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Product Innovation Design Process Model Based on Functional Genes Extraction and Construction

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Abstract: The product innovation design is an innovation-intensive process that requires abundant knowledge and design experience, even across industries and disciplines, as a resource for problem solving. Therefore, designers need to have a good command of more design knowledge in this process. However, due to varied expressions of design knowledge (function, principle, structure) in different fields lead to the difficulty in representation of design knowledge, which makes designers unable to innovate by directly using design knowledge. Therefore, to solve the problem above, this paper, analogous to biological gene, proposes a product innovation process model based on functional gene extraction and construction. The proposed process model normalizes design knowledge through functional genes and help designers acquire design knowledge in different fields, which further promotes the product innovation design. The process model consists of four following steps. First, Obtain the overall function of product based on user needs and decompose it. Second, Build the functional gene model based on digital twin ones to expand the breadth of design knowledge and facilitate the retrieval. Third, Screen similar functional gene by the functional similarity algorithm. Finally, Obtain the design scheme through recombination, transcription, and translation of the functional gene. The feasibility of the research method is verified by using a shared bicycle parking device as an example.

Keywords: functional gene; concept design; digital twin; transcribe; translate

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1. Introduction

In today's competitive marketplace, companies rely heavily on innovation to succeed [1]. And the conceptual design is the core stage of generating innovation [2–4]. In this phase, the combination of knowledge between the different levels (requirements, functional, original understanding, and conceptual solution) results in an innovative schematic solution [5]. The product design under the concept of customer-driven design, a fundamental part of the conceptual design process, is the ability to ensure that product features meet customer needs [6,7]. In this stage, designers need to use a lot of innovative knowledge and design data [8]. Conceptual design is mostly based on the reuse of existing products and knowledge inside and outside the industry [9], such as patents [10]. However, designers have difficulties in making innovative designs due to the different descriptions of design knowledge (functions, principles, and structural solutions) in different fields, which affect the generation of innovative ideas. Moreover, as the storage forms of different domain knowledge are complicated and unorganized. For example, patents are stored in the form of natural language and cases are presented in the form of physical prototypes. The product solution obtained by the designer based on complicated and disorganized knowledge is difficult to meet the user needs, which makes the product solution need multiple iterations [11,12]. Therefore, it is important to standardize the design knowledge of different fields to clarify the key information and constraints of the design.

Functional gene and product gene is a characterization method of product genetic information, which can inherit key information in the form of genes. Analogous to biological genetic processes, functional genes have the characteristics of heredity, variability, self-organization, and adaptability [13]. Functional genes and product genes are mainly related in two ways. One is that functional genes are part of product genes, and product genes include functional genes, principle genes, structure genes, etc. [14]. The other is from the perspective of function. Functional genes are equivalent to product genes and are the collection of product functional information, which can generate structural schemes through transcription and translation [15]. This paper mainly studies the extraction and construction of functional genes from the perspective of function. Therefore, the construction of functional genes can effectively improve the utilization efficiency of existing knowledge (function, principle, structure) and help designers to better carry out product innovation design. Then, to broaden the source of functional gene extraction, this paper introduces digital twins. The digital twin is an emerging information technology in recent years. It refers to the real-time simulation of a system model and data in virtual space [16]. Its rich data, knowledge, and various models provide knowledge resources for acquisition basis. Extensive studies have used DTs to improve product design. For example, DT was used in design planning and identification, conceptual design, specific design, detailed design, and virtual verification [17]. A product DT was applied to collect required data in an iterative design process of complex systems [18]. A baseline DT object-oriented framework was obtained to facilitate the collaboration of different DT classes to provide benefits above and beyond what is provided by individual DTs [19]. Therefore, applying the digital twin to the product concept design phase is a very effective method.

In summary, this paper combines functional genes and digital twins and proposes a product innovation design process model based on functional gene extraction and construction. The process model builds its functional genetic model by using the rich data, knowledge, and models of digital twins. Then the functional genes of the target products are screened using functional similarity algorithms. Next, the functional similarity algorithm is used to screen the functional genes of the target product. The functional genes screened from the parental system are "spliced" and "transcribed" as the functional principle understanding of the target system, and then "translated" into the design scheme of the target system. Finally, its digital twin model is constructed.

Contributions of this research are as follows:

- Combining functional genes and digital twins provides a rich model resource for functional gene construction. Using the rich resources of digital twins to drive the transcription and translation of functional genes that improve design efficiency.
- A system innovation design process model based on functional genes has been proposed, which effectively improves the reusability and inheritance of product functions, solves the problems that may occur in the reuse process, and shortens the design cycle of a new generation of products.

The rest of the paper is organized as follows. The second part briefly reviews the research status of product genes, functional genes, and digital twins. In the third part, the definition and coding structure of functional genes are introduced. The fourth part describes the innovation process model and its concrete steps; The fifth part is the case study, explaining how to use the proposed process model to solve the design problem. The sixth part summarizes all the research findings.

2. Literature Research

2.1. Current Research Status of Product Gene and Functional Gene

In biological research, people define genes as the basic genetic material that can transmit genetic information to the next generation, so that the next generation has the same or similar characteristics like both parents [20]. In recent years, many researchers have conducted extensive studies on the genetic problems between parental and target products [21]. And they have discovered that similar genes are also present in the product design, especially in the mechanical products [22]. For example, the product design process is compared with the biological gene expression process, and the key information in the design process is regarded as genetic information to determine the subsequent design and the manufacturing process.

At present, the concept of the product gene has not yet formed a unified that scholars have defined product genes from different angles. Gu et al. [23,24] compared biological systems, and proposed the concept of mechanical product information gene. They believed that the product information gene was standardized to a certain degree that has a certain level of versatility and similarity in the product information. Feng et al. [25] put forward the concept of "product gene" by the analogy of biological genetic process and product concept design process. The product gene was defined as heritable knowledge about product function and its realization method, which was composed of action process characteristics and solution characteristics. From the perspective of growth design, Chen et al. [26] believed that the product gene refers to a collection of information, which specified the structure of a specific product and its automatic growth mechanism. Under the suitable external environmental conditions, the specific product structure can be automatically generated and complete some functions. According to their different roles in the growth design process, they were divided into functional genes, control genes, and structural genes. Tai et al. [14] believed that the product gene is the basic information unit that determined product characteristics, including the function, principle, structure, and material information of the related product. The product gene is composed of a functional gene, principal gene, and structural gene, which determines the principal understanding of the product. Yang et al. [27] defined product genes as a standardized collection of genetically valuable information that determined the life cycle of the product. From the perspective of function, Li et al. [15] defined product gene as a collection of standardized and heritable basic information expressed by the specific function, including behavior and key attribute to realize functional element.

Research scholars apply product genes to all aspects of the mechanical field based on the heritability, variability, self-organization, and self-adaptability of product gene. Gero et al. [28] used genetic engineering, genetic algorithms, and genetic coding methods to develop an evolutionary design model. Chen et al. [29] proposed a genetic algorithm-based conceptual design approach. By using biological genetics as a blueprint, the method applied product gene to obtain the original understanding. Shang et al. [30] used functional surface for the formal representation of the product gene and constructed a conceptual design process model based on product gene. Wang et al. [31] applied genetic engineering to product design and used object-oriented technology to realize the inheritance of product information. Kumar et al. [32] proposed a feature-based functional model by finding the similarity between functional semantics and structures. The relationship between incoming knowledge and existing knowledge was determined by logical reasoning. Hao et al. [33] proposed a gene expression process model for product gene transcription and translation based on the principle of mechanical localization and kinematic pairing theory. Teng et al. [34] proposed a method to establish a gene database for mechanical products. The gene recombination and hybridization design were effectively combined to accomplish the rapid design of mechanical products. Zhu et al. [35] introduced a computer-aided conceptual design expert system (CACDESE) for energy transformation based on product genetic theory. Chen et al. [36] provided a new design theory and method for product innovation design by using genetic engineering technology. Feng and others discussed the mechanism of product genes, revealed his bridging role between functional design and principal scheme design, and finally proposed a conceptual design method based on product gene inheritance and recombination [24]. Chen et al. [37] established a conceptual structure growth design process model based on product genes and realized product design with a software system. For product variant design, Liu et al. [38] applied gene recombination and gene mutation to the product design process and proposed a product gene expression method described by physical quantity, which operated on the functional physical quantity information. This provided systematic support for modular variant design at the functional level. In recent years, product genes have also developed in the direction of intelligence. On the basis of product feature expression models and functional models, Hao et al. [39] have further decomposed product functions and maps them into features. Finally, they described them by encoding product features. The product function lays the foundation for the intelligent design of the product. Ai et al. [40] proposed an intelligent modeling method for supporting customized product modeling, which improved the efficiency of product design. Li et al. [41] proposed a conceptual design method based on product genes and combined K-mean clustering with feature selection methods to achieve intelligent acquisition of the product gene.

2.2. Research Status of Digital Twin

The in-depth integration of complex product design and manufacturing information physics is one of the key links to realizing the personalized needs of customers [42]. The emergence of digital twin provided an effective way for the consistent expression of the ideal design information of complex system and product entity state. Digital twin refers to the real-time simulation of the model and data of the system in the virtual space. The virtual model is consistent with the entities in real physical space. It is the mapping of the physical entities in the physical space and contains various models and resources. Manufacturing big data is of great significance for product life cycle management [43–45]. Researchers believe that applying digital twin technology to the design stage of complex systems is of great research significance. In 2003, the concept of the digital twin was originally proposed by Michael Grieves [46] in his product lifecycle management course at the University of Michigan. NASA has pioneered the use of digital twins in the operation and maintenance of space vehicles. They defined digital twin as a simulation process that integrated multi-physical parameters, multiscale models, and multi-probabilities to construct a fully mapped virtual model based on the physical models of aircraft (in this specific case) [47]. The digital twin was applicable to the fields of product design, manufacturing, services, operations, and maintenance [48]. Wang et al. [49] integrated digital twin (DT) with model-based systems engineering (MBSE) for the system design complexity analysis and prediction. The system model reduced ambiguity by unifying system requirements, functions, structures, and behaviors. Bachelor et al. [50] presented how DT changes how the MBSE process was managed, overcoming the issues associated with federated IT infrastructures, and tools integration. Dong et al. [51] combined digital twin and product redesign. They redesign products by means of functional remodeling, making full use of the rich data and knowledge resources in digital twins. Zhou et al. [52,53] proposed a functional model construction method of digital twins for smart products by combining the functional modeling tools in TRIZ. The functional model of the digital twin model was constructed to improve the efficiency of the application of the digital twin model. In order to improve the solution of an intelligent product service system in the conceptual design stage, Wu et al. [54] used the five-dimensional model of digital twin and the correlation of functional modeling for optimization. This approach improved the intelligence of the intelligent product service system. Nie et al. [55] used the digital twin technique to dynamically induce feature parameters and monitor the associated parameter changes due to feature parameter changes. Tao et al. [17,56] proposed a digital twin-driven product design framework, expounding the important role and application methods of digital twins in the stages of product conceptual design, concrete design, detailed design, and virtual verification. Victor et al. [18] gave the mathematical definition of digital twin in engineering design that collected data required for the design to make design decisions, clarified the iterative design of complex systems, and standardized the design process. Dassault established a digital twin 3D experience platform, which can feedback on user information to the virtual model in the product design process. It realized continuous improvement of product design and applied it to the physical model of the product to realize the information interaction of design, production, and manufacturing [57]. In order to reflect the evolution of dynamic parameters of complex electromechanical systems, Zhang et al. [58] combined digital twin with TRIZ to serve the conceptual design stage. They extracted design parameters and failure parameters in the design process that evolved the parameters to discover the potential question of the system in the design and manufacturing process. John et al. [59] developed a new digital twin design framework to obtain change in the asset life cycle of digital twin from the perspective of data architecture. This helped to study the data interaction between physical entities and virtual models. At the same time, an ontology-based design framework was developed, which provided opportunities for data and model traceability and provided a new method for the development of model-based systems engineering.

2.3. Review Summary

The above discussion reveals that the product gene and the functional gene are a good way to normalize design knowledge. This approach has worked well for standardizing design knowledge. However, the above approach to product genetics is not unified and most of them are constructed based on the knowledge of this domain, which limits designers to use design knowledge from different domains. Therefore, a functional gene construction method is proposed in this paper from a functional perspective. Secondly, the functional genes are applied to the product design process to improve the reusability and inheritance of design knowledge in the product design process. At the same time, the digital twin can provide a wealth of data, knowledge, and model resources for design engineering, facilitating designers to design new solutions. Therefore, this paper combines the two to help designers gain design knowledge from different fields, which better drives product concept design.

