

Function Flow-based Product Design Process Modeling*

Shuxia Li

School of Business

East China University of Science & Technology

Shanghai, China

Department of Industrial and Operations Engineering,

University of Michigan

Ann Arbor, Michigan, USA

sxli@{ecust.edu.cn, umich.edu}

Hongbo Shan*

College of Mechanical Engineering

Donghua University

Shanghai, China

Department of Mechanical Engineering

University of Michigan

Ann Arbor, Michigan, USA

hbshan@{dhu.edu.cn, umich.edu}

Abstract – Traditionally, product design process is divided into multiple phases, and the distributed design flow across these phases emphasizes on task solving and realization within one of the design phases in term of the perspective of designer. Increasing personalized product design demand, however, often leads to frequent redesign of design work mainly due to distortion of ambiguous and discrete customer requirement information by multiple delivering. Since the customer requirement information and requirement function affect both product conceptual design and later product design process, designing an integrated product design process is challenging. The purpose of this research is to develop a systematic product design process model based on requirement function and its function flow, which can acquire, deliver, transfer and realize the unambiguous customer or designer requirement and requirement function. In this study, the definition of requirement, function and requirement function are given, and the mutual relationship among them is analyzed. Then, an integration mode of product design process, which consists of qualitative conceptual design phase and quantitative detail design phase, is proposed according to the nature invariability of function. Furthermore, a new function flow-based product design process model is presented. The function flow, formed by transformation, evolution and connection of the requirement function, is used to describe the correlation of customer requirement function, designer requirement function, and assembly function along with product design process. A hierarchy model of intermediate product corresponding to this product design process is also established, which includes requirement product, function product, principal product, conceptual product and detail product. Also, a case study is given to validate the model proposed. This product design process modeling method can help transferring different type of requirement functions effectively and avoiding mistake or misunderstanding of solution on design requirement between different phases to the greatest extent.

Index Terms – *Product Design Process; Function Flow; Customer Requirement; Requirement Function.*

I. INTRODUCTION

Research on the product design process is the activities of subdivision, analysis, integration and evaluation with a scientific and systematic approach to summarize the essence of the product design process based on the in-depth study of the product design theory and methods[1]. In this process, the product design development is characterized by the features of

the overall systematicness and risky [2]. Accordingly, the degree of trueness about the qualitative & non-quantitative customer requirement information in the origin of product design directly affects the correctness and completeness of the result of design process. The previous product design process researches mainly emphasize on the result of detailed product design, while giving less attention to the research of the product conceptual design process and its connection or integration between conceptual design phase and detail design phase. In the traditional design process, different departments shall be responsible for the relevant design task independently in a design project and the product design process is usually divided into multiple phases. The design intention and design target information are communicated in the form of the distributed design flow between the different design phases [3]. This method has good effect on the design or revised design of the products with clear and definite customer requirement information. However, Increasing personalized product design demand, however, often leads to frequent redesign of design work, the decrease of the product development speed and the increased design and development cost mainly due to distortion of fuzzy and discrete customer requirement information by multiple delivering. In addition, most of the existing CAD system emphasizes on the task solving and realization within one of the design phases in term of the perspective of designer. In contract, the research on how to obtain the valuable requirement information from the customers is limited. Especially, the influence of these requirement information and requirement functions in product conceptual design phase on the whole product design process still needs explored. This research is to develop a systematic product design process model based on requirement function and its function transformation flow, which can acquire, deliver, transfer and realize the unambiguous customer or designer requirement and requirement function.

II. REQUIREMENT, FUNCTION, AND REQUIREMENT FUNCTION IN PRODUCT DESIGN PROCESS

A. Requirement in Product Design Process

Requirements are commonly recognized as what the customers need, which are able to trigger a program or system

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development with the characteristics, functions and attributes contained in the target system discovered at the outside of the system to satisfy the user's needs, binding upon the target system [4]. This definition of the requirements is put forward from the perspective of the software engineering. In the modern product design process, as the origin to initialize the product design process, requirement should take the specialties of design process into consideration.

The emergence, evolution and realization of the requirements are also considered as the product innovation process. With the progress of the product design process, it derives from qualitative to quantitative, from the description of the original user's requirements to an actual, detailed and quantitative product design depiction process to satisfy the user's needs. Based on this idea, the definition of requirement is proposed as follows.

