A Study of Product Service System for Product Family Based on Extension Design

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Abstract

This paper, from the perspective of extension design, investigates the product family architecture composed of demand domain, functional domain, technology domain, and physical domain and establishes a product service system, which is centered on the product family development platform, based on the extension innovation method. The basic-element logic language and method of extension design is employed to analyze the characteristics of product family design including generalization, parameterization, modularization, and intelligence. In this paper, the product family design platform, including four models and three resource libraries, is developed through the formalized and modeled basic-element representation, configuration of modular elements, and intelligent generation path. Combined with artificial intelligence technology, this research constructs a smart product service system framework oriented towards product family design and proposes an extension design generation system.

Keywords: product family design, smart product service system, service design, extension design generation system

Introduction

The development of market competition and scale economy allow manufacturers to believe that diversified product categories can meet personalized user demands. However, enriching the product catalog requires increasing the cost of production, resulting in the inapplicability of traditional mass production to reach such modernized demands. To this end, manufacturers turn their attention to “Design for Mass Customization” (DFMC), a method that can provide products and services satisfying the specific needs of customers at a cost of time and expense approximate to those of mass production (Tseng, 1996). Under the DFMC model, to develop a product family, thanks to its advantages in cost and efficiency, has been recognized as effective in adapting the diversification of product demands in economies of scale (Meyer & Utterback, 1992; Sundgren, 1999), and it can realize the integration of mass production and customized services. A product family is a group of related products built on a common product platform which can meet diverse needs by sharing things such as common platform features, components, and subsystems (Simpson, 2001), and to design a product family is to change the adjustable variables while maintaining the unchanged public variables, thus realizing the satisfaction of diverse demands (Dai & Scott, 2007). Therefore, it can be considered that the universal system and parameterized configuration of the platform are the key to a product family design. As for the research on the product family system, Erens & Verhulst (1997) and other researchers have established the Product Family Architecture (PFA) based on functional domain, technology domain, and physical domain, which offers a platform for participants, who intend to satisfy their customers by transforming products, to cooperate in product development. Gero & Kannengiesser (2004) puts forward the FBS model, that is, Function Behavior Structure, to create the whole system on the basis of an ontology involving the functional purpose, behavioral characteristics, and physical structure of the product. FBS embodies the intertwined relationship among functional, behavioral, and physical domains. In product design, function is the purpose of behavior, behavior is the performance characteristic of function realization, and structure is the representation of behavioral characteristics. Based on the analysis of PFA and FBS, the functional domain was found to express the overall product function and the goals of its sub-function structure, while the behavioral domain describes the principles of functions from a technical point of view, and the physical domain illustrates the assembly model of physical components of the product structure.

In the field of the customer demand-oriented product family design, the parametric research, however, based on the definition of user demand and the mapping relationship between demand and function, has not been incorporated into the product family architecture. Although Simpson (2007) has unified front-end demand satisfaction, intermediate product design, and back-end supply chain design into a product family platform-based developing process, there is still a lack of scientific study on the demand domain as the start of PFA. Therefore, this paper, from the perspective of extension design, extends PFA, which is composed of the demand domain, functional domain, technology domain, and physical domain, to establish a product service system with the product family development platform as the core. The questions involved are as follows. How does the platform match the design requirements with existing resources? How can the contradicting state of design be converted to the target state? What is the mechanism for the interrelationship between uniqueness and generality in product configuration design? What are the module division logic and the method of strategy generation? How can the multi-stakeholders participate in the whole cycle of product development? How does the digital technology boost the advancement of the intelligence and generalization of the platform?

To solve the above questions, this paper, utilizing the method of extension design, the logic of service design, and digital technology, analyzes the commonality of the product family architecture (PFA) and the extension design generation system (EDGS) with parameterized configuration to explore the framework of a smart product family platform (Table 1).

