International Journal of Industrial Engineering, 13(3), 270-279, 2006.

AN INTEGRATED PRODUCT AND PROCESS DEVELOPMENT MODEL SUPPORTING LIFE CYCLE

Hong-Zhong Huang [1], Ying-Kui Gu [2], Zhi-Gang Tian [3]
1. School of Mechatronics Engineering, University of Electronic Science and Technology of China, Chengdu, 610054, China, hzhuang@uestc.edu.cn
2. School of Mechanical Engineering, Dalian University of Technology, Dalian, 116023, China
3. Department of Mechanical Engineering, University of Alberta, Edmonton, Alberta, T6G 2G8, Canada

Product life cycle is a continuous and variational time process and can be divided into a sequence of life phases. In this paper, product development process is viewed as an optimization process to find a process set under given evaluation factors so that the set of evaluation indices of entire life cycle will be optimized. Based on this, the model of integrated product and process development is developed by which most development issues can be described as constrained optimization problems. The process of product function decomposition is presented and the state equations of process, energy, material and information of product development are developed. The mapping relationships among functional domain, physical domain and process domain are analyzed. Finally, a case is given to illustrate the proposed method.

Significance: The model of integrated product and process development, the state equations and the mapping relationships among different design domains are analyzed from different perspectives. It provides not only a systematic approach to accomplish the integrated product and process development, but also an integrated decision support mechanism for the product developers. The approach developed in this paper is significant to improve product quality, reduce life cycle cost, shorten development time and fully utilize the design resource.

Keywords: Life cycle design, Process modeling, Integrated product and process development, Function decomposition, Equation of state.

(Received 14 July 2004; Accepted in revised form 12 July 2005)

1. INTRODUCTION

Product development is usually regarded as the set of activities beginning with the perception of a market opportunity and ending in the production, sale, and delivery of a product. However, because more and more requirements arise from every possible step of a product life cycle, the concept of product development has been expanded so that it includes consideration of the entire life cycle of a product. The life cycle design and concurrent engineering have been developed to meet the increasing requirements coming from every step of a product life cycle. Quality, cost and development time are the primary factors that can embody the competition capability of a product. The objective of life cycle design is to improve product quality, reduce development cost, and shorten development time. Life cycle design inherits the ideology of concurrent engineering, and it is a new design method to take the value of the whole life cycle into account in the initial design stage. By adopting life cycle design, not only the functions and structures of a product, but also the whole process of product life cycle, such as design, manufacturing, assembling, operating, maintaining, recycling, and so on, are to be designed. Therefore, all the factors related to product life cycle could be programmed and optimized well in design stage.

It has been realized that it is the product design stage that plays the most important role in a product's performance during its entire life cycle. Based on the decomposition of product life cycle, and considering the requirements of customers, producer and environment, many research issues are raised including: design for manufacture (DFM), design for assembly (DFA), design for maintainability (DFMa), design for disassembly (DFD), design for recyclability (DFR), design for reliability (DFRe), and so on (Yu, 2002; Tang, Qin and Peng, 2001; Kuo, Huang and Zhang, 2001). These issues sometimes are referred as Design for "X" (DFX). Since 1990s, hundreds of papers have been published pertaining to DFX applications in manufacturing, and most of them are widely distributed over many different disciplines and publications.

In design stage, the most important task is to build the models of product and its development process. Many models were built and many design methods were presented, such as structure-oriented product model (Krause and Kjellberg, 1993), geometry-oriented product model (Yu, 2002; Krause and Kjellberg, 1993), feature-oriented product model (Krause and Kjellberg, 1993; Brunetti and Golob, 2000; Gayretli and Abdalla, 1999), knowledge-based product model (Krause and Kjellberg, 1993; Gayretli and Abdalla, 1999), integrated product model (Yan, Zhou and Donald, 1999; Negele, Fricke, Schrepfer and Hartlein, 1999; Smith and Morrow, 1999; Lee, Sause and Hong, 1998), Petri net model (Huang, Zhou and Zu, 2005; Yu, 2002; Zhao and Jin, 2000), objective-oriented process model (Gayretli and Abdalla, 1999; Liang and Grady, 1998; Ahmadi, Roemer and Wang, 2001), agent-based process model (Yu, 2002; Krause and Kjellberg, 1993), axiomatic design model (Harutunian, Nordlund, Tate and Suh, 1996), and so on.

The research issues and models mentioned above describe a product design process from different perspectives, and are of avail to develop the product in different stages of product life cycle. However, these methods have their limitation to some extent. They only aim to one stage of product life cycle or one performance index of a product, and the integrity, consistency and interaction of design objectives and constraints are ignored to some extent.