[Definition 1] Requirement, *R*: it is a behavior that the subjects use the appropriate tools or symbol system to describe the characteristics, functions and attributes of the future products, also the expectation for the certain functions and attributes of the future products in the product design process.

In this definition, the subjects include the customers and designers. In addition, according to the requirements sources, the requirements may also be classified as the customer requirement and designer requirement.

Here, the "customer" not only refers to the individual user, but also a targeted group due to their function requirements of the future products. Customer requirement for the products comes from the usage process of the products or the actual function need. The target group customers give the formal description of the products according to their expectation which is so called customer requirement. To some degree, it depends on the status on subjective understanding of customers and their design knowledge. Traditionally, designer requirement is often used as the starting point of concept design instead of customer requirement concept design, which may lead to function inconsistency between final product and the actual customer requirements, since there are the discrepancy and the information asymmetry in the designer's and customer's experience, knowledge, social status, and so on.

Designer requirement takes the customer requirements as the input and consideration factors, and the designers are required to propose the design objective which can meet this customer requirement. The subject of the designer requirements is the designers or the combination of designer with the machine or computer system which is designed to complete the certain design task. Some design terminology may be used to express the requirements and some tools or approaches shall be adopted to analyze and deal with the customer requirements in order to gain the description of the product characteristics, functions and attributes. Therefore, the designer requirement is the extended description of the customer requirement for future products.

B. Function in Product Design Process

As an important factor to be considered by researchers in every engineering field, function is always related to some factors such as target, behavior, structure and environment in some way. Because of the diversity of function and the variety of function application field, function should be defined respectively according to the nature of problem and the characteristics of system.

Gruber et al [5] proposes that the product design can be considered as ontology as an explicit detailed specification of a conceptualization, focusing on the subjects, concepts and other entity in the research field and their relationship. It may be a symbol of an entity or represents a concept or object. The conceptualization feature of this is an abstract and simplified expression of the objective world. Its essence is the existence and lies in making the implicit information become explicit. From this point of view, function and ontology have something in common, since they all take the objective existence as "core" [6][7]. Both function and ontology can be used in other engineering fields and be evolved into the concept of Engineering Ontology [8]. And Kitamura et al [9] puts forward the concept of function ontology and establishes the function structure framework of product model in order to describe the knowledge in conceptual design process.

In view of this, ontology can be considered as a special expression form, which is an extension of function in form, and can be used as an important concept in order to define function. In this paper, the definition of function in the product design process is given as follows.

[Definition 2] Function, *F*: is the essence of the existing objects or the specific ontology of the requirements, which represents some behavior attributes, and is an abstract conceptualized description for the fact.

In this definition, the "existing objects" include not only the individual users or user groups at the bottom of the original design process, but also the objects to be designed in the adaptive design. The "specific ontology" refers to the detailed specification of the existing objects, with the description to be easily processed by the computer, i.e. the abstract conceptualized description. Such a definition of the function can also be understood as the description of the relation, behavior or contents of the specific subject with a certain language in the specific field or scope. The advantage of the definition is to emphasize the objective existence of the function. Although there may be different representation forms due to the influence of the working environment, the objective existence of functions is inherent no matter how it changes. And, the introduced concept of ontology can reveal the behavior attribute of the objective existence of function. By incorporating the concept of ontology, the traditional function-behavior-structure (*FBS*) model for product design process is greatly simplified.

C. Requirement Function in Product Design Process

According to the definition of function mentioned above, it is obvious that the objective existence of functions makes the requirement be impacted by the working environment. And in

the actual product design process, the expression forms of requirements may vary because of the effect of different person or different environment. However, the function, as the description of the conceptualized essence, will remain unchanged, no matter how the forms of requirement change. Therefore, the function corresponds to the inherent ontology object of the essential existence while the requirement corresponds to the representation forms of the function. Here, the concept of the requirement function is put forward to introduce the essence of requirement.

[Definition 3] Requirement Function, *RF*: is the induction and summarization of the essential requirements in multiple forms for future products as expressed by the specific subjects; and is the expression of product functions in forms of requirements.