Framework	**PFA**	**EDGS**	**Key points**
Customer	X	Demand Model	Need
Functionality	Function	Functional Model	Purpose
Technique	Behaviour	Technology Model	Principle
Manufacturability	Structure	Structural Model	Component

Table 1. Comparison of product family design framework (Sources: Simpson, 2007; Gero, 2004)

Extension Design Generation System (EDGS) for product family design

As a new design concept and innovative method, extension design, based on extenics and a knowledge-driven perspective, investigates how to establish a model, cluster knowledge, and derive schemes, also in addition to the modification, optimization, and evaluation of design. It can be seen as a new modern design theory and method that handles contradictions in the design object, system, and process on an intelligentized basis to seek the best design plan (Cai &Yang,2013). Extension design is aimed at resolving the common contradictions in product family design, namely, the ones among demand and function, technology, structure or cost, and those between subsystems. It expresses problems and requirements in the form of basic-element and designs the module configuration of the product family extension innovation method, which is a formalized and modeled approach to reveal the law of creativity and dialectical thinking. The core of this method is to deal with the contradictions in design through the Double Diamond model (Li, 2018). As adopting the formalized system to express the idea of problem-solving, extension design can take advantage of the advantages of the Internet, such as the fast speed and large storage capacity, to assist in generating various solutions in a systematical manner. Therefore, this paper puts forward the Smart Product Service System (EDGS) that is constructed on the basis of extension design and is oriented toward a product family. EDGS can be considered as a product family design platform while also being a product service system seeking the best solution, which integrates the service design logic and the extension innovation method and combines smart technology to deal with the contradictions in design object, system, and process.

The extension innovation method includes four stages, namely, modeling, extension, transformation, and evaluation, which, as a whole, is in line with the Double Diamond Model, to deal with contradictions in design. Mapping the four stages to the process of design thinking, namely, to empathise, define, ideate, prototype, and test, this paper draws a product family architecture consisting of demand, functional, technology, and physical domains. The results are as follows. First, empathise and define map out the demand domain. Second, define and ideate map out the functional domain. Third, ideate and prototype map out technology (behavioral) domain. Finally, prototype and test map out the physical domain. The research then extracts four product family models from the above domains and configures related design modules according to their characteristics. In order to adapt the product family platform to the smart and general needs for development, it also provides three resource libraries including a basic-element library, extension rules library, and case library. Accordingly, the EDGS framework composed of four models can be established for the product family platform (Fig. 1).