3. The Concept of Functional Gene and Its Coding Structure

Biological gene structure is divided into the coding regions and the non-coding region. The coding region refers to the part that can be transcribed into RNA and can synthesize the corresponding protein. The non-coding region cannot be transcribed into messenger RNA, but it regulates gene expression. Promoters and terminators belong to this region. Analogous to the structure of biological genes, the functional gene coding is divided into the coding region and the non-coding region. Through the analysis of related research on the functional gene, the expression method, meaning, characteristics, and related researchers of functional genes are summarized, as shown in Table 1.

Table 1. Table of functional gene coding form.

Serial Number	Content	Meaning	Features	Author
1	{T, P, C}	T: characteristics of the target; P: Characteristics of the action process; C: Features of the working conditions;	Advantages: Describes the essence of function well and reveals its role as a bridge between function design and principle scheme design; Insufficiency: The parameter change corresponding to the function does not involve the realization probability of the function.	Feng, et al. [25]
2	F = f(G1, G2, . . . , Gm)	G: The geometric characteristics of a specific component's behavior; m: function or sub-function is composed of m specific component behaviors;	Advantages: Use behavioral semantic models and mathematical mapping rules to link functions and geometric features. Disadvantages: This mode is more suitable for the design process of machine tool products.	Hao, et al. [39]

Table 1. *Cont.*

Serial Number	Content	Meaning	Features	Author
3	{N, IPU, OPU, NP, RP, EF}	N: the logical address of the gene; IPU: the input physical quantity of the functional element; OPU: the output physical quantity of the functional element; NP: the logical position of the next functional element; RP: transcription factor, representing the physical principle of the conversion of input and output physical quantities; EF: enabling factor, representing the constraints of product technology implementation, available resources, and another implementation related to specific technical solutions factor.	Advantages: clarify the state of the input and output physical quantities of the function in the product design process, and specify the involved sequence, principle of action, etc.; Insufficiency: The influence of the parameters corresponding to the function element on the function element needs to be quantified.	Liu, et al. [38]
4	{#i, Fi, start, Nη, Ax, Am, By, Bn, Nη + 1, end}	Fi: the ith functional element; Start: promoter, the factor that causes the functional element Fi to execute, and also the factor that induces transcription; Nη (Nη + 1): the η (η + 1) gene fragments in the functional gene address; Ax, Am: product attributes; By, Bn: acting verb; end: the factor that makes the functional element Fi perform the function and is also the factor that ends the transcription;	Advantages: clarify the key information involved in the design process and improve design efficiency; Disadvantages: The product attributes and functional verbs can be selected in a large range, which results in a lot of work in the transcription process.	Li, et al. [15,41]

Combined with the definition of function [60–63] and the related studies mentioned above, functional genes are defined as the basic genetic units that determine the functional expression of the product and are the standardized collection of genetic information about the product function. The functional genetic information here is characterized by the standardization of functions, which provides convenience for designers to use design knowledge in other fields for product innovation design. As shown in Figure 1, the coding region of a functional gene contains the main information of the function-"predicate (action, Verb) + object (action object, Object) (+property (Property)) + enabling factor (EF) + transcription factor (RP)", in which specific actions, action objects, and attributes adopt the standardized expressions in the form of input and output streams [64]. The enabling factor (EF) represents the constraints, state characteristics, and technical requirements related to the specific design scheme; the transcription factor describes the current transcription status (0: not transcribed; 1: transcribed); in the non-coding region, the address (Nj) represents the jth gene segment in the functional gene chain, FRi describes the ith function name of the product, which can retain the specific object of the product function.

Compared with the traditional functional design process, the coding of the functional gene integrates complex and disorderly functional information resources in the product design process. And it enables functional knowledge to be stored in an organized and retrievable form. This approach facilitates designers to acquire knowledge in different fields to better serve the product concept design process.

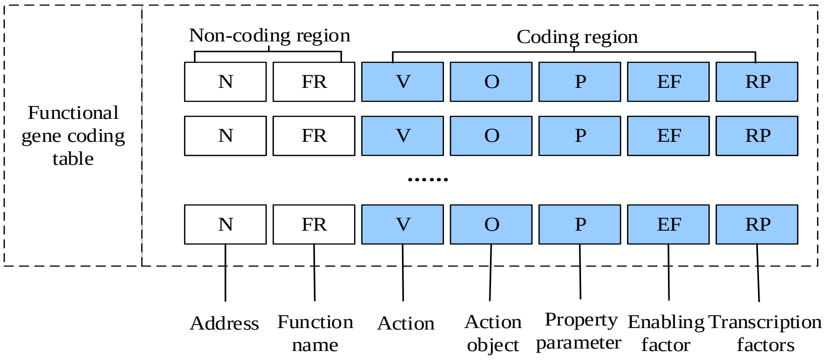


Figure 1. The coding structure of functional genes.

4. System Innovation Design Process Model Based on Functional Gene

The process model mainly includes the following eight steps, as shown in Figure 2. First, the requirement analysis and function decomposition of the target product is carried out. Second, the digital twin is extracted for normalized expression in the form of functional genes according to the coding rules. Third, according to the functional requirements of the target system, the association matrix and the importance matrix between the parental system and the target system are established. Fourth, according to the semantic similarity algorithm, the functional similarity matrix between the parental system and the target system is established. Fifth, the functional genes of the parental system were screened based on the calculation of the functional similarity matrix. Sixth, the functional genes are recombined and transcribed to obtain a functional progenitor understanding of the target product. Seventh, the recombinant functional gene is translated into a design scheme then the design scheme is evaluated, and the best design scheme is selected. Eighth, the design is carried out based on the functional genes translated into a design solution to obtain a digital twin model of the target product.

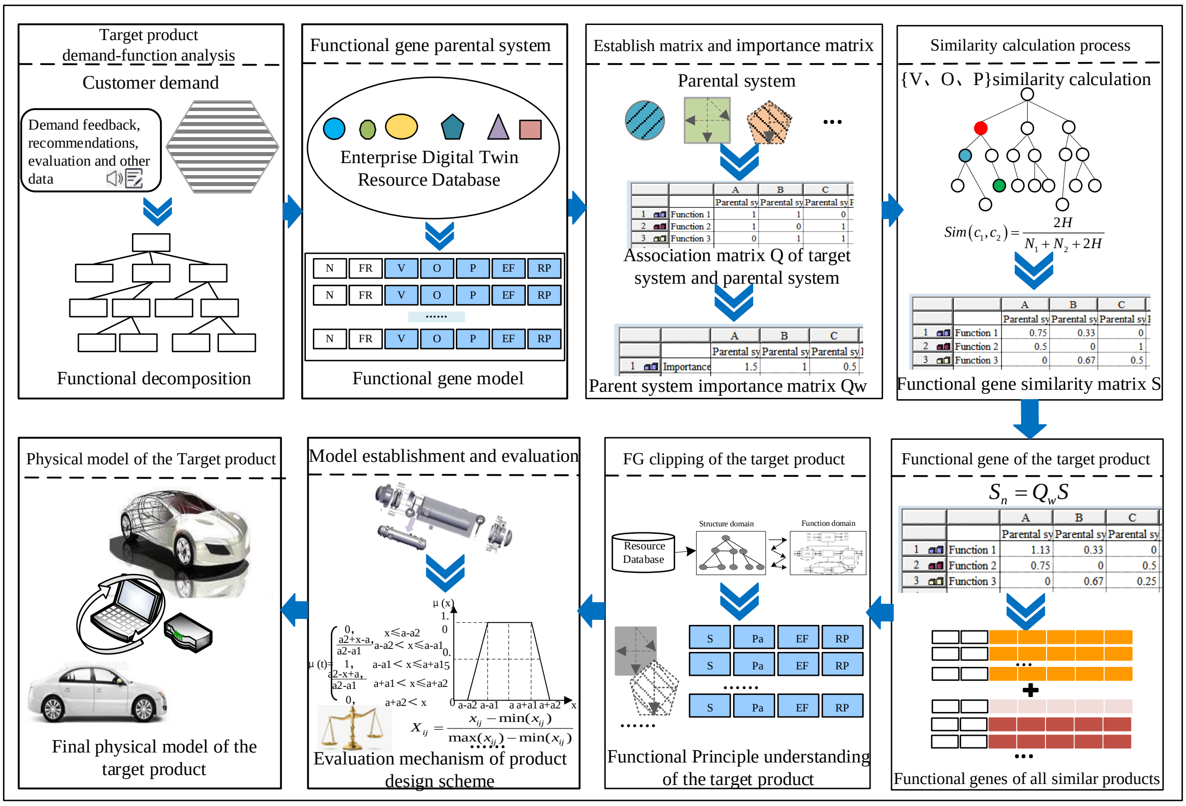


Figure 2. Product innovation design process model based on functional genes extraction and construction.

4.1. The Screening Process of the Functional Genome of the Target System

The screening process of the functional genes of the target system includes three specific steps, mainly to obtain the functional requirements of the target system, screen the parental system, and determine the functional gene of the target system.

Step A1: The functional requirements of the target system are captured.

First, the designer uses a survey system to collect data on user requirements and suggested ratings for the target product. The collected data are then subjected to word separation and annotation, deactivation, and word frequency statistics by using the jieba library. Finally, the WordCloud library is used to map the user requirements into the form of a word cloud as shown in Figure 3.

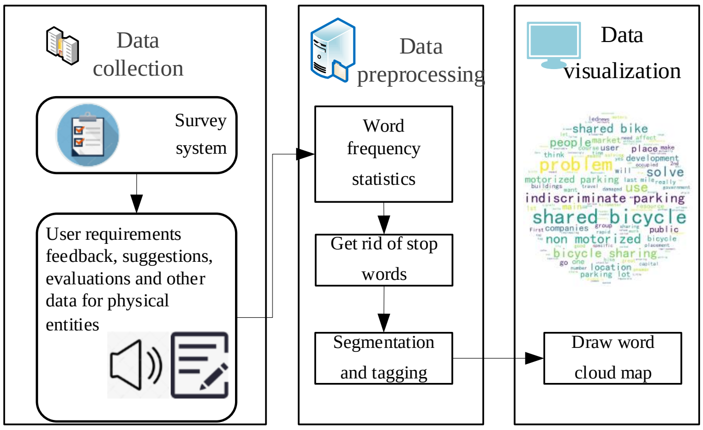


Figure 3. Process diagram of user requirements acquisition.

Next, according to the mapping relationship between user requirements-functions, the total functions of the target product are determined and decomposed into functions, as shown in Figure 4.

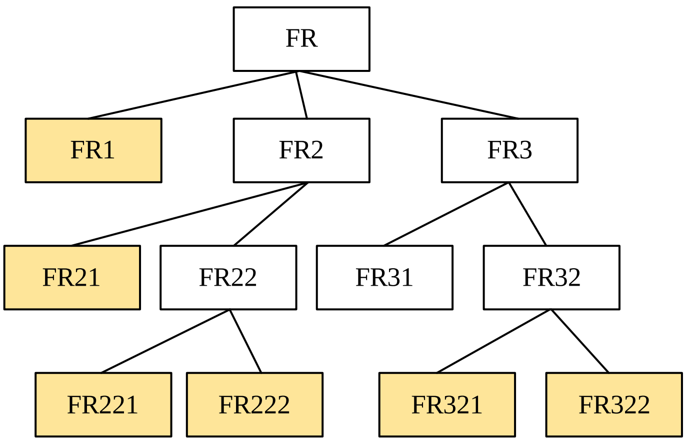


Figure 4. The functional decomposition process of the target product.

Step A2: Appropriate parental systems are screened to obtain some functional genes

After determining the function element of the child system in the previous step, the functional names are standardized into the form of {V, O, P} through the functional term set. Then, the functional gene is screened out from the enterprise digital twin resource library [65] according to {V, O, P}. The screening process is divided into the following steps. Firstly, a suitable parental system must be screened out. Then, some of the heritable functional genes are obtained from the parental system. Finally, the genetic functional gene {EF} is modified according to the specific functional requirements of the target system, so as to obtain part of the functional gene.

Step A2.1: According to {V, O, P}, the corresponding functional gene from the enterprise digital twin resource library are screened. Then, the correlation matrix Q between the target system and the parent system is obtained.

First, MySQL is used to store the functional genes of the parent system. In addition, python is used to analyze the text data between the functional gene of the parent system and the functions of the target system. Then, MATLAB is used to calculate each matrix and the three together serve the retrieval process. As shown in Figure 5, the GUI interactive interface developed based on MATLAB is friendly to operation. The specific steps are as follows.

① In the software operation interface, we can enter the functions of the target system, select appropriate words from the drop-down menus of Verb, Object, and Property, and standardize the function expression form that obtain the functional genes of the target system {FR, V, O, P}.

② Then, we retrieve the related parent system through MySQL.

③ Finally, we export the retrieved data to an excel sheet, and form the correlation matrix Q between the target system and the parent system. As shown in Table 2, where 1 represents that the functional gene of the parental system has a certain similarity with the target system {V, O, P}, and 0 represents no similarity.

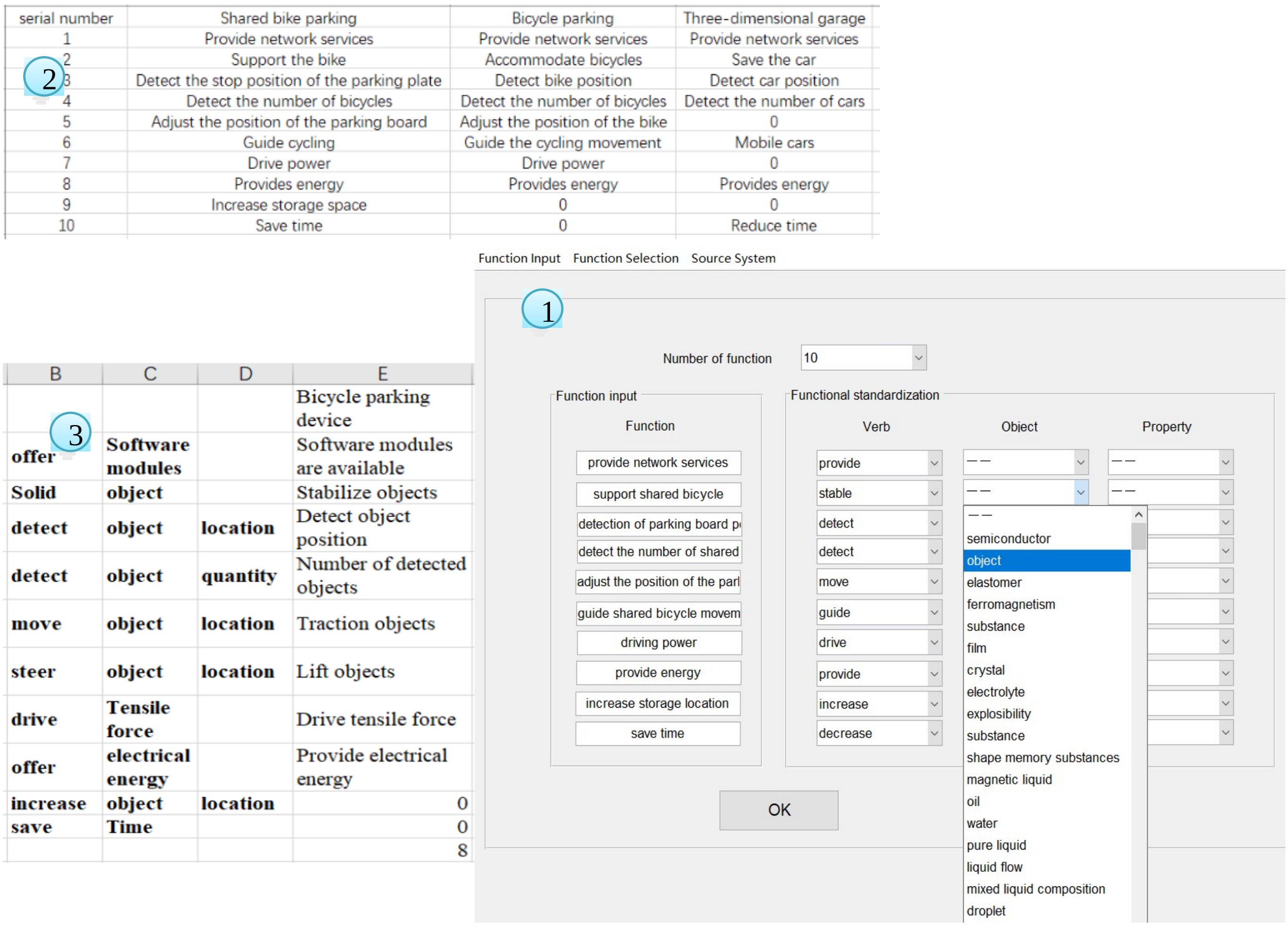


Figure 5. Retrieval process of association matrix.

Table 2. Correlation matrix Q of the target system and parent system.

Function	Parental System 1 (P1)	Parental System 2 (P2)	...	Parental System n (Pn)
$\{V_1, O_1, P_1\}$	1	0	...	1
$\{V_2, O_2, P_2\}$	0	1	...	1
...	...	...	...	
$\{V_n, O_n, P_n\}$	1	1	...	0

Step A2.2: The parental importance matrix Qw is obtained.

This step is to obtain the relative weight of each parent system and the target system (parent system importance matrix Qw), so as to provide a basis for screening the most similar parent system. Figure 6 shows the process of obtaining the parental importance matrix. The calculation formula is as follows:

$$Qw = \frac{f_j}{\overline{f}} \tag{1}$$

Among them, f_j is the total number of functions of jth parent system in matrix A, f is the average number of functions, f_j and f are obtained by Formulas 2 and 3 respectively.

$$f_j = \sum_{i=1}^{m} q_{ij} \tag{2}$$

Among them, $q_{ij} = 0, 1$ (if there is a function i in the parental system n, then $q_{ij} = 1$, otherwise, $q_{ij} = 0$) $i = 1, 2, \ldots, n$, $j = 1, 2, \ldots, m$.

$$\overline{f} = \frac{1}{n} \sum_{i=1}^{m} \sum_{j=1}^{n} q_{ij} \tag{3}$$

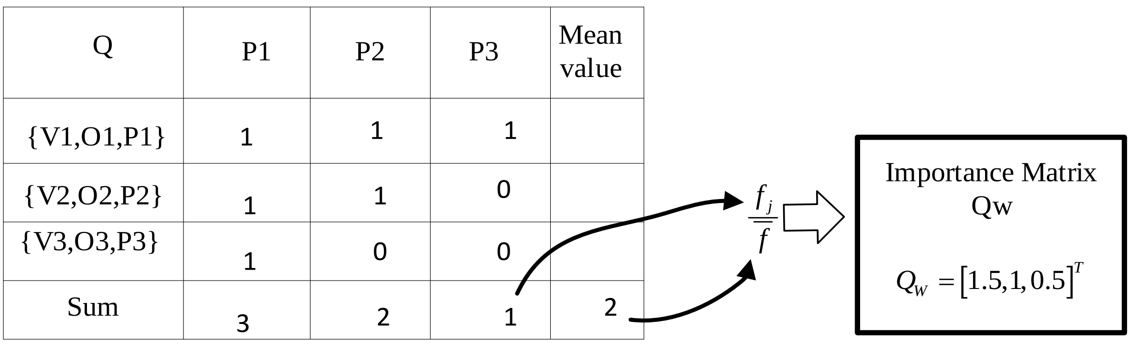


Figure 6. The process of obtaining the parental importance matrix.

Step A2.3: The similarity between the parent system and the target system is calculated.

As a preprocessing before screening the most similar parental system, it is necessary to calculate the similarity [66] of {V, O, P} in the functional gene of the parental system and the target system. The specific calculation process is as follows.

The ontology of operation set, flow set, and attribute set is based on the functions of existing products, and the similarity between {V1, O1, P1} in the functional gene of the parent system and {V2, O2, P2} in the target system is calculated according to the similarity Formula (3).

$$Sim = \begin{cases} (1-w)Sim(v_1, v_2) + wSim(o_1, o_2) \\ (1-w)Sim(v_1, v_2) + \frac{w}{2}(Sim(o_1, o_2) + Sim(p_1, p_2)) \end{cases} \tag{4}$$

Among them, v_1 and v_2 belong to the operation set, o_1 and o_2 belong to the flow set, p_1 and p_2 belong to the attribute set. According to the normalized expression of the target system function, it is judged whether the attribute p_1 exists, and w is the weight coefficient, which is chosen as 0.3 in this paper.

First, the ontologies for the operation set, stream set, and attribute set are created [64]. Then the distances between functional verbs, stream nouns, and attribute sets are calculated according to Equation (5). Finally, after weighting and transformation, the similarity of the functions is obtained. The ontology similarity is calculated as shown in Figure 7.

$$Sim(c_1 \quad c_2) = \frac{2H}{N_1 + N_2 + 2H} \tag{5}$$

where c_1 and c_2 are two ontology nodes, N_1 and N_2 are the nearest distances from c_1 and c_2 to their common nodes, respectively, and H is the distance from c to the root of the ontology tree, as shown in Figure 7, and its similarity can be calculated by using Equation (5). Results of the calculation of functional similarity is calculated as $Sim(c_1 \quad c_2) = \frac{2\times1}{1+2+2\times1} = 0.4$.

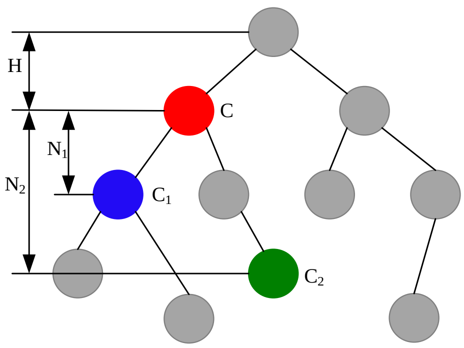


Figure 7. Schematic diagram of ontology similarity.

The different levels of classification of operation sets, flow sets, and attribute sets correspond to different levels in the tree diagram and need to be coded for similarity. The similarity between basic operations under the same class of operations is 0.5. For example, the similarity of the basic operations' "synthesis" and "production" in the operation set is calculated as $Sim(c_1 \quad c_2) = \frac{2\times1}{1+1+2\times1} = 0.5$. The size of the similarity between the class operation and its corresponding basic operation is 0.67. The similarity between the basic operations "change" and "increase" is calculated as $Sim(c_1 \quad c_2) = \frac{2\times1}{1+0+2\times1} = 0.67$. The similarity between basic operations and synonyms is brought into the formula of semantic similarity, which is calculated as $Sim(c_1 \quad c_2) = \frac{2\times2}{1+0+2\times2} = 0.8$. Similarly, in the flow set, the similarity of the same sub-flow is 0.67, and the similarity of tertiary flows of the same class but different sub-flows is 0.33. In the property set, the similarity between "density" and "yield point" under the same mechanics is 0.75. The similarity in mechanics and thermodynamics is calculated as 0.5, and the similarity between substance-solid and substance-property is calculated as 0.25.

Step A2.4: Normalization of the similarity matrix

As shown in Figure 8, according to Formula (6), the parental system importance matrix Qw is combined with the {V, O, P} similarity matrix S to obtain the normalized parental similarity matrix Sn to complete the standardization of the parental system similarity matrix.

$$Sn = QwS \tag{6}$$

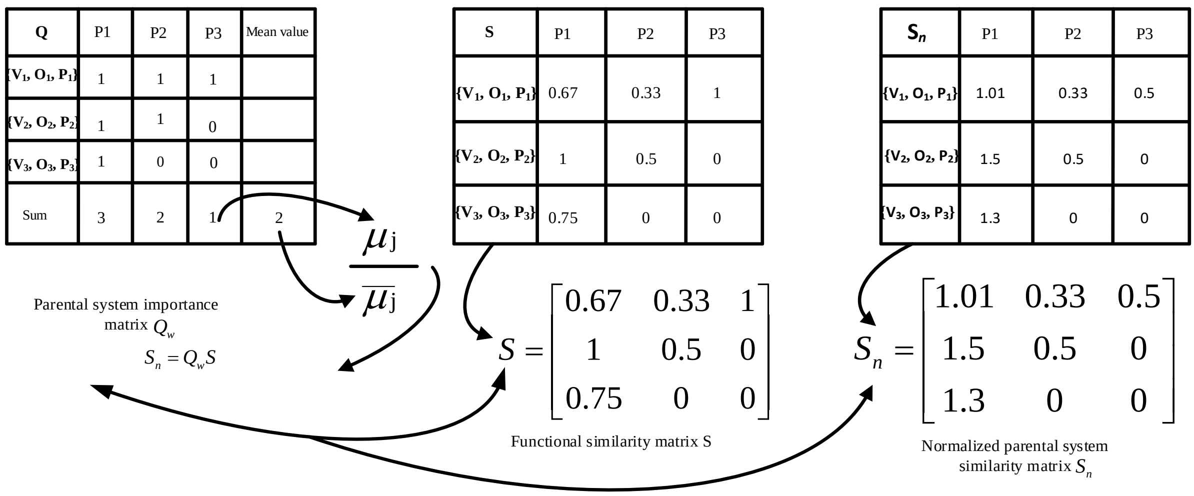


Figure 8. The standardization process of the similarity matrix of the parental system.

According to the above steps, the corresponding heritable functional gene can be screened from the parental system, and then the {EF} in the genetic functional gene of the parental system can be modified according to the specific requirements of the target system, thereby obtaining part of the functional genome of the target system. The functional gene not obtained in the enterprise digital twin resource library will be obtained in the next step.

Step A3: The functional genome of the target system is complemented.

For the functional gene that has not been screened in the corporate digital twin database, patent resources are used to supplement them to complete the determination of all the functional gene. The specific process is as follows.

(1) The Python Synonyms toolkit is used to generalize the next generation functional words, so that the expanded variant of {V, O, P} in the functional gene is derived.
(2) A patent set is preliminarily screened out by searching patent documents in the Internet patent database using extended variant words.
(3) The Python-based third-party library is used to perform sentence segmentation, word segmentation, part-of-speech tagging and stop word removal on the preliminarily screened patent abstracts, identifying and determining functions of the preliminary screening patent set. Users can obtain patent resources containing the next-generation functional genes.
(4) According to the user requirements of the target system, the {EF} information is modified and supplemented into the next-generation functional gene, which provides the basis for the transcription and translation of subsequent functional genes.

4.2. The Functional Gene Expression Process of the Target System

Based on the similarity between product conceptual design and biological genetic process, in order to reuse and stably inherit functional information to target products, the most basic function of the product is compared with the most basic unit of biological chromosomes-genes. Functional genes are like those that carry genetic material. DNA fragments and functional sources containing structural information are analogous to proteins, and the intermediate process from function to structure can be regarded as the expression process of functional genes [38]. As shown in Figure 9, the analysis is carried out from the three parts corresponding to the biological gene expression process and the system design process: DNA segments that carry genetic material correspond to genes and functional genes; the processing of RNA corresponds to the acquisition of functional principle understanding; translation of biological proteins corresponds to the generation of system plans. The biological gene expression process is the transcription of DNA to generate RNA, and the translation of RNA to generate protein. The corresponding product design process is the transcription of functional genes into functional principle understanding, and the functional principle understanding into system solutions.

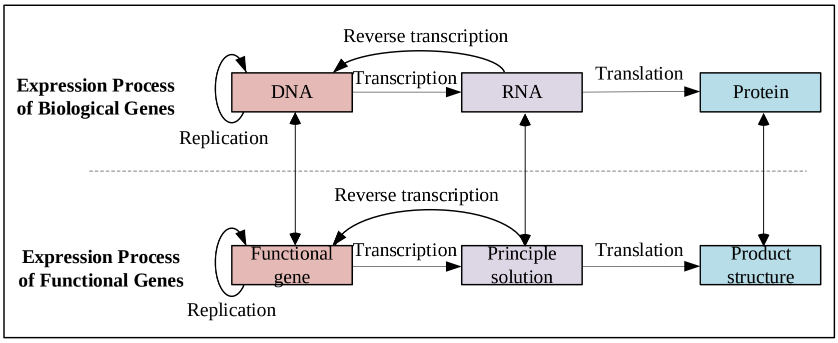


Figure 9. Biological gene expression process and product design process.

Drawing on the similarity between the biological genetics and the product design process, the functional gene expression process of the target system is shown in Figure 10. With the support of the corporate digital twin resource library and patent resources, the functional gene is transcribed to the design scheme. In the process, the functional gene of the target system was first transcribed to obtain the corresponding functional principle understanding of the parental system {S, Pa, EF, RP}. Then, the enabling factors {EF} were compared to improve {S, Pa, EF, RP} that the improved functional principle is {S', Pa', EF, RP}. Finally, the functional principle is translated to obtain the design scheme of the descendant system. This section mainly contains three specific steps.

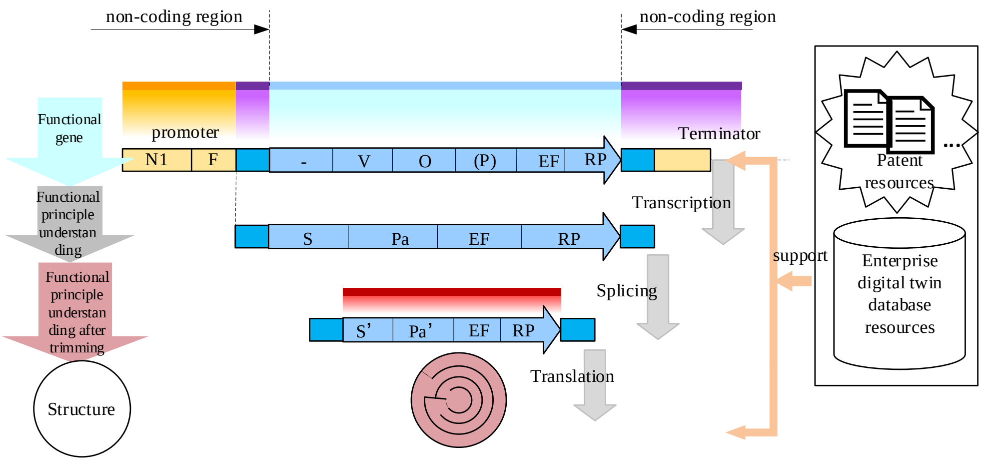


Figure 10. The expression process of functional genes in the target system.

Step B1: Functional gene is transcribed into functional principle understanding.

Functional principle understanding is to find the corresponding structural information (S) and physical parameters (Pa) based on functional gene. The method of acquiring functional principle understanding is divided into two steps.

Step B1.1: Enterprise digital twin repository drives functional gene transcription to functional principle understanding.

Based on AD theory [67,68] and related data obtained from digital twin, the mapping relationship of the existing product "function-structure (parameter)" and the correlation matrix can be established. In addition, the mapping between the product module library and the product knowledge base is completed. They are stored in the enterprise digital twin resource library, and the functional principle corresponding to the functional gene {S, Pa, EF, RP} can be queried from it.

Step B1.2 Proprietary resources drive functional gene transcription to functional principle understanding.

The new functional principle understanding {S, Pa, EF, RP} is obtained from the structural information (S) and physical parameters (Pa) corresponding to the functional gene obtained in the patent resource. First, all the elements in the relevant patents are obtained through pattern matching from the claims; then, the Apriori algorithm is used to find the most frequent combination of elements that can achieve the next-generation function; finally, the sentences describing the frequent elements are found in the claim text. The structure and parameter information in the sentences related to the frequent elements are mined that the functional principle understanding is also obtained.

Step B2: The functional principle understanding is spliced.

Functional gene splicing is to make the functional gene of the product transcribed and translated into a feasible design scheme. In the process of screening the functional gene, the functional gene needs to rely on the relevant genetic information carried by the functional gene of the parental system, and certain processing can be carried out to obtain the functional principle understanding of the target system. The splicing of functional gene is divided into the understanding of the function and the determination of the functional gene {Ni}.

Step B2.1 The functional principle understanding of the target system is improved.

According to the principle of analogy source design [69,70], the relationship between parental system functional gene A, parental system functional principle understanding B, and target system functional gene A' and target system functional principle understanding B' is established, as shown in Figure 11. B can be obtained from A, and there is a mapping relationship β between the two; from A to A', there is a similar relationship; then there is a mapping relationship β' between A' and B', and there is also a similar relationship between B and B'. Therefore, in the process of designing the target system, the target system functional gene understanding B' is obtained according to the functional gene A of the parent system, the principle l understanding B, and the target system functional gene A'.

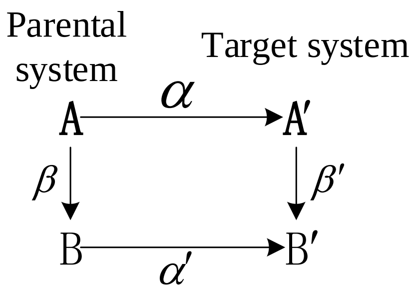


Figure 11. The process of obtaining the principle understanding of the next generation function.

Step B2.2 The storage address {Ni} of the functional gene is determined.

First, the fusion process of the functional gene needs to be analyzed. The type of complexity existing in the target system is judged by the DCC [71–73], and the TRIZ tool is used to solve the morbid characteristics of the target system so that the functional principle understanding is improved. In order to obtain the design plan, it is necessary to further determine the address of the functional gene and establish the "functional cycle" of the target system. In DCC theory, the functional cycle is defined as a set of functional requirements that are repeated in the base cycle [74]. The functional requirements of the system are realized by a set of functions. The function cycle is the sequence of execution of functions in the system [75,76]. When the system runs continuously and repeatedly along this set of functional sequences, the functional requirements of the system can always be realized. The functional cycle is a fundamental requirement for the system to maintain stable operation.

As shown in Figure 12, the process of determining the address of the functional gene of the target system can be based on the relationship between the functional gene of the parent system, the connection of elements, the relationship between input and output flows, and the relationship between matter and field. By combining the above four relationships to adjust the address of the functional gene, the "functional cycle" of the target system can be obtained to reduce the complexity of the target system that the designer can obtain the design scheme.

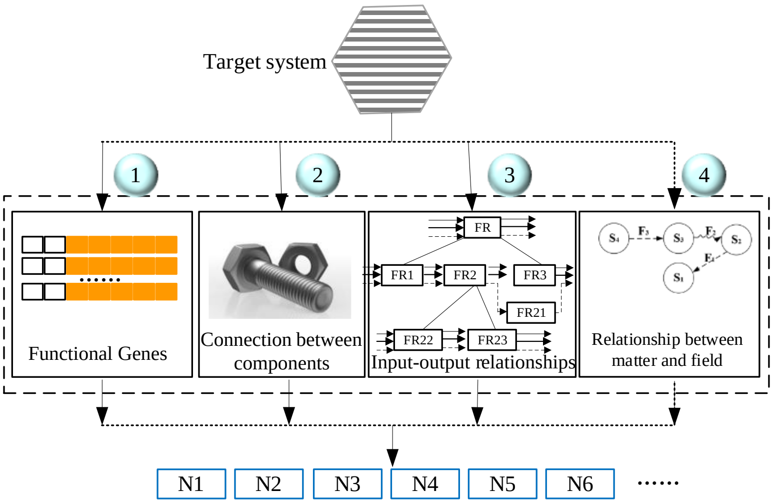


Figure 12. The process of determining the functional gene address.

4.3. Program Evaluation

Comprehensive customer needs and the difficulty of the design plan are evaluated to determine the most suitable design scheme. In this paper, the fuzzy number evaluation mechanism [77] is combined with the gray correlation method [78] to evaluate the design plan qualitatively and quantitatively.

(1) The qualitative evaluation index level set is defined as {good, good, fair, poor, bad}. The area enclosed by the membership function curve of the design scope is defined as the fuzzy design scope. Then the area enclosed by the membership function curve of the system scope is defined as the fuzzy system scope, and the intersecting part of the fuzzy design scope and the fuzzy system scope is defined as the fuzzy common scope. In this paper, the trapezoidal distribution function is used as the fuzzy membership function of the qualitative evaluation index of the design scheme.

(2) According to the evaluation index level of each design scheme, the fuzzy system scope of each index and fuzzy public scope can be determined, and Formula (7) is used to calculate the fuzzy information amount I of each scheme for each index.

$$I = \log_2 \frac{\text{fuzzy system scope}}{\text{ambiguous public domain}} \tag{7}$$

(3) Formula (8) is used to normalize the original data.

$$X_{ij} = \frac{x_{ij} - \min(x_{ij})}{\max(x_{ij}) - \min(x_{ij})} \tag{8}$$

Among them, x_{ij} is the original independent index, and X_{ij} is the normalized data. If X_{ij} is negative, Formula (9) is used.

$$X_{ij} = \frac{\max(x_{ij}) - x_{ij}}{\max(x_{ij}) - \min(x_{ij})} \tag{9}$$

(4) The ideal index set is defined as Formula (10), and the canonical index set is defined as Formula (11).

$$X_0 = \{x_{01} \quad x_{02} \quad \ldots \quad x_{0n}\} \tag{10}$$

$$X_i = \{x_{i1} \quad x_{i2} \quad \ldots \quad x_{in}\}, (i = 1 \quad 2 \quad \ldots \quad m) \tag{11}$$

Among them, n represents the number of evaluation indexes, and m represents the number of design schemes.