In another viewpoint, product development is a spiral evolution process subject to development constraints. In such a process, many factors, such as quality, cost, time and so on, should be considered and optimized at the same time. However, because of the dynamic uncertainty, fuzzy multi-factors (Gu and Huang, 2004), and because of time coupling and constraints coupling, the product design process become more complex than before. Therefore, product development should be viewed as a multi-objective optimization problem. The objective and subjective factors related to product development should be integrated in the product and its development process modeling.

In this paper, the product development process is viewed as an optimization process to find a process set under given evaluation factors such that the set of evaluation indices of entire life cycle is optimized. The model of integrated product and process development is developed and the process of product function decomposition is described. The state equations of process, energy, material and information of product development are developed. Based on the axiomatic design principle, the mapping relationships among functional domain, physical domain and process domain are analyzed.

This paper is organized as follows. Section 2 and Section 3 describe the process of product function decomposition and the model of integrated product and process development respectively. Section 4 describes the state equations of development process. Section 5 describes the mapping relationships among different design domains. An example is given to illustrate the definitions and mapping relationships proposed above in Section 6. Conclusions are provided in Section 7.

2. PRODUCT FUNCTION DECOMPOSITION

Function is the abstract description of tasks that the product should complete, and it should reflect the purpose and characteristics that the product should have. Therefore, the intention of product development is to realize one or more given functions and satisfy customer's requirements. As we know, function can be divided into sub-functions. Generally speaking, the realization of function F depends on the activities of product's parts or components. Every part can complete part of the function, and the integration of all sub-functions results in the general function. F can be denoted by

$$F = \{F_i \in F \mid i = 1,2,\cdots,n\} \tag{1}$$

Therefore, the primary task of product development is to divide the general function into sub-functions. It is the so-called function granulation.

Function granulation is a process of function decomposition step by step, until the sub-functions are independent. The decomposition process is depicted in Figure 1.

After the function is decomposed, the parallel sub-functions in the same branch or the sub-functions in different branches should be independent. But the non-parallel sub-functions in the same branch have interrelationships. From the viewpoint of function granulation we can see that the high-level functions can affect and determine the low-level functions. The transfer relationship between high-level functions and low-level functions is from bottom to top. The low-level function has direct influence on the high-level function. If low-level function isn't realized, the high-level function couldn't be realized. However, if the high-level function isn't realized, the low-level function may still be realized. Take the sub-function *FR*21 for example, the functions *FR*21, *FR*22 and *FR*23 are in the same branch, and they are independent. *FR*21 is not in the same branch as *FR*11, *FR*12 and *FR*1. So, *FR*21 is independent with *FR*11, *FR*12 and *FR*1. However, *FR*2, *FR*211, *FR*212 and *FR*213 are in the same branch, but they are not parallel. *FR*2, *FR*211, *FR*212 and *FR*213 have interrelationships among them. The realization of *FR*21 is the result of completiing *FR*211, *FR*212 and *FR*213, and it is the base of the realization of *FR*2. If *FR*21 isn't realized, *FR*2 couldn't be realized, but *FR*211, *FR*212 and *FR*213 may still be realized.

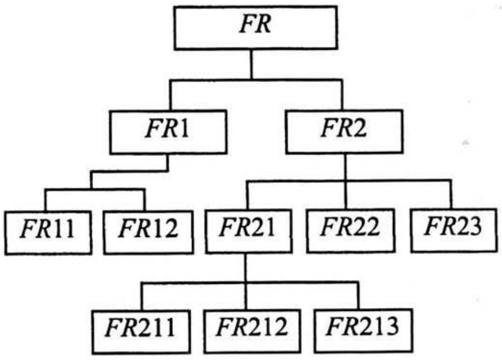

Figure 1. Granulation of product function

3. MODEL OF INTEGRATED PRODUCT AND PROCESS DEVELOPMENT

Process is a basic unit of activity that is carried out during a product life cycle. In this sense, the entire development process can be viewed as a set of activities that their physical meanings vary continuously along with time. Product development is a dynamic, sequential, time-change process P, and each stage of it can be viewed as a process granule P_i. The entire process P can be denoted as

$$P = \{P_i \in P \mid i = 1,2,\cdots,n\} \tag{2}$$

The granularity of processes depends on the product developer's concern and interest, and the appearance of processes varies along with a product's entering its different life phases (Yan, Zhou and Donald, 1999).

Because process varies along with time, the process granule has time characteristic. Process P is an ordered sequence that extends along with the main thread of product life cycle.