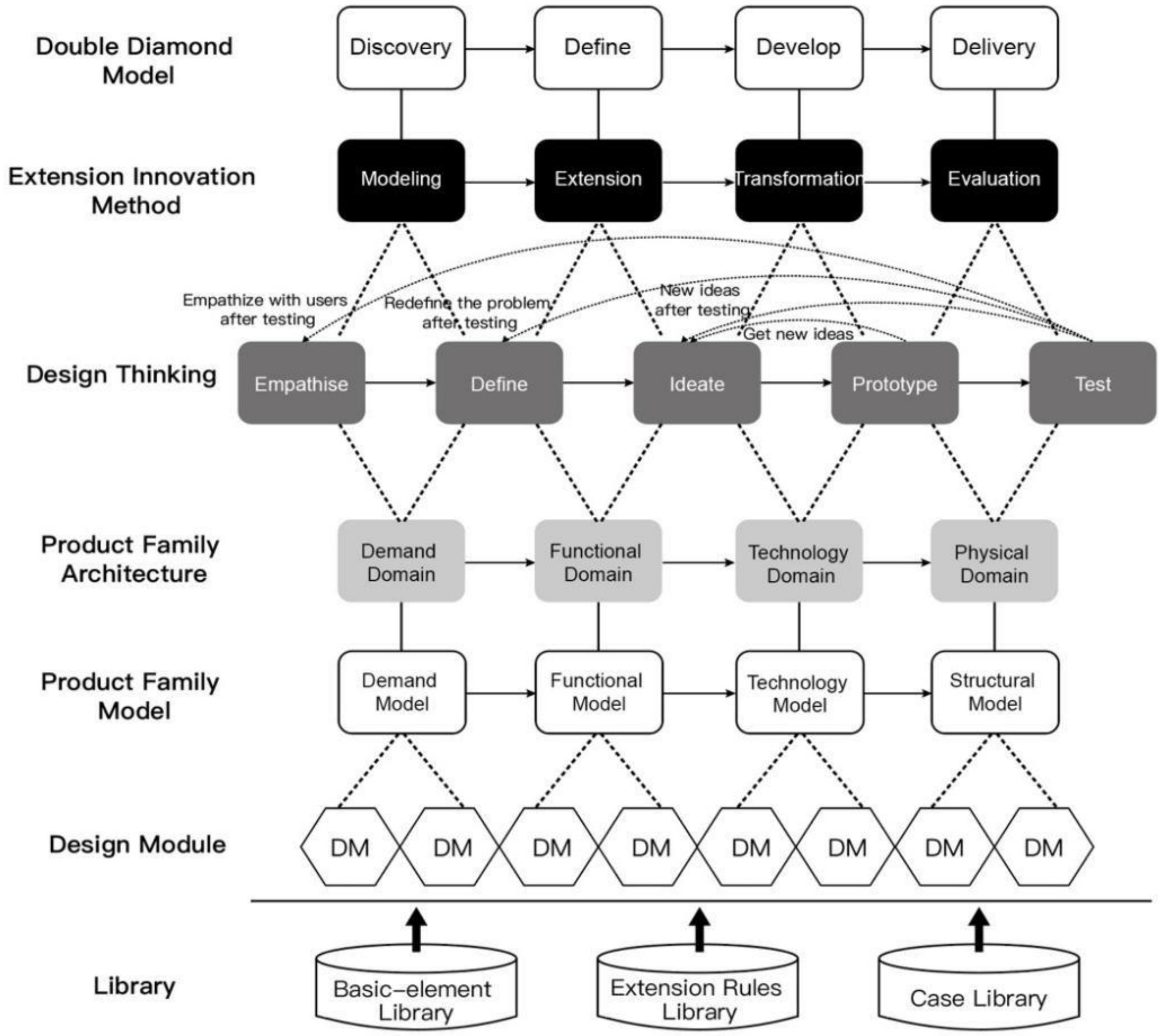

Figure 1. EDGS Framework for a Product Family Platform

The EDGS fabric expands the product family model into four parts: demand model, functional model, technology model, and structural model. To specify, customer demands assist in obtaining the functional characteristics of the required product. These functional characteristics then give hints about necessary technical principles and solutions. Finally, all of these features and principles can be reflected in the physical structure model of the product. The product family model describes the relationship between the front-end demand, mid-end design, and back-end production in terms of the four domains of demand, function, technology, and physics, where demand satisfaction is related to functional goals, function realization is associated with technology support, and technological transformation is correlated with structural realizability and cost. In the following sections, this paper carries out a detailed analysis of the four models and the process of platform development.

Extension Design

Extension design employs formalized basic-elements to present the knowledge of design problems to handle demands and contradictions. “Basic-element” is used as the extension logic language to describe matter, affair, and relation and object, characteristic, and value, as a triple, correspond to matter-element, affair-element, and relation-element, respectively, thus constituting the logical cells of extension design (Fig. 2).

$$M(t) = \begin{bmatrix} O_m(t), & c_{m1}, & v_{m1}(t) \\ & c_{m2}, & v_{m2}(t) \\ & \vdots & \vdots \\ & c_{mn}, & v_{mn}(t) \end{bmatrix} = (O_m(t), C_m, V_m(t)).$$

Figure 2. Formalized Expression of Basic-element in an Extension Model

Demand Model

First, this paper, in the demand model, defines the customer demands and certifies the basic-element model of the product. Through the qualitative and quantitative analysis of the basic-element formalization, it then translates the design problems into basic-elements, identifies demands and key points to figure out the general and customization ones, and ultimately, quantitatively maps the characteristics of those demands by means of basic-element parameterization, thus determining the parameters of matter-element, affair-element, and relation-element (Fig. 3).