Corresponding to the two forms of “requirement”, i.e., customer requirement and designer requirement, *RF* is also divided into two types: Customer Requirement Function (*CRF*) and Designer Requirement Function (*DRF*). The *CRF* refers to the essence of function fulfillment that is expected by customer in the final products. *DRF* means the design control parameter derived by the designers according to the customer requirement function, and function information which is easy for design description. As for the *DRF*, it is the direct expression form in the function transformation process, and is the realization of product function description in the knowledge space of the designers. Whether it is correct or not will directly determine the degree of the consistency between the function revealed by the final products and the original customer requirements, and affect the correctness of the function solving result. *RF* is always the convergent expression of the requirements and also the summarization of the essence of the requirements.

D. Relation among Requirement, Function and *RF*

Requirement representation has multiple forms and multiple meanings, while the corresponding function remains essentially unchanged. Requirement function is a general term to define the “requirement” with the attribute of function to avoid the various interpretations in the design process or in the requirement information transfer and processing. In this way, the ambiguous requirement information of customers with the multiple restricted factors, such as the market, the cost and so on can be defined and analyzed more accurately.

Function is the core of *RF* and *RF* gives the function formalization of requirement, which expresses and organizes the qualitative requirement information with specific functional paradigm.

III. FUNCTION FLOW-BASED PRODUCT DESIGN PROCESS MODEL

A. Product Design Process in the Domain of Function

Generally, most of the product design process models only describe its structure, corresponding knowledge and behavior without involving with the functions and its knowledge. It is very important to concentrate on the function’s form and content along with the progress of design process by combining the function concept into the product design process, in order to

correctly acquire customer requirement with no ambiguity and to realize the product design scheme and prototype solving that meet the original function. Taking this into consideration, the product design process, in the function domain, is defined as follows.

[Definition 4] Product Design Process, *PDP*: is a human-computer interaction from qualitative to quantitative product description and solving design process, in which the start point is customer requirement, the goal is to satisfy the requirements function. The definition can also be expressed as:

$$PDP = \langle RF, Customer, Designer, Machine \rangle$$

Because of the existence of uncertainty of system and the qualitative feature of customer requirements at the initial phase of the product design process, any single solving process cannot represent or reflect all the behavioural characteristics of the product design. Only with the progress of the design process, the continuous accumulation of product design knowledge, and gradual decrease of the freedom in the design, the function are realized and become more and more explicit.

Traditionally, *PDP* was divided into multiple phases including task clarification phase, conceptual design phase, embodiment design phase and detail design phase etc [10]. Although these traditional division methods can be used to help the designers to clarify the design tasks to be performed at each phase, there are more possibilities of personal intervention with a more detailed division of the design phase and the customer requirement information. As a result, designer requirement information is more likely to be lost or misinterpreted due to the subjective consciousness. In addition, such a division of the *PDP* is usually based on the design requirements concluded by the designers, which is different from the fact that the actual *PDP* is based on the customer requirement.

In this paper, the functions are considered as the axis to ensure that the *CRF* is focused on. The *PDP* is divided into two phases, the Conceptual Design Phase (*CDP*) and Detail Design Phase (*DDP*). The former is a qualitative design phase while the latter is the quantitative design phase. The scope covered by *CDP* starts from the qualitative customer requirement information that is put forward by the customers and ends till the designer presents the Product Principle Structure Model (*PPSM*) that can meet the *CRF*. The *CDP* contains two levels: Customer Requirement Function Level (*CRFL*) and Design Requirement Function Level (*DRFL*) which includes the acquirement, solution, and optimization of *DRF*. The *DDP*, which is input the generated *PPSM* in conceptual design phase, includes the contents of Concurrent Detail Design Level (*CDDL*). According to the concurrent engineering solution methods, such as Design for X (*DFX*), *CAD* tools, Product Information Modelling (*PIM*), Manufacturing Process Modelling (*MPM*), Rapid Prototype Technology (*RPT*), Assembly Sequence Planning (*ASP*), and so on, the detailed description of product can be achieved through seeking for the physical components or function solid. The *PDP* based on this function transformation flow can be shown as the Fig. 1.

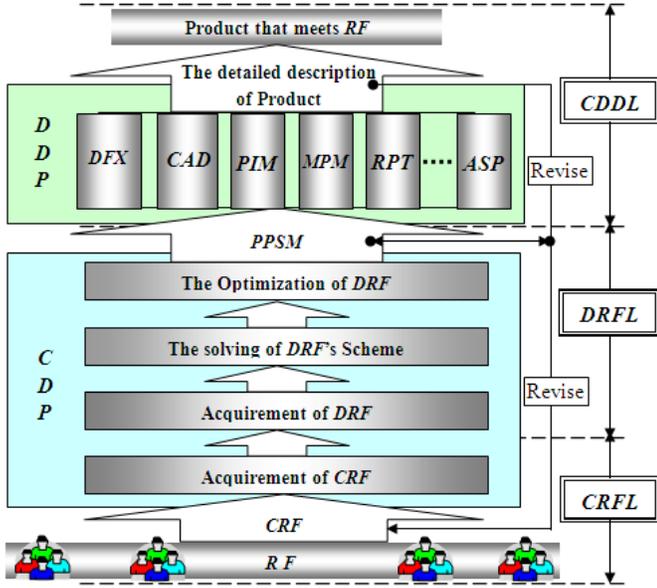


Fig. 1 The PDP based on function transformation flow

In this process, the essential aim of product design is clarified, i.e., to meet the customer requirements, not the designer requirement. It is the customer requirements that dominate the whole design process. Meanwhile, the division of the qualitative phase and quantitative phase can help designer select and apply different design methods according to the characteristics of CDP or DDP accordingly.

B. A Hierarchy model of Intermediate Product in PDP

As mentioned above, CRFL fulfils the acquirement of CRF from CR, while DRFL transforms the CRF into DRF which can be recognized by the designers, and solve and optimize the DRF to draw PPSM. In order to clarify the transmission of the function in this level, DRFL is divided into three sub-levels, corresponding to the content acquirement of CRF, the solving of DRF, and the optimization of DRF. These are sub-level of Design Requirement Function Acquisition (*sDRFA*), sub-level of Design Requirement Function Solution (*sDRFS*) and sub-level of Design Requirement Function Solution Optimization (*sDRFSO*). At CDDL, the quantitative design of the conceptual products, conceived in DRFL, shall be completed.

In the hierarchy structure, there are various partial design results for each level, which may realize different requirement functions of their respective levels. In this paper, Intermediate Product (*IP*) is used to represent the solutions relating to the different *RF* at each level. The *IP* of CRFL is defined as Requirement Product (*RP*). Since DRFL includes three sub-levels, i.e., *sDRFA*, *sDRFS* and *sDRFSO*, there are three different *IP*s also for these levels. The *sDRFA* Design mainly realize the function acquisition of design requirement, so the *IP* of *sDRFA* is defined as function product (*FP*). The *sDRFS* solves the DRF of *sDRFA*, the result of which is only a product principle structure model. It should be further optimized through *sDRFSO* in order to form the CDP. As a result, the *IP*

corresponding to the latter two sub-levels are called Principal Product (*PP*) and Conceptual Product (*CP*) respectively. The *IP* of CDDL is Detail Product (*DP*). According to this concept of *IP* and PDP in the domain of function, a hierarchy model of *IP* in PDP corresponding to Process-Phase-Level-Sub-level-*IP* can be established as shown in Fig. 2. This hierarchy structure makes the solution of the *RF* in the design process convenient for target decomposition and function refinement and analysis.

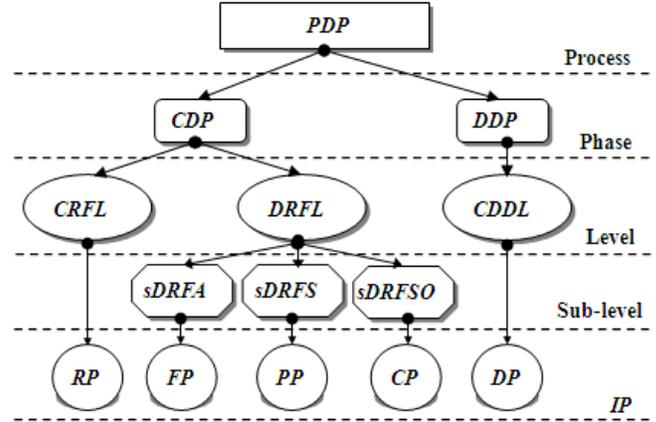


Fig. 2 A hierarchy model of *IP* in PDP

C. The Function Flow in PDP

In the traditional Function-Behavior-Structure (*FBS*) model of PDP [11], as soon as the product functions are defined, it is focused on the acquisition of the corresponding PPSM and the solution of detail design through the mapping relationship among function, behavior and structure. And once entering the DDP, the key point, to be considered by designers, is how to realize the function through specific structure. Less attention is paid to the changes of functions and function itself in design progress. Therefore, to some degree, the function, in the model of *FBS*, is considered as a kind of static, unchanged object. Whereas, in factual PDP, function's internal requirements and external forms are changing along with the design progress in difference design phases. That means the content and form of function all change from phase to phase. This is consistent with the behavior attribute of function based on the above definition and model. So it is very important to understand how the function is correctly acquired, reasoned and evolved in PDP.

Data interactions, control transmission and information iteration in the PDP form data flow, control flow and information flow. Similarly, the continual evolution and transformation of function along with design progress in PDP also lead to function flow. So the definition of function flow is as follows.

[Definition 5]Function Flow. According to the concept of the input and output flow of the system, all the expression forms of different functions at each phase and level are integrated with the *IP* attributes in the design progress to meet the customer requirement. In this process, the contents and forms of function is made transformed as the design progress

moving forward, extending and repeating. Such function transformation process among different phase is called function flow.

Based on this definition, in the above mentioned two phases, *CDP* and *DDP* in *PDP*, shown in Fig. 2, the contents and forms of function change with the ongoing of the design progress, represent the three function forms, *CRF*, *DRF* and assembly function (*AF*). This indicates that function does not remain constant in the design progress. On the contrary, it changes and transforms along with the progress of design process.

In the hierarchy model of *IP*, the corresponding *IP* of *CRFL* is *RP*, representing the *CRF*. Although there are three sub-levels in *DRFL* with three *IP* of *FP*, *PP* and *CP*, they are all focused on the *DRF*. The *DP* with the detailed structure and attribute is the *IP* of *CDDL*, representing the *AF* of products. So, the expression of function flow in the design process under the hierarchy model of *IP* is shown in Fig. 3.

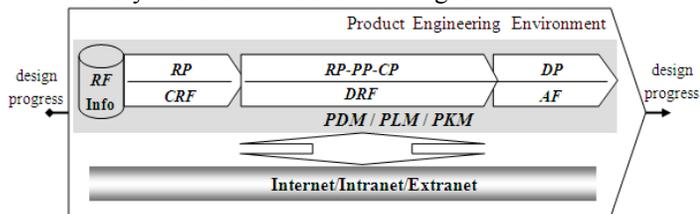


Fig. 3 The function flow-based product process model

All these process are also carried out in product engineering environment, which includes the web environment and platform of information interaction, such as Product Data Management/Product Lifecycle Management /Product Knowledge Management (PDM/PLM/PKM) on the Internet/Intranet/Extranet basis.

Fig. 3 indicates that the function flow can be formed in the *PDP* based on the product engineering network environment, in which the different *IPs* and corresponding functions are the core. It is worth to mention that the function flow is the form of function transmission represented by the different functions of the *IPs* along with the progress of product design process.

IV. CONCLUSION AND FUTURE WORKS

In this paper, requirement function acquisition, transformation, solution and optimization, which constitute the function flow in product design process, is proposed as the key to realize the smooth and non-ambiguity transformation from the qualitative information of conceptual design phase to the quantitative information of detail design phase. Based on definition of requirement, function and requirement function, adequate descriptions of customer and designer requirement function can assure the original innovation in conceptual design phase and reduce information misinterpretation between different design processes as much as possible. And a function flow-based integrated product design process model as well as a hierarchy intermediate product structure is presented in order to realize the maximum consistency between the function characteristics of actual products and the original customer requirement.

However, there remain many open issues to be studied. The ontology representation and extract for function flow and associate knowledge transfer still need much work. And how to build the synchronous mapping relationship between the customer knowledge space and designer knowledge space also needs further discussed.

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