(5) The absolute value of the maximum and minimum values between the design schemes is calculated by Formulas (12)–(14).

$$\Delta_{ik} = |x_{0k} - x_{ik}| (i = 1, \quad 2, \quad \ldots \quad m; k = 1, \quad 2, \quad \ldots \quad n) \tag{12}$$

$$\Delta_{\min} = \min_i \min_k |x_{0k} - x_{ik}| \tag{13}$$

$$\Delta_{\max} = \max_i \max_k |x_{0k} - x_{ik}| \tag{14}$$

Δ_{ik} represents the absolute value of the difference between x_{0k} and x_{ik}, $\Delta_{\min}$ and $\Delta_{\max}$ represents the minimum and maximum values of Δ_{ik}.

(6) The gray correlation coefficient ζ_{ik} is determined by Formula (15).

$$\zeta_{ik} = \frac{\Delta_{\min} + \sigma\Delta_{\max}}{\Delta_{ik} + \sigma\Delta_{\max}} \tag{15}$$

Among σ is the identification coefficient, $\sigma \in [0, \quad 1]$, when $\Delta_{ik} = \Delta_{\min}$, $\zeta_{ik} = 1$, the correlation is the largest; when $\Delta_{ik} = \Delta_{\max}$, $\zeta_{ik} = 0$, the correlation is the smallest. Therefore, $\zeta_{ik} \in [0, \quad 1]$.

(7) The gray correlation degree r_{ik} is calculated by Formula (16).

$$r_{ik} = \frac{1}{n}\sum_{i=1}^{n} \zeta_{ik}(t) \tag{16}$$

r_{ik} is the gray correlation coefficient of the nth scheme specification index set.

(8) From steps (3)–(7), the size of the quantitative evaluation index in the design plan can be calculated. Then The evaluation value S of a single scheme is calculated by Formula (17).

$$S = \sum_{a=1}^{n} I_a - r \tag{17}$$

(9) By sorting the evaluation value S of the scheme, the most suitable design scheme is obtained.

5. Case Verification

Since the first batch of shared bicycles appeared on the Peking University campus in 2014, shared bicycles have been accepted by more and more users due to their convenient use and low payment. Major businesses have also been put into production. Therefore, the number of shared bicycles is approaching. There has been explosive growth in the past few years, and more than 500 cities around the world have been equipped with shared bicycle rental systems. Due to deficiencies in the planning and design of urban public spaces, lack of supporting public services, related systems, and management, etc., these problems that random parking of shared bicycles and crowded parking of shared bicycles have appeared. To solve these problems, it is necessary to consider how to use less land area and park more bicycles.

The current shared bicycle parking device is expensive, and the space utilization rate is low, and it is not suitable for large-scale use in various public places. Several common shared bicycle parking devices are listed below. As shown in Figure 13, they are the common parking device, the double-layer three-dimensional parking device, and the ferries wheel parking device.

(a) (b) (c)

Figure 13. (**a**) Common parking device, (**b**) Double-layer three-dimensional parking device, and (**c**) Ferris wheel parking device.

5.1. Functional Gene Screening of Shared Bicycle Parking Devices

Step A1: The demand for shared bicycle parking devices is analyzed.

In this paper, the user demand for shared bicycle parking devices is obtained based on the results of a survey conducted by Yueqing Institute of Technological Innovation on the use of shared bicycles in recent years. The relevant data and user requirements of the shared bicycle parking device are analyzed through the python language as shown in Figure 14. Therefore, it is necessary to design a shared bicycle parking device with high space utilization, small footprint, and convenient access. The constraints are energy saving and simultaneous access for multiple people.

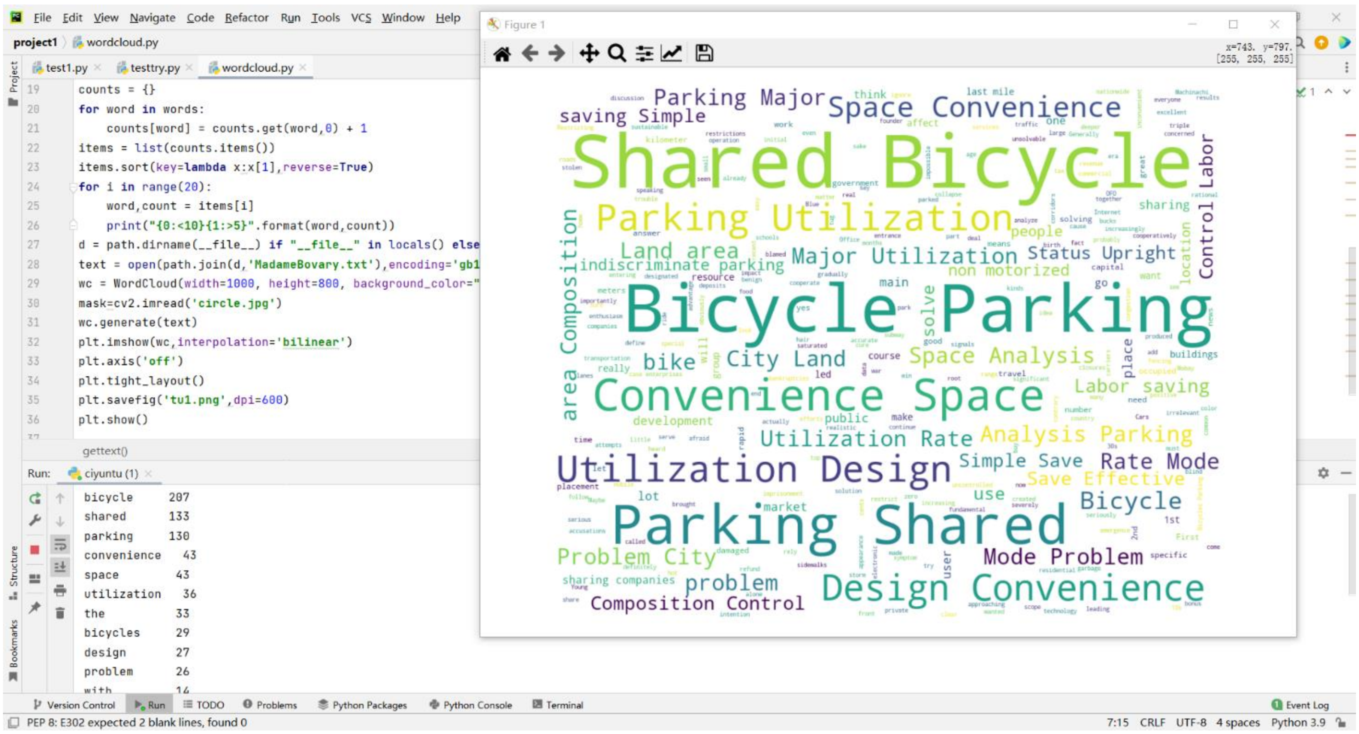


Figure 14. Word cloud of user requirements for the shared bicycle parking devices.

According to the user requirements and constraints, the shared bicycle parking device is first decomposed to obtain the total function requirement (FR). FR represents that intelligent access shared bicycles, and then the FR is decomposed into sub-functions until the smallest functional element is obtained. The function tree of the target system is shown in Figure 15.

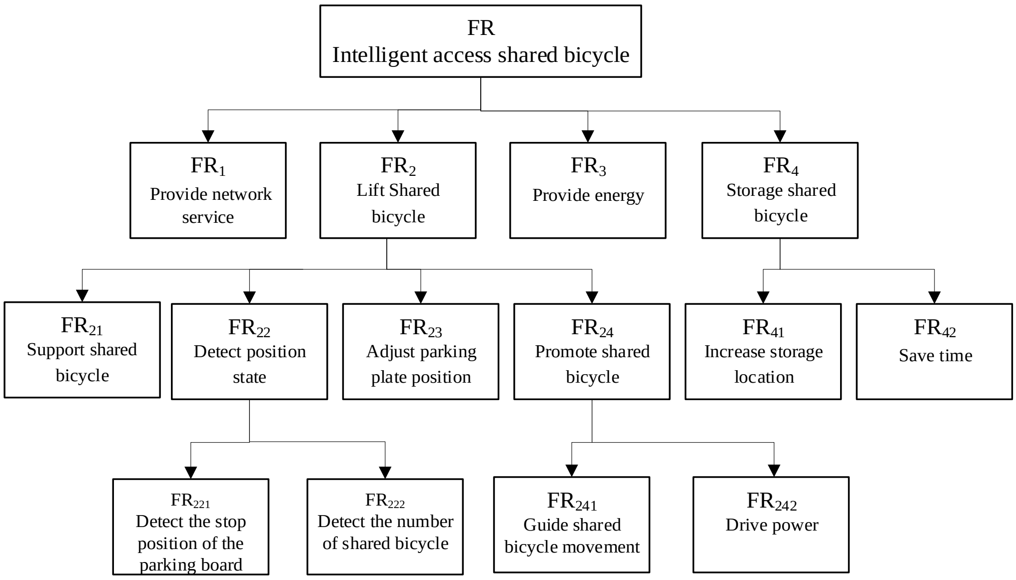


Figure 15. Schematic diagram of functional decomposition of shared bicycle parking device.

In order to facilitate the screening of the functional gene of the shared bicycle parking device, the functional names are standardized by using the functional terms centralized operation set, flow set, and attribute set to obtain the {FR, V, O, P} of the functional gene. This paper uses the GUI in MATLAB to establish a search interface, as shown in Figure 16. The user enters the decomposed function name of the shared bicycle parking device, and then they select the appropriate Verb, Object, and Property as the standardized expression of the function. Finally, they click OK to get the relevant parental system.

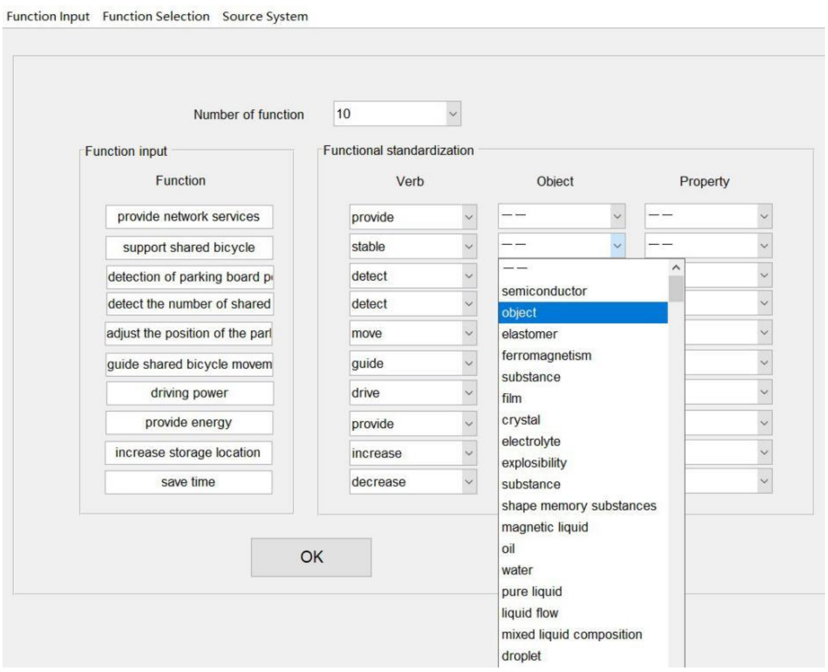


Figure 16. Shared bicycle parking device function normalization process and search interface.

Step A2: A portion of the functional gene is obtained from the screened parental system. First, the target system is a shared bicycle parking device. According to the {FR, V, O, P} in the shared bicycle parking device functional gene, the results of retrieving the knowledge, data, and model resources of related products in the enterprise digital twin resource library are shown in Figure 17. The parent system of the shared bicycle parking device includes a bicycle parking device, three-dimensional garage, tower elevator, electronic weight scale, conveyor, vending machine, crane machine, automatic lifting clothes pole, and automatic control door.

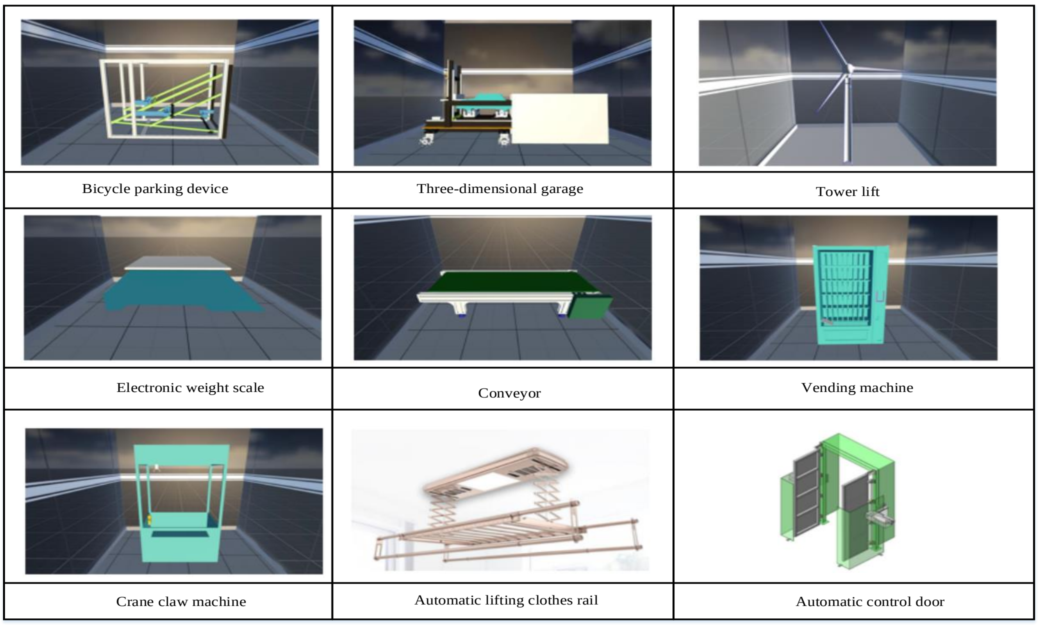


Figure 17. Results of parent system retrieval.

Step A2.1–A2.4:

The correlation matrix Q between the shared bicycle parking device and the parent system is obtained from the correlation between the shared bicycle parking device functional gene and the parent system functional gene, as shown in Table 3. According to the correlation matrix Q between the shared bicycle parking device and the parent system, the average number of functions and the total number of functions of each parent system are obtained, and the parent importance matrix is Qw = [1.439, 1.259, 1.259, 0.719, 0.899, 1.079, 0.899, 0.719, 0.719].

Table 3. Association matrix Q between shared bicycle parking device and parent system.

Q	Bicycle Parking Device	Three-Dimensional Garage	Tower Lift	Electronic Weight Scale	Conveyor	Vending Machine	Crane Claw Machine	Automatic Lifting Rack	Automatic Control Door
FR_1	1	1	1	1	0	1	1	0	0
FR_{21}	1	1	1	1	1	1	1	1	0
FR_{221}	1	1	1	0	1	1	0	0	1
FR_{222}	1	1	1	1	0	1	0	0	0
FR_{23}	1	0	1	0	0	0	1	1	1
FR_{241}	1	1	0	0	1	1	1	1	1
FR_{242}	1	0	1	0	0	0	0	0	0
FR_3	1	1	1	1	1	1	1	1	1
FR_{41}	0	0	0	0	0	0	0	0	0
FR_{42}	0	1	0	0	1	0	0	0	0

Table 4 shows the similarity of {V, O, P} in the functional gene of the parental system and the functional gene of the shared bicycle parking device.

Table 4. {V, O, P} similarity matrix S.

S	Bicycle Parking Device	Three-Dimensional Garage	Tower Lift	Electronic Weight Scale	Conveyor	Vending Machine	Crane Claw Machine	Automatic Lifting Rack	Automatic Control Door
FR_1	1.00	1.00	1.00	1.00	0.00	1.00	1.00	0.00	0.00
FR_{21}	0.86	0.77	0.86	0.86	0.30	0.77	0.77	0.77	0.00
FR_{221}	1.00	1.00	1.00	0.00	1.00	1.00	0.00	0.00	1.00
FR_{222}	1.00	1.00	1.00	1.00	0.00	1.00	0.00	0.00	0.00
FR_{23}	0.71	0.00	0.86	0.00	0.00	0.00	0.86	1.00	1.00
FR_{241}	0.77	0.77	0.00	0.00	0.77	0.62	0.77	0.77	1.00
FR_{242}	1.00	0.00	0.77	0.00	0.00	0.00	0.00	0.00	0.00
FR_3	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
FR_{41}	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
FR_{42}	0.00	1.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00

The normalized parental similarity matrix Sn is obtained by Formula (6), as shown in Table 5. According to Table 5, the most similar parent system is determined as the bicycle parking device, as shown in Figure 18.

Table 5. {V, O, P} similarity matrix Sn.

S	Bicycle Parking Device	Three-Dimensional Garage	Tower Lift	Electronic Weight Scale	Conveyor	Vending Machine	Crane Claw Machine	Automatic Lifting Rack	Automatic Control Door
FR_1	1.44	1.26	1.26	0.72	0.00	1.08	0.90	0.00	0.00
FR_{21}	1.24	0.97	1.08	0.62	0.27	0.83	0.69	0.55	0.00
FR_{221}	1.44	1.26	1.26	0.00	0.90	1.08	0.00	0.00	0.72
FR_{222}	1.44	1.26	1.26	0.72	0.00	1.08	0.00	0.00	0.00
FR_{23}	1.02	0.00	1.08	0.00	0.00	0.00	0.77	0.72	0.72
FR_{241}	1.11	0.97	0.00	0.00	0.69	0.67	0.69	0.55	0.72
FR_{242}	1.44	0.00	0.97	0.00	0.00	0.00	0.00	0.00	0.00
FR_3	1.44	1.26	1.26	0.72	0.90	1.08	0.90	0.72	0.72
FR_{41}	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
FR_{42}	0.00	1.26	0.00	0.00	0.90	0.00	0.00	0.00	0.00

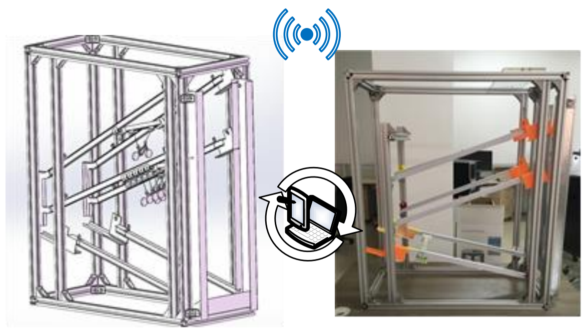


Figure 18. The bicycle parking device.

The functional genome of the bicycle parking device was retrieved from the corporate digital twin resource library, as shown in Table 6, including its enabling factor (EF) and transcription factor (RP).

Table 6. Functional genome of bicycle parking device.

N	FR	V	O	P	EF1	EF2	EF3	RP
#1	Provide energy	Provide	electricity		Power generation	Voltage 220 V	Number of power ports	0
#2	Provide network services	Provide			Response time T < 15 s	Processing speed	Coverage	0
#3	Accommodating bicycles	Stable	object		Number of storages	Size of space	Easy to operate	0
#4	Detect bicycle position	Detect	object	position	Response time	Measurement accuracy	Sensitivity	0
#5	Traction bicycle exercise	Guide	object	position	Traction direction	Motion accuracy	Automation	0
#6	Adjust the bicycle position	Mobile	object	position	Moving distance	Moving speed	Reliability	0
#7	Detect bicycle position	Detect	object	position	Detection accuracy	Detection distance	Response time	0
#8	Detect the number of bicycles	Detect	object	quality	Detection accuracy	Accuracy	Response time	0
#9	Free bicycle	Take out	object		Response time	Easy to operate	Stability	0
#10	Recycling suspension rod	Transfer	object		Response time	Endurance range	Automation	0

Step A3: Supplement the functional gene of the shared bicycle parking device.

On the basis of the most similar parent system, the functional gene of the shared bicycle parking device is constructed.

First of all, the similar or identical {V, O, P} of the most similar parent system and the shared bicycle parking device is retained such as FR_1 to provide network services, FR_{21} to support shared bicycles, FR_{221} to detect the stop position of the parking board, FR_{222} to detect the number of shared bicycles, FR_{23} adjusts the stop position of the parking board, FR_{241} to guide the shared bicycle movement, FR_{242} to drive power, and FR_3 to provide energy. Secondly, for FR_{42} to save time, you can filter from stereo garages and tower elevators. Through comparison, it is found that the similarity of stereo garages is higher. Therefore, the functional gene corresponding to stereo garages is selected to be added to the functional genome of the shared bicycle parking device. For the above screening, the functional gene FR_{41} that is not found in the parental system, and the patent resources are used to obtain the expanded patent set of "increased storage location". Therefore, the {EF} of this functional gene is obtained. Through screening from the parental system and patents, a functional genome similar to that of the shared bicycle parking device is determined. In order to obtain the functional genome of the shared bicycle parking device, it needs to be modified {EF} according to the functional requirements of the product. After the modification, the functional genome is obtained, as shown in Table 7.

Table 7. Functional genes of shared bicycle parking devices.

N		FR	V	O	P	EF1	EF2	EF3	RP
#1	FR_1	Provide network services	Provide			Response time T < 15 s	Processing speed	Coverage	0
#2	FR_{21}	Support shared bicycles	Stable	object		Can store 60 volumes	Endurance range	Easy to operate	0
#3	FR_{221}	Detection of parking board position	Detect	object	position	Response time	measurement accuracy	Sensitivity	0

Table 7. *Cont.*

N		FR	V	O	P	EF1	EF2	EF3	RP
#4	FR_{222}	Detect the number of shared bicycles	Detect	object	quality	Detection accuracy	Accuracy	Response time	0
#5	FR_{23}	Adjust the position of the parking board	Move	object	position	Move distance	Moving speed	reliability	0
#6	FR_{241}	Guide shared bicycle movement	Guide	object	position	Direction	Motion accuracy	automation	0
#7	FR_{242}	Driving power	Drive	Stretching force		Tolerance range	Conversion efficiency	automation	0
#8	FR_3	Provide energy	Provide	electricity		Power generation	Voltage 220 V	Number of power ports	0
#9	FR_{41}	Increase storage location	Increase	object	position	Parallel operation	Processing speed	Easy to operate	0
#10	FR_{42}	Save time	Decrease	duration		Response time		Easy to operate	0

5.2. Expression of the Functional Gene in the Shared Bicycle Parking Device

By analogy with the related theory of gene expression in the biological genetic process, the expression process of the functional gene of the shared bicycle parking device is that the functional gene is transcribed to the functional principle understanding. Finally, the functional principle understanding is translated to the design scheme.

Step B1: Based on all the functional genes, the functional principle of shared bicycle parking device is determined.

Through the previous section, the functional gene of the shared bicycle parking device is determined. In this section, it is necessary to call the enterprise digital twin resource library and patent resources to obtain the functional principle understanding of the shared bicycle parking device. Among them, the FR_1 to FR_3 are originally understood as the corresponding parts of the bicycle parking device: software modules, parking devices with multi-layer tracks, ultrasonic sensors, photoelectric sensors, lifting mechanisms, slot trolleys, pulleys and solar power generation devices. The parking lock of the three-dimensional garage is used as the principle understanding of FR42. The functional principle of FR41 is to park bicycle rails side by side, which is obtained by information extraction and text analysis of 53 patents which are roughly screened from 3678 related patents in 2017–2019. The functional principle understanding corresponding to each functional gene is shown in Table 8.

Table 8. The functional principle understanding of the shared bicycle parking device.

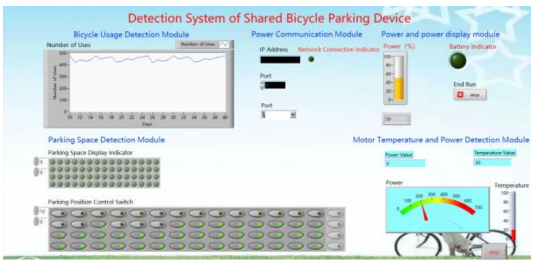
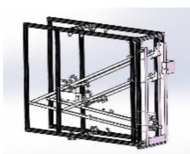
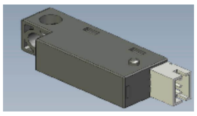
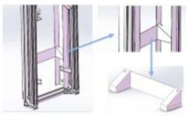
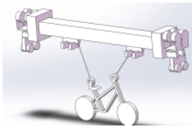
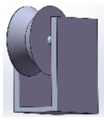
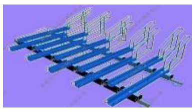
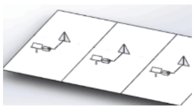
Address	FR		S	Pa	EF1	EF2	EF3	RP
#1	FR_1	Software module		Service time	Response time T < 15 s	Processing speed	Coverage	1
#2	FR_{21}	Parking device with multi-layer track		Track width b, length l, track inclination a, the height of the parking device	Can store 60 volumes	Endurance range	Easy to operate	1

Table 8. *Cont.*

Address	FR	S	Pa	EF1	EF2	EF3	RP
#3	FR_{221}	Ultrasonic sensor 	Response time	Response time	measurement accuracy	Sensitivity	1
#4	FR_{222}	Photoelectric Sensors 	Detect the number of shared bicycles	Detection accuracy	Accuracy	Response time	1
#5	FR_{23}	Lifting mechanism 	Track width, moving speed, track length	Moving distance	Moving speed	reliability	1
#6	FR_{241}	Card slot trolley 	The length of the slot trolley, the diameter and number of the slot wheels	direction	Motion accuracy	automation	1
#7	FR_{242}	Pulley 	Rally F	Tolerance range	Conversion efficiency	automation	1
#8	FR_{3}	Solar power generation device 	Output power	Power generation	Voltage 220 V	Number of power ports	1
#9	FR_{41}	Bicycle rail 	Number of rails	Parallel operation		Easy to operate	1
#10	FR_{42}	Parking lock 	Response time	Response time		Easy to operate	1

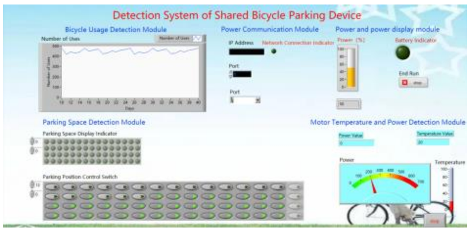
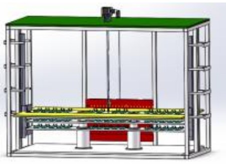
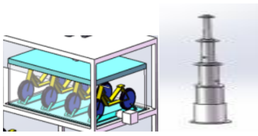
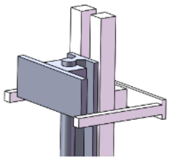
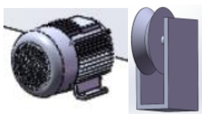
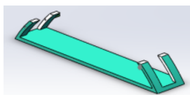
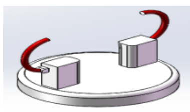
Step B2: Splicing the functional principle understanding of the shared bicycle parking device.

According to the specific implementation factors of the shared bicycle parking device, the functional gene is spliced that it is divided into the improvement of the understanding of the functional origin and the determination of the address of the functional gene.

Step B2.1: The functional principle understanding of the shared bicycle parking device has been improved.

First, the functional principle understanding is spliced, so that the functional gene inherited from the parental system can perform their functions stably in the shared bicycle parking device. The improved functional principle understanding of the shared bicycle parking device is shown in Table 9.

Table 9. The functional principle understanding of the improved shared bicycle parking device.

N	FR	Pa		S	EF1	EF2	EF3	RP
#1	FR_1	Service time t	Software module		Response time T < 15 s	Processing speed	Coverage	1
#2	FR_{21}	Parking board width b, length l, parking device height h	Device with multi-layer parking board		Can store 60 volumes	Endurance range	Easy to operate	1
#3	FR_{221}	Response time t	Ultrasonic sensor		Response time	measurement accuracy	Sensitivity	1
#4	FR_{222}	Detect the number of shared bicycles k	Pressure Sensor		Detection accuracy	Accuracy	Response time	1
#5	FR_{23}	The speed v and distance l of the moving parking board	Elevator box, (or telescopic rod device)		Moving distance	Moving speed	reliability	1
#6	FR_{241}	Length of parking slab slide rail l, depth	Parking board slide		direction	Motion accuracy	automation	1
#7	FR_{242}	Rally F	Pulley, motor		Tolerance range	Conversion efficiency	automation	1
#8	FR_3	Output power P	Solar power generation device		Power generation	Voltage 220 V	Number of power ports	1
#9	FR_{41}	Number of rails n	Bicycle rail		Parallel operation		Easy to operate	1
#10	FR_{42}	Response time t	Parking lock		Response time		Easy to operate	1

Through the above-mentioned conversion of the functional principle understanding, the functional structure diagrams of the shared bicycle parking device can be obtained (in Appendix A).

Subsequently, the functional models of the shared bicycle parking device are established (in Appendix B).

According to the functional principle understanding and functional model of the shared bicycle parking device after editing, the DCC theory is used to analyze the complex types of the shared bicycle parking device, as shown in Table 10. The morbid characteristics generated by the functional gene fusion are analyzed using DCC theory. Then, the TRIZ tool is used to solve the problem. Finally, the functional principle understanding of shared bicycle parking devices is updated.

Table 10. Complexity analysis.

Problem Description	Complexity Analysis	Solution
The panels that have been cleaned are likely to be contaminated during the cleaning process of the adjacent panels, resulting in poor dust removal.	The information content *I* is not 0, so it is judged that there is complexity in the structure of the solar power generation device: the system has no complexity in the initial stage of operation and can meet the design function requirements, but as time changes, the complexity of the system also changes, which may have harmful effects on the system, which belongs to the time-dependent combinatorial complexity.	Material-field model is shown in Figure 19. S4 represents natural wind, S3 represents dust, S2 represents solar panels, S1 represents electrical energy, F3 represents the gravitational field, F2 represents the gravitational field, and F3 represents the electromagnetic field. In a system, useful and harmful effects exist at the same time, and the harmful effects can be eliminated by changing S1 or S2. According to the selected No.10 (1.2.2) standard, the solar panel after dust removal is turned to the back of the solar panel that is being dusted, to prevent dust from falling on the solar panel that has been dusted again, thereby reducing the system Combination complexity in the design process. The solution was obtained: a natural wind dust removal device was developed. As shown in Figure 20.
When the pressure sensor detects the number of shared bicycles, the sensor is in direct contact with the bicycle rail and indirectly with the shared bicycle. However, the contact between the sensor and the bicycle rail that makes the accuracy of the sensor bias.	According to the complexity judgment method, the information content *I* is not 0. Therefore, there is complexity in the design process when the pressure sensor detects the number of shared bicycles. Over time, the accuracy of multiple pressure sensors changes, which is a time-dependent combination complexity.	The invention principle No. 1: the principle of division based on the principle of conditional separation can be used. Change the part of the bicycle rail that contacts the pressure sensor to rubber cushions and change the other parts of the bicycle rail to acrylic plates to ensure the accuracy of the pressure sensor. At the same time, the bicycle rail can support shared bicycles, as shown in Figure 21.

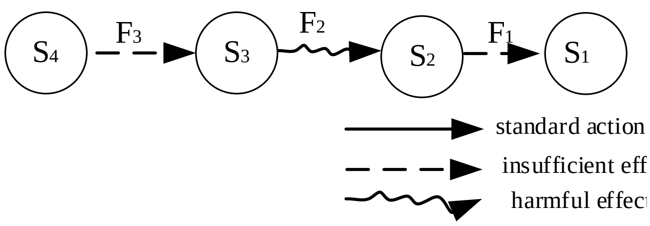


Figure 19. Hazardous substance field model.

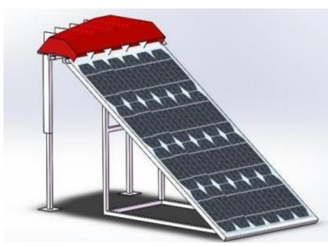


Figure 20. Natural wind dust removal device.

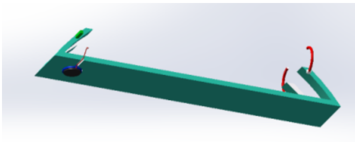


Figure 21. Schematic diagram of the parking lock device.

In order to smoothly translate the functional gene address of the shared bicycle parking device into a design plan, the address of the functional gene needs to be adjusted. Combining the functional gene address of the bicycle parking device, the connection relationship between the components in the functional model of the shared bicycle parking device, the relationship between the input and output streams in the functional structure, and the relationship between the physical parameters in the functional principle understanding, the adjusted sequence of the functional gene addresses of the shared bicycle parking device is obtained, as shown in Figure 22.

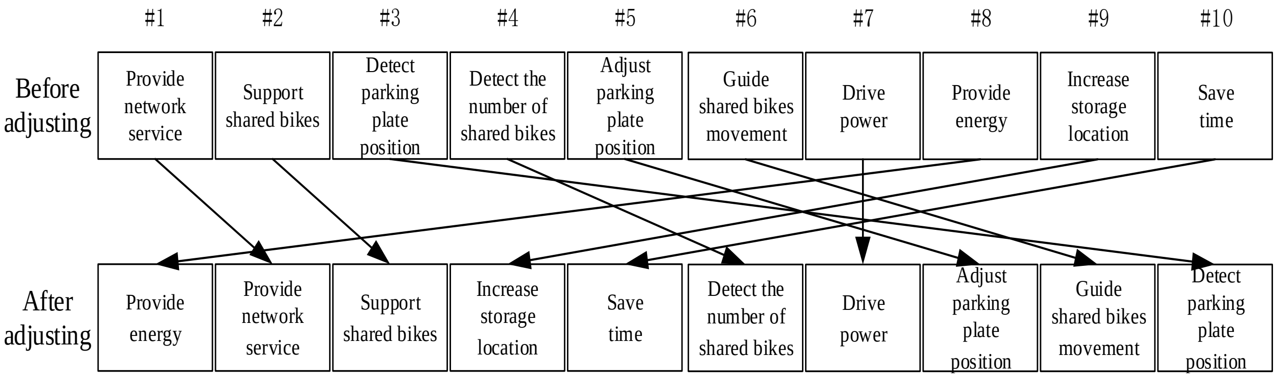


Figure 22. The result of adjusting the functional gene address of the shared bicycle parking device.

5.3. Scheme Evaluation of Shared Bicycle Parking Device

According to user requirements and expert suggestions, the operability, cost, structural complexity, and design cycle of the shared bicycle parking device evaluation plan are determined as four important evaluation indicators, as shown in Table 11. Cost and design cycle are quantitative evaluation indicators, while operability and structural complexity are qualitative evaluations. The qualitative evaluation index level set is {good, good, fair, poor, poor}. The designated design range for operability is good. Therefore, the designated design range for structural complexity is fair. The design range of the cost is less than 0.65, and the design range of the design cycle is 15 days.

Table 11. Evaluation table of the evaluation plan of shared bicycle parking device.

Evaluation Index	Program 1	Program 2
Operability	better	general
Cost	0.92	0.75
Structural complexity	better	better
Design cycle	15	25

In the evaluation index of the shared bicycle parking device, the trapezoidal distribution function is used as the fuzzy membership function of the qualitative evaluation index of the design scheme. First, the Formula (7) is used to calculate the information content *I* of operability and structural complexity, and then the gray-level correlation algorithm is used. The cost and design cycle are calculated by the grayscale correlation algorithm. Then, the Formula (8) and the Formula (9) are used to normalize the two. The Formula (10) to Formula (16) are used to calculate the gray correlation coefficient. Finally, the Formula (17) is used to calculate the evaluation value of the scheme. The settlement result is shown in Table 12. The evaluation results of each scheme show that Scheme 1 is less than Scheme 2, so Scheme 1 is adopted as the most suitable scheme for design.

Table 12. Program evaluation results.

Evaluation Index	Scheme 1	Scheme 2
Operability	0	3
Structural complexity	0	0
cost	0.58	0.28
Design cycle	−0.58	2.72

5.4. Constructing a Digital Twin Model of a Shared Bicycle Parking Device

The construction of the digital twin model of the shared bicycle parking device includes three aspects: a virtual model, a physical model, and the data of the virtual model and the physical device. Figure 23 shows that invoking the enterprise digital twin resource library and building a digital twin model of a shared bicycle parking device is mainly divided into five layers. They are physical layer, model layer, data layer, service layer and application layer [79].

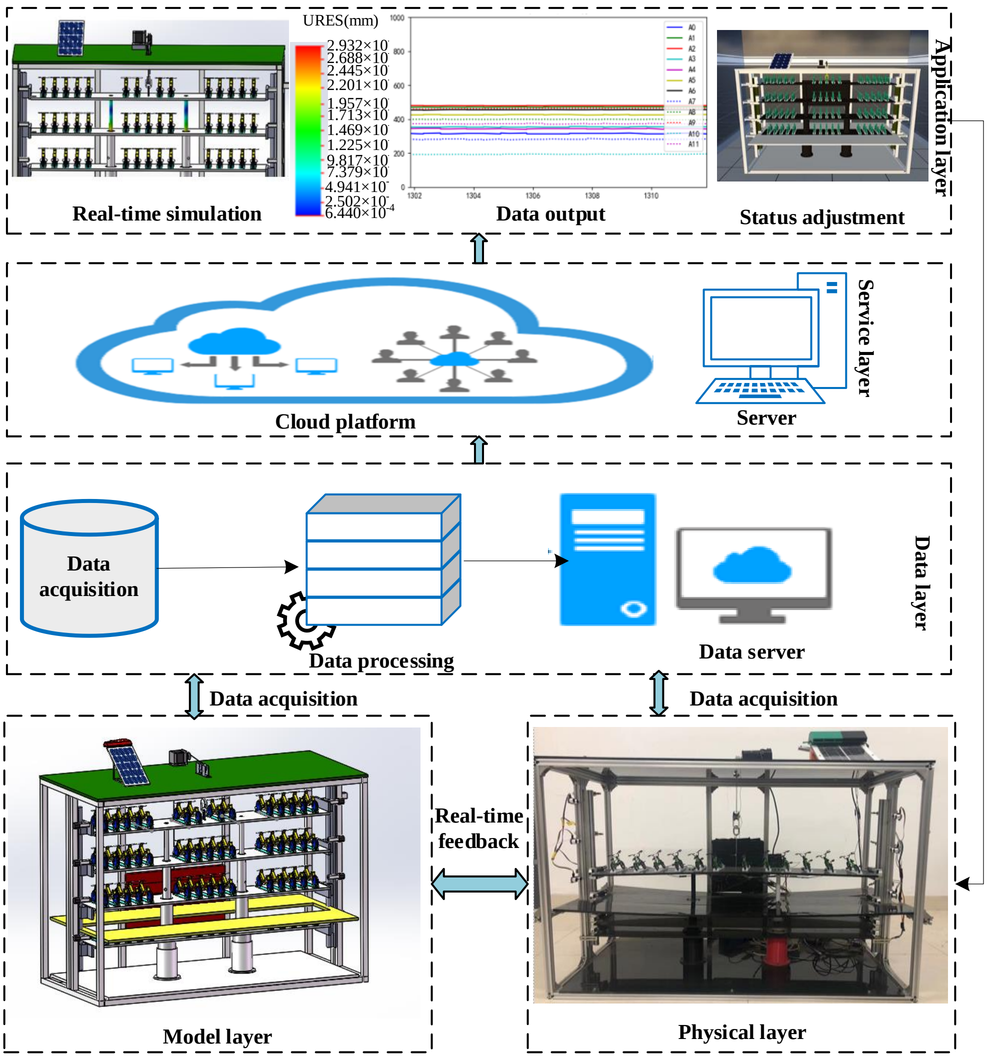


Figure 23. Digital twin model of the shared bicycle parking device.

6. Discussion

The paper proposes a functional gene extraction and construction method to normalize the expression of design knowledge (function, structure, and principle). This method can effectively standardize the design knowledge of different fields and facilitate designers to use the design knowledge of different fields, thus improving the efficiency of product innovation and design. The main contributions of this study include the following three aspects.

(1) Compared with traditional design methods, such as functional models, functional structure etc. [80–84] The traditional design approach focuses mainly on the connection and interaction relationship between systems. However, the representation of heritable information (function, principle, structure, constraints, etc.) is not highlighted, leading to some difficulties in the selection of design knowledge by designers, thus limiting the generation of innovative solutions. However, this study proposes the construction of functional genes FG = {N, FR, V, O, P, EF, RP} that can identify the key information and constraints in the parental system and facilitate designers to acquire knowledge in different fields to better serve the product concept design process. It also helps designers to generate innovative ideas and reduce genetic problems due to knowledge reuse.

(2) In contrast to previous product genes and functional genes [15,23–25,38,41], the functional genes constructed in this paper are expressed through a standardized language (V O P) for function. This approach improves the standardization of functional genes, facilitates the screening and application of design knowledge from different fields, and reduces the problem of designers using knowledge from other fields. Then, this paper provides a rich knowledge source for product innovation with the help of enterprise digital twin libraries. It helps designers to better retrieve and utilize functional genes and generate more innovative ideas.

(3) Functional genes play an important role in the design process of product design and provide an actionable approach for solving the difficulties of design knowledge representation in different fields. The proposed method can effectively characterize complicated and disordered design knowledge in a standardized way, reducing the problems in the design process and improving the efficiency of innovative product design.

7. Conclusions

This paper addresses the problem of difficulty in characterizing design knowledge (function, principle, structure) in different fields due to different expressions of knowledge in different fields, which makes it difficult for designers to use design knowledge directly. Drawing on the similarity between biological genetic processes and product design processes, the paper constructs a functional gene with "predicate (action, Verb) + object (object) (+property) + enabler (EF) + transcription factor (RP)" as the main part. The establishment of functional genes can clarify the design stage information (function, principle, structure) and constraints, and use digital twin rich data, knowledge, model resources to serve the product design process, so that designers can obtain more design knowledge to drive product conceptual design.

Although a new design process model is proposed in the paper, this research still has certain limitations and needs further development and improvement. First of all, the enterprise digital twin resource library framework is relatively broad, and the rules in it need to be further improved; second, the current number of parent systems obtained from the enterprise digital twin resource library is relatively small, which makes the current plan to be able to be screened in a small range, which may affect the final design proposal. Third, in the example verification part, the damage of shared bicycles was not considered during the design of the shared bicycle parking device. The damaged shared bicycles will always be stored in the parking space, resulting in only this layer working. Fourth, the functional genes established in this paper are expressed in text form, which has a lot of work for the construction of the early functional gene model.

In order to overcome the above limitations, there are four ways to improve the design process model mentioned in the article in the future: First, we will learn more knowledge and formulate more complete rules to build the enterprise digital twin resource library framework; second, we need to further expand the product resources in the enterprise digital twin resource library, so that there are more choices and possibilities when designing a new generation of products; third, a monitoring device that can automatically identify damaged shared bicycles can be added to the phenomenon of bicycle damage; fourth, with the rapid development of computer-aided innovation, the next step will be to study the intelligent extraction and construction methods of functional genes to reduce manual involvement and improve the efficiency of functional gene construction, thus improving the intelligence level of product design.

Author Contributions: Conceptualization by P.Z. and H.W.; project administration, P.Z.; methodology by H.W., Z.Z. and P.Z.; resources by Z.Z., Y.W. and P.Z.; writing—original draft by H.W. and Z.Z.; writing—review and editing by H.W., Y.Z. and Z.Z. All authors have read and agreed to the published version of the manuscript.

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Appendix A

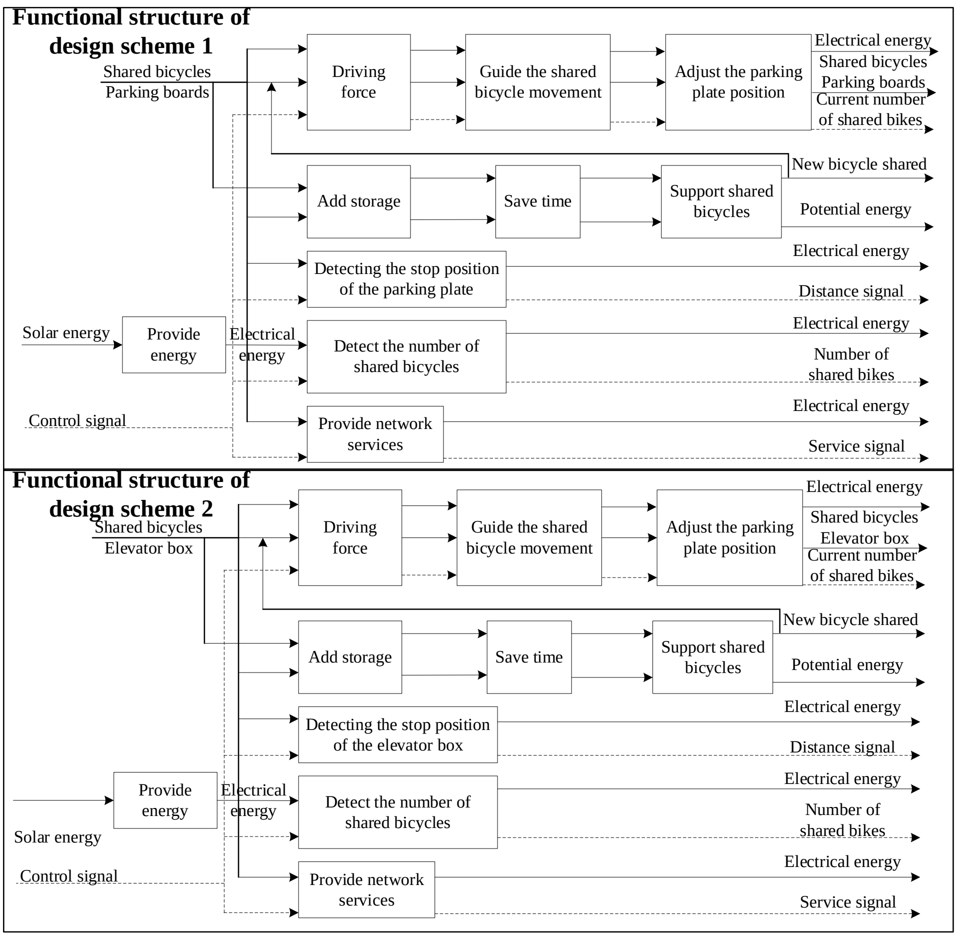

Figure A1. Functional structure diagram of shared bicycle parking device.

Appendix B

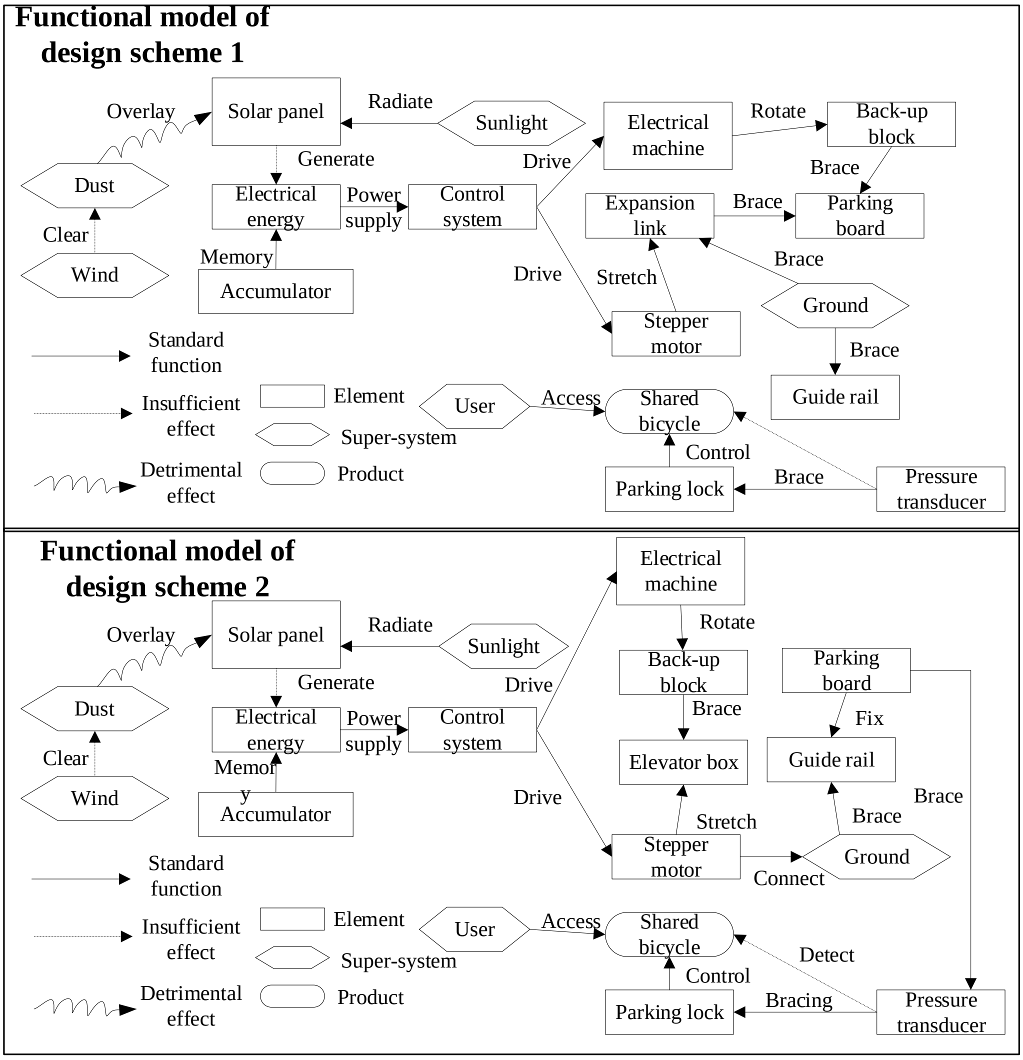

Figure A2. Functional model of shared bicycle parking device.

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