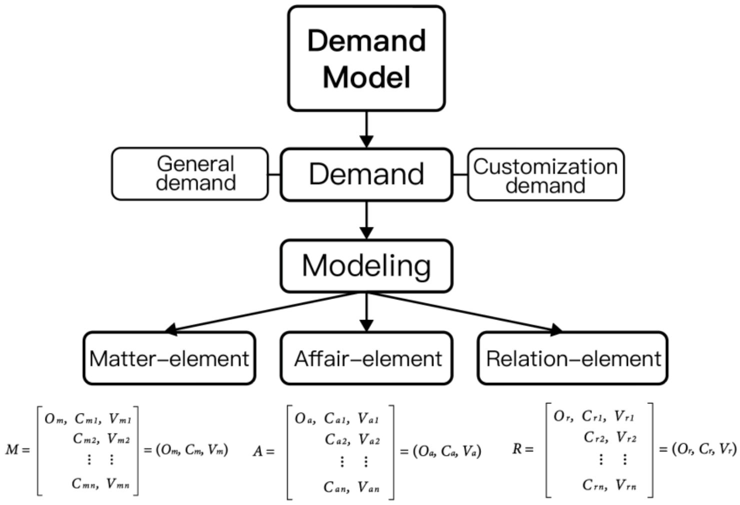

Figure 3. Demand Model of a Product Family

Functional Model

Second, the functional model, on the basis of the established demand model, is utilized to conduct an analysis of the expansion of product functions (Fig. 4). According to the demands (including general and customization demands) and basic-element parameters, this study, through function mapping, converts the attributes of demand into general function and customization function, and represents them as basic-elements. Then, an analysis of the correlation between the demand and functional models is carried out by correlation function to deduce the corresponding functional modules which are the objects of analysis from the perspective of basic-element expansion. The expansion method is derived from the extension innovation method, including divergence analysis, correlative analysis, implication analysis, scalability analysis, and conjugate analysis (Cai & Yang, 2014). The expansion analysis of functional modules has seen the classification of the existing general functional parts of the platform as general function modules (F_{p1}, F_{p2}, F_{p3}, ⋯), and the parts that require customized functions as customization function modules (F_{i1}, F_{i2}, F_{i3}, ⋯).

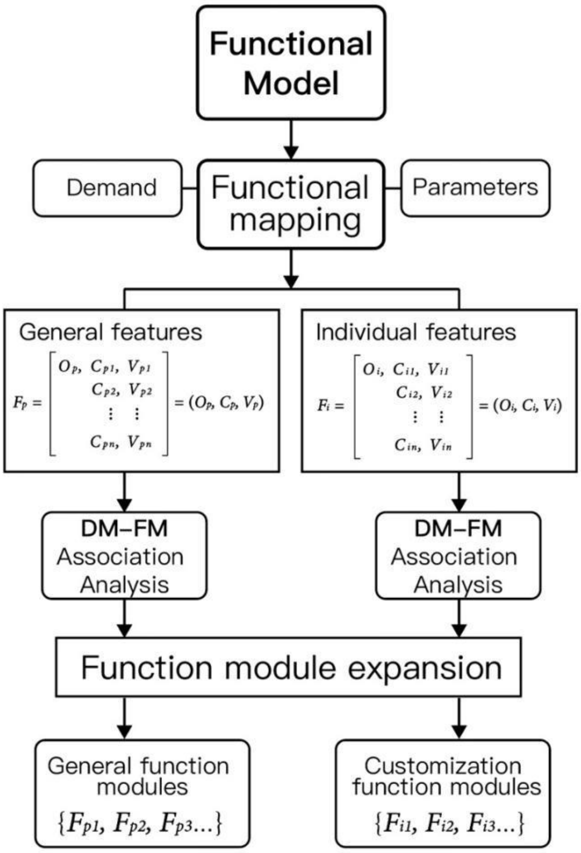

Figure 4. Functional Model of a Product Family

Technology Model

The realization of functions requires the support of technical principles. This research, based on the general and customization function modules established by the expansion analysis of functional modules, executes a technological mapping in the technology model (Fig. 5), during which the analysis of the link between the functional and technology models is carried out (through the correlation function calculation). It is concluded that there are four kinds of mapping relationships in the correlation between function and technology. Taking "*f*" as function and "*t*" as technological principle, the research specifies them as:

- A one-to-one relationship, that is, a function (*f*) is realized by a technological principle "*t*".
- A one-to-many relationship, that is, a function (*f*) is realized by multiple technical principles "*ts*".

- A many-to-one relationship, that is, multiple functions are realized by one technological principle "*t*".
- A many-to-many relationship, that is, multiple functions are realized by multiple technological principles "*ts*".

The cluster analysis of the technological module helps clarify the technological support of the required functions to build the general technical modules (T_{p1}, T_{p2}, T_{p3}, ⋯) and the customization technical modules (T_{i1}, T_{i2}, T_{i3}, ⋯) of the technological principles. Next, the key to the success of the product family design is to effectively transform the technology into the physical prototype structure.

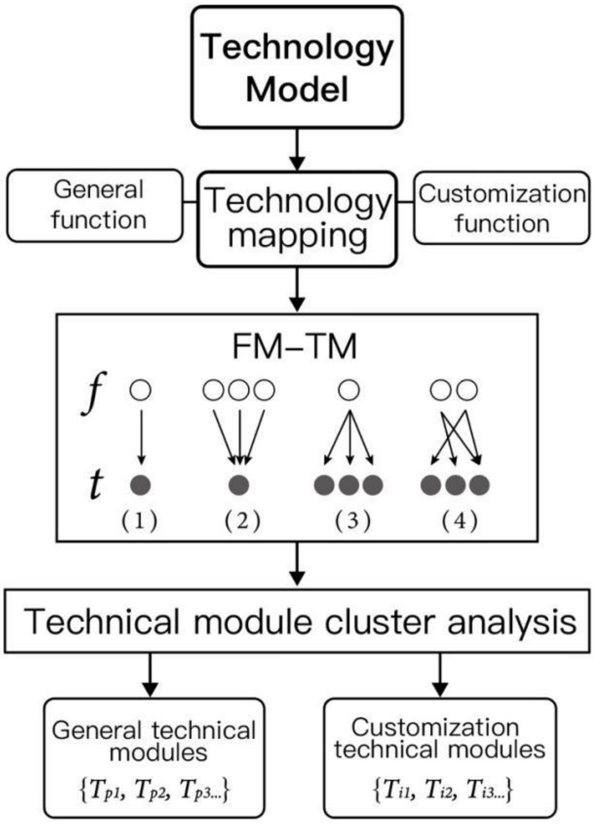

Figure 5. Technology Model of a Product Family

Structural Model

The structural model, on the basis of the establishment of functional and technology models, is to materialize the functional and technological modules and thus establish product prototypes with the structural combination of physical components (Fig. 6). According to the differences between general and customization technologies in terms of the configuration of platform modules, the structure module can be divided into general and customization. A general structural module refers to a sharable and reusable invariable component with relatively stable design parameters on the platform, that is, a general component, while a customized structure module concerns a variable component with design parameters related to individual needs that can meet the personalized customer demands and adapt to the diversified subdivision of products. It can also be called a customized component. In the structural model, the standardization and applicability of the structure and interface of modules are viewed as the key factors affecting the final product formation. In other words, in the configuration design of the product family platform, standardized module interface is the premise to ensure that the modules are able to be assembled and replaced. To this end, this paper uses the correlation function to quantitatively analyze the matching degree among modules and achieves the product structure module with the optimal solution of adaptability through combination and operation. Then, the CMF (color, material, finishing) module and prototype module are employed for the parametric design of structure details, during which the machinability, low cost, maintainability, and humanity of the product structure should be ensured. After continuous tests and iterations, the final product prototype design comes into shape.

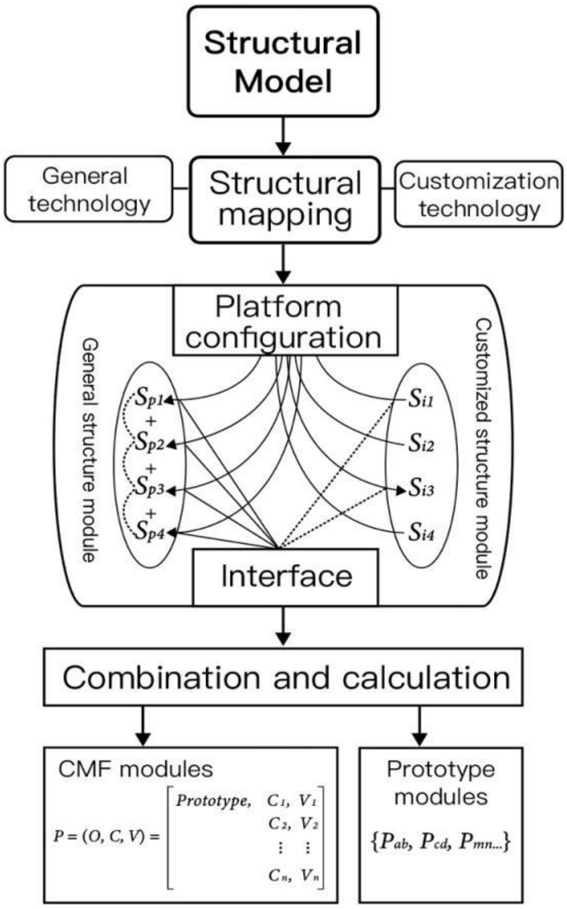

Figure 6. Structural Model of a Product Family

Resource Libraries

Based on the EDGS framework, the resource libraries, including the basic-element library, extension rules library, and case library, are allocated to support the platform. A basic-element library is a database of the characteristics and values of a large number of things and relationships in a certain field, which can be extracted from big data and information through searching, keyword extraction, text clustering, and other technologies, thus building a general basic-element library to provide rich component resources for product family design. The extension rules library is an extension innovation method and rules are applicable to the product family model and design module, involving the modeling rule of the demand model, the extension rule of the functional model, the transformation rule of the technology model, and the optimization rule of the structural model. A case library is a collection of similar mature products and components on the platform, a resource library providing general and customized components for the product family, and also examples for the application of case-based reasoning (CBR).

Extension Design Generation System (EDGS)

It can improve the construction and use efficiency of the platform resource library to develop a smart design platform by combining the three resource libraries in EDGS with digital technology (Fig. 7). When building the basic-element and case libraries, web crawler technology can be made of use to automatically fetch relevant information on a specific topic in the Web. The clustering technology can be employed to categorize the data according to the design elements, generating various types of sub libraries. This can help establish large-scale basic-element libraries and case ones to serve intelligent searching and matching functions. In the extension rules library, the extension innovation method and rules can be resorted to to train AI and facilitate a more automatic, fast, and efficient configuration of product family design, such as module recognition, interface coupling, and dynamic adaptation. To create a smart platform for product family design, it is helpful to quickly and efficiently distribute a variety of design components in pursuit of the enhancement of the efficiency of innovative design and a decrease in cost.

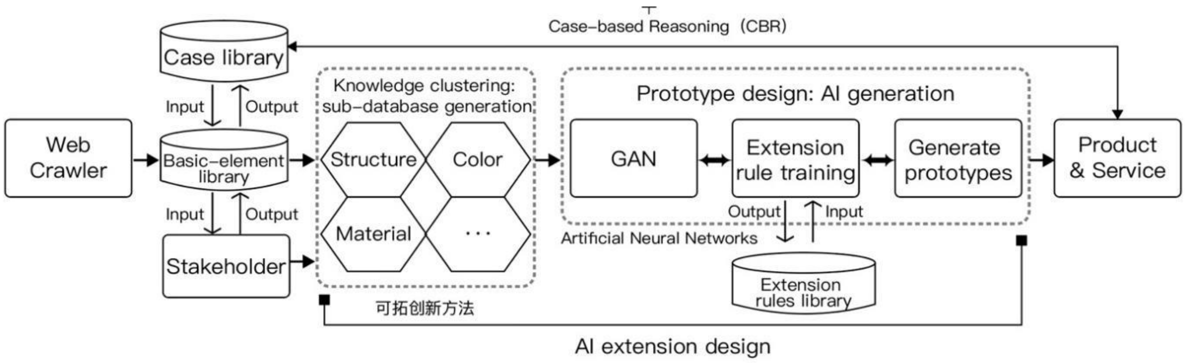

Figure 7. The Path of Smart Extension Design Technology

To sum up, this paper, integrating service design thinking and the extension innovation method, constructs an EDGS development process for a product family design (Fig. 8), which includes four models (demand model, functional model, technology model, and structural model) and three resource libraries (basic-element library, extension rules library, and case library). The basic-element definition of customer demand enables searching and matching in the basic-element library to extract the existing products that can meet the demands. If there are few products that can satisfy the needs, similar ones may be extracted, and a configuration design will be executed according to the extension innovation method in the extension rules library. The optimal structural scheme is finally chosen in the process of combination and operation to yield the product prototype, and the new products will be incorporated into the case library.

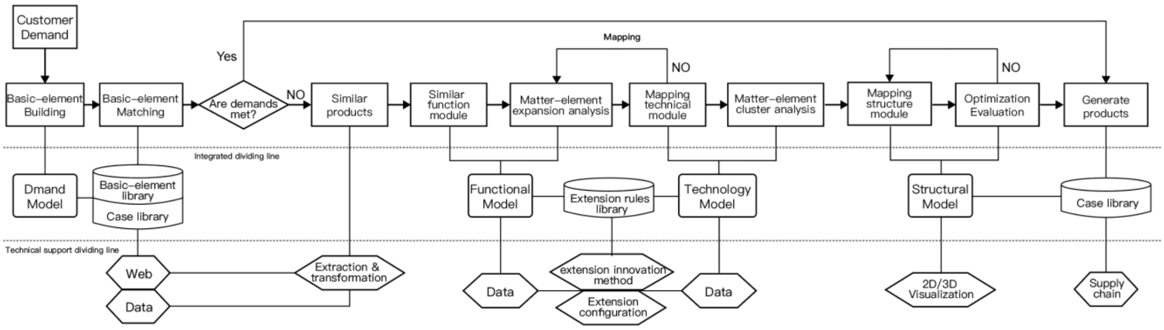

Figure 8. The Flow Chart of EDGS Development for Product Family Design

Smart product service system based on EDGS

The formalized expression and innovative method and logic of extension design are suitable for programs solving problems in a computer-intelligent manner. Therefore, this paper, based on EDGS, is aimed at exploring the smart product service system for product family development. It is of great significance for a successful smart product service system to establish an appropriate knowledge representation and methods of retrieval, configuration, generation, and evaluation. Based on the EDGS development framework and the product service system process, four steps of "discovering problems, defining functions, developing technologies and delivering products" are formed.

In the first stage of discovering problems, formalized basic-elements are used to model customer demands and determine the relationship between basic-elements. Similar basic-elements in the library can be retrieved and matched by means of the analogical matching of their semantic network. The function definition stage sees the extraction of the functional modules of similar products based on the attributes of demands. The analysis of functions is expanded in line with the adaptability of the function module and the attributes of customer needs, thus exporting a functional matter-element system diagram. As for the development of technology, this system draws mapped technology modules from the functional ones to facilitate a correlation analysis of function and technology in order to constitute the relevant configuration of the technology module. Next, the realization of product function is motivated by the technologies obtained through the cluster analysis of the technical module. To deliver products, the mapped structural modules and components are configured for the functional and technical modules, and a scheme of effective physical structure product configuration, i.e. new product (prototype) development, comes into being through the combination and operation of the components. In the entire product service system, multi-stakeholders actively participate in providing systematic solutions involving the construction of the basic-element library, service management, manufacturing, and supply chain support (Fig. 9).

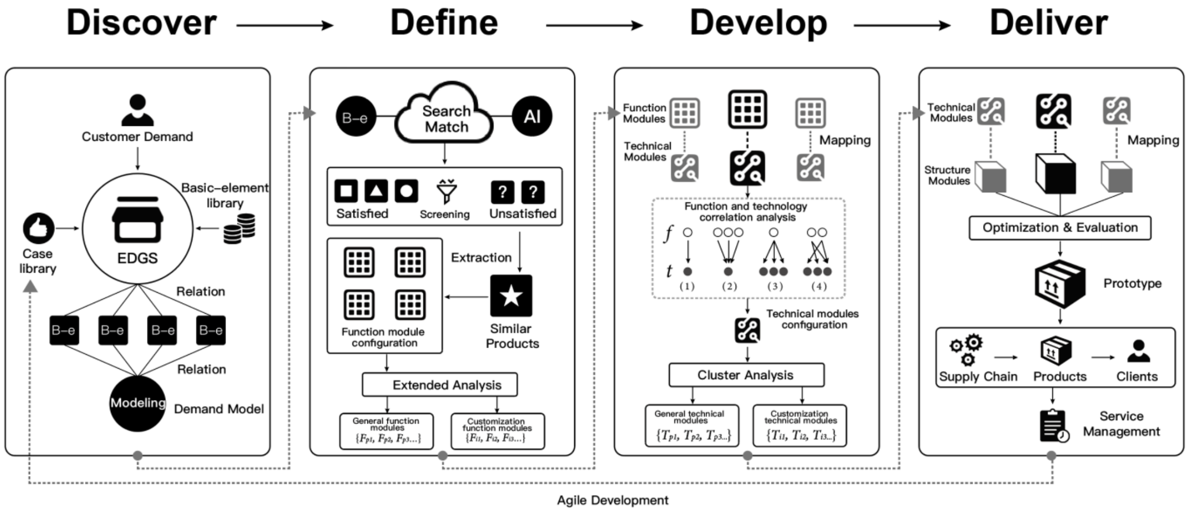

Figure 9. Smart Product Service System

Discussion

This paper explores the scientific configuration method of product family development from the perspective of extension design to build a smart product service system that takes EDGS as its frame. Different from the previous product family design focusing on the CBR configuration method, the extension innovation method of EDGS-based design conducts a scientific and intelligent problem-solving process by establishing the basic-element model, reflecting formalization, modeling, and the combination of qualitative and quantitative methods. It provides an innovative design theory and method for the description, analysis, and solution of product family configuration and development problems. Therefore, this research can be seen as valuable in finding the rules of the design and configuration of the product family and improving the possibilities of success and design agility. It also offers an effective tool and system for the design of new products that can satisfy the requirements of personalized user demands and a low cost. Current studies have systematically studied the product family architecture, which includes the demand, functional, technology, and physical domains, based on extension design and developed corresponding models and resource platforms. However, there is still a lack of deep discussion on computer-aided innovative design and human-computer interaction regarding the acquisition, analysis, conversion, and generation of the knowledge related to product family platforms. In the future, platforms of smart design and generation and human-computer interaction methods oriented toward a product family will become one of the most important directions for the application of AI technology for modern design. Meanwhile, the extension product service system based on extension design will be regarded as an important and exploratory field of scientific design research which requires interdisciplinary integration and development.

Conclusion

Design for mass customization (DFMC) has been considered as one of the production modes to provide diversified products at a reasonable cost. In the context of DFMC, the development of a product family design has become a feasible way to realize product customization under economies of scale, whose economic value and social significance have been widely considered. Given an initial tendency in the research on system-wide solutions centered on a product family design platform, this research, based on the perspective of extension design, analyzes the developing framework, technological path, and systematic process of product family development and creates an extension design generation system (EDGS) oriented to the product family platform. In EDGS, the formalized basic-element language is used in the entire process of product development. Concentrating on the characteristics of product family design, this paper puts forward the basic-element representation, the mapping relationship of modules, and resource support at each stage of design, namely, the four models (demand model, functional model, technology model, structural model) and three resource libraries (basic-element library, extension rules library, case library). Using the extension innovation method and the product service system, this system can coordinate design modules, configuration relationships, and platform resources to obtain the most feasible design scheme. Additionally, the basic-element modeling theory and method of extension design assist in promoting the integration of computer science into design science and realizing the collaboration with artificial intelligence technology. This system, taking the advantages of fast algorithm and large storage capacity of AI which are then combined with EDGS, can systematically assist in generating various design plans to solve problems, resulting in the formation of a smart product service system. In the future, efforts will be exerted to develop a human-computer interaction software of the EDGS platform to realize integrated product service design, involving the front-end import of customer demands, the mid-end extension design and configuration, and the back-end product manufacturing and delivery, etc. The goal is to provide different products to the market with the shortest design and development cycle and at the lowest cost and finally offer valuable research results to empower enterprises to innovate independently with the help of smart and innovative design platforms.

Acknowledgments

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