The process granules in product life cycle are not isolated. There exist close relationships among them. The granule P_i is the evolutional result of the $i-1$ granules before it. At the same time, P_i has important influence on the following $n-i$ processes, and its output is the direct input of the following $i+1$th process. That is to say that the activities in one life phase may influence the activities in its posterior life phase. As a result, in order to improve the performance of one life phase, not only should the activities in this life phase be adjusted, the activities in its prior life phases should be adjusted as well. However, in order to simplify the modeling analysis, when the process P_i is analyzed, it must be isolated from the other processes.

To carry out one process of life cycle design has many means, which can produce many design schema. Take the processing of an axis as example, it can be processed by lathing, milling, planning, grinding, and so on. In another example, when we select a sensor, we can adopt the series-wound mode or the shunt-wound mode based on the type of sensor and the practical measure environment. Moreover, the design of product's parameters has very important influence on the performance of product life cycle. Therefore, how to select an optimal means to realize process requirements and how to design product's parameters are the key problems of development process programming. However, no matter how to program the development process, or adopting what means to establish the process model, the basic goal is to improve product's quality, cut life cycle cost and shorten development time. So, the effective process-programming model should be established to realize the following two intentions, and the different design requirements, designer's preferences should be taken into account too.

(1) Selecting an optimal design plan. (2) Optimizing design parameters.

To product life cycle design, the evaluation factors such as cost, reliability, weight, environmental friendliness, can be selected to evaluate its corresponding performance.

Let $C=(c_1, c_2, \cdots, c_j, \cdots, c_m)$ be vector set of evaluation factors of development process. To a sub-process P_i, its evaluation index vector can be denoted as follows.

$$C_i = \begin{pmatrix} c_{i1} & \cdots & c_{ij} & \cdots & c_{im} \end{pmatrix}^T = \begin{pmatrix} c_1(P_i) & \cdots & c_j(P_i) & \cdots & c_m(P_i) \end{pmatrix}^T \tag{3}$$

where $c_j(P_i)$ is the jth index of phase P_i. It could be the degree of membership or degree of satisfaction of certain preference.

We have n evaluation index vectors. The set of evaluation indices of entire life cycle can be expressed as follows.

$$C = \begin{pmatrix} C_1 & C_2 & \cdots & C_j & \cdots & C_n \end{pmatrix} = \begin{pmatrix} c_1(P_1) & \cdots & c_1(P_i) & \cdots & c_1(P_n) \\ \vdots & & \vdots & & \vdots \\ c_j(P_1) & \cdots & c_j(P_i) & \cdots & c_j(P_n) \\ \vdots & & \vdots & & \vdots \\ c_m(P_1) & \cdots & c_m(P_i) & \cdots & c_m(P_n) \end{pmatrix} \tag{4}$$

Thus, there are various transforms of C that are defined to evaluate the product's overall performance from different perspectives.

To an evaluation index c_j, the integration effect in the entire process can be denoted as follows.

(1) Linear integration:

$$c_j = \sum_{i=1}^{n} c_j(P_i) \tag{5}$$

(2) Non-linear integration. The non-linear integration effect is complicated. Take the integration effect of product as example, its integration mode can be expressed as

$$c_j = \prod_{i=1}^{n} c_j(P_i) \tag{6}$$

Whether the life cycle design is good or not is not decided only by one evaluation factor. The goal of life cycle design is to make the whole system and all performances optimal by effective process programming.

In the design process, not all sub-processes have the same influence on the whole process. Based on the influence degree of P_i to P, a general weight α_i is proposed and applied to each life phase to evaluate its important degree, and is constrained by

$$\sum_{i=1}^{n} \alpha_i = 1, \quad (i = 1, 2, \cdots, n) \tag{7}$$

Thus, Eqs (5), (6) can be substituted by

$$c_j = \sum_{i=1}^{n} \alpha_i c_j(P_i) \tag{8}$$

$$c_j = \prod_{i=1}^{n} \alpha_i c_j(P_i) \tag{9}$$

Moreover, every evaluation factor c_j has different influence on process granule P_i. Based on its effect degree, weight β_{ij} is proposed and applied to each evaluation factor to evaluate its important degree, and is constrained by

$$\sum_{j=1}^{m} \beta_{ij} = 1, \quad (j = 1, 2, \cdots, m) \tag{10}$$

After the normalization of all evaluation factors, the evaluation vector set C can be transformed into the evaluation index $C^{'}$.

$$C^{'} = \sum_{i=1}^{n} \left[\alpha_i \sum_{j=1}^{m} (\beta_{ij} c_{ij}) \right] \tag{11}$$

where α_i denotes the influence weight of ith process to the entire process. c_{ij} denotes the influence weight of jth evaluation factor of ith process. β_{ij} denotes the influence weight of jth evaluation factor to process P_i.

Different C (or C') describes the attributes and performances of the product from different aspects. Therefore, the essence of life cycle design is to find a best method to optimize C and realize the function requirements of the process under given evaluation factors. In other words, the modeling of product and its development can be expressed as: "find a process set under given evaluation factors such that C (or C') is optimized".

4. STATE EQUATION OF LIFE CYCLE

The life cycle process P is a function of time. So, at each moment t, the process has different states. Product life cycle is a sequential process that realizes the function of each stage under its control mechanism and constraints.

Let x_t, y_t, u_t be the input, output and state of process P_t at the moment t respectively. The process P_t can be defined by the following state equation.

$$\begin{cases} u_{t+1} = f(x_t, u_t) \\ y_t = g(x_t, u_t) \end{cases} \tag{12}$$

Let $U^{t+1}(x_t, u_t)$, X^t and $Y^t(x_t, u_t)$ be the possible value set. The state equation of P_t can be denoted by

$$\begin{cases} U^{t+1} = F(x_t, u_t) \\ Y^t = G(x_t, u_t) \end{cases} \tag{13}$$

where F and G express the mapping of sub-set space from $X \times U$ to U and Y respectively.

The state equation indicates that each process can be viewed as an input-output process under its constraints. That is to say, under the state u_t, the process system can be defined as the integration of time ordered pairs (x_t, y_t), and the necessary condition is that (x_t, y_t) is a segment closure. One has

$$P_t = \{(x_t, y_t)\}, (x_t \in X, y_t \in Y) \tag{14}$$

where (x_t, y_t) is an input-output pair of P_t. Therefore, a complicated process system can be simplified as a simply mathematics model.

5. MAPPING RELATIONSHIP AMONG DESIGN DOMAINS

The design process is to develop and select a means to satisfy design objectives, subject to a series of constraints. Axiomatic design describes the design process as the mapping activity between customer domain, functional domain, physical domain, and process domain. Therefore, design is an optimization process to transform customer requirements into design specifications, design specifications into physical solutions, and design solutions into manufacturing processes, by which customer requirements are satisfied (Harutunian, Nordlund, Tate and Suh, 1996).

5.1 Mapping Relationship between Function Domain and Physical Domain

To function domain and physical domain, let FR be the functional requirement set, $FR = (FR1 \quad FR2 \quad \cdots \quad FRn)$, DP be design parameter set, $DP = (DP1 \quad DP2 \quad \cdots \quad DPm)$. The mapping activity from the physical domain to the function domain is to realize the functional requirements by configuring the design parameters. That is to realize the following mapping.

$$f : DP^m \to FR^n \tag{15}$$

Based on the practical design problems, the mapping can be classified into two categories, i.e. one to one mapping and one to more mapping. When the granulation of function requirement is small enough, all the mappings from physical domain to function domain can be defined as one to one mapping.

Functional requirement FR is a function of design parameter DP, i.e.

$$FR = A \cdot DP \tag{16}$$

where FR, A, DP are matrix of functional requirement, matrix of mapping, matrix of design parameter, respectively.

Generally speaking, FR is a multi-variable function of DP, and can be denoted as follows:

$$f_i(DP1, DP2, \cdots, DPm) = FR_i, \quad (i = 1,2,\cdots,n) \tag{17}$$

From the view of function, design parameter DP is an explanatory variable, and its variation will make the corresponding variation of functional requirement FR. However, in design process, FR is a design goal. The design process is to realize FR by optimizing design resources, which is implemented through the variation and optimization of DP. Therefore, the variation of DP shouldn't weaken FR, but instead make FR be realized more effectively.

The mapping matrix from the physical domain to the functional domain can be obtained by the differential of function expression (Harutunian, Nordlund, Tate and Suh, 1996), i.e.

$$A = \begin{pmatrix} A_{11} & \cdots & A_{1j} & \cdots & A_{1m} \\ \vdots & & \vdots & & \vdots \\ A_{i1} & \cdots & A_{ij} & \cdots & A_{im} \\ \vdots & & \vdots & & \vdots \\ A_{n1} & \cdots & A_{nj} & \cdots & A_{nm} \end{pmatrix} = \frac{\partial(f_1, f_2, \cdots, f_n)}{\partial(DP1, DP2, \cdots, DPm)} \tag{18}$$

Mapping matrix A reflects the influence degree of design parameters DP on the function requirements FR.

From the system viewpoint, the function domain and the physical domain compose a system, and functional requirement universe Ω_1 and design parameter universe Ω_2 are its sub-systems. There exist some corresponding relationships among the elements in the two sets, such that

$$R = \Omega_1 \circ \Omega_2 = \{(FRi, DