core intellectual property. (2) To prevent the infringement of others' intellectual property, when using external databases such as patent repositories and shared design resources, it is important to analyze their protection scope. Functional genes can be marked with infringement risk indicators, allowing for screening and removal during the retrieval process, thereby eliminating the risk of infringement from the source of design knowledge.

5.3. Identification of Genetic Defects

With the increasing diversification of user demands and application scenarios, the complexity of products has been rising, leading to an intensified risk of product defects [102,103]. Product defects can include design flaws, manufacturing defects, or functional limitations. Analyzing the gene expression process, gene defects can be divided into two parts: inherent gene defects and defects generated during the expression process.

(1) With advancements in genetics, many diseases are controlled by genes or caused by genetic variations [104]. Therefore, in the product design process, measures such as diagnosing and repairing functional genes can be taken to prevent failures in the offspring subsystems. This can address the nonlinear, coupled, and irreducible characteristics of gene recombination, allowing for smooth transcription and translation to obtain design solutions. It reduces the blindness and complexity of the design process, achieving a stable inheritance of design information for excellent product design.
(2) There are still significant imperfections in the gene expression process. The realization of specific product functions is related to specific parameters [105]. By analyzing the complex coupling relationships among system parameters, conflicts in the system can be discovered during the conceptual design stage and resolved during the design stage [106]. Therefore, during the gene expression stage, monitoring and analyzing physical parameters or other information can help identify potential problems that may exist in the target system. These problems can be addressed during the conceptual design stage, reducing the number of design iterations and improving the efficiency and quality of product design.

6. Conclusions

Biosystems serve as a valuable source of knowledge for product designers, and applying the concept of biological genes to the product design process holds significant significance. At the macro level, researchers analyze the growth and behavioral mechanisms of organisms, engaging in various studies such as structural design, new material development, and bio-sensor research. At the micro level, the genetic mechanisms of biological genes provide insights for product design.

This article explicitly defines functional genes as a refinement of product genes and summarizes them as the fundamental genetic units determining the expression of product functions in the product design process. Functional genes are presented as a standardized expression collection of functional genetic information. Furthermore, the article details the five characteristics of functional genes, including independence, stability, heritability, plasticity, and adaptability, along with the information inheritance and variation paths. The coding forms and graphical expressions of functional genes are organized and analyzed. Partial examples of the application of functional genes are showcased from both the genetic and variation perspectives. Finally, the article points out the shortcomings in current research on functional genes, including unclear gene information content, incomplete intellectual property protection, and a lack of defect identification.

In conclusion, the role of functional genes manifests in 1. Improving product design efficiency through the reuse and expression of functional genes; 2. Enhancing design innovation through the acquisition of interdisciplinary knowledge and manipulation of functional gene variations. Currently, functional genes have undergone structural modeling and expression mechanism research, gradually expanding into applied research. With the rapid development of AI and the refinement of the intrinsic mechanisms of biological genes, the intelligent simulation of biological gene mechanisms through computer-assisted methods, coupled with the analysis and management of functional gene knowledge bases, will provide robust support for the quality and efficiency of product design.

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Abbreviations

Functional gene (FG): the fundamental genetic unit that determines the functional expression of products during the product design process, a collection of standardized expressions of functional genetic information. Product gene (PG): refers to the basic information unit in the process of transplantation, expansion, reproduction, and proliferation of the product in the change of time and space, and is the successor and disseminator of product science and technology. Product life cycle: It is the entire movement of a product from the time it is ready to enter the market until it is eliminated from the market, and is determined by the production cycle of demand and technology. Conceptual design: a series of orderly, organizable, and targeted design activities from analyzing user needs to generate a conceptual product, which manifests itself as a continuous evolutionary process from rough to refined, from vague to clear, from abstract to concrete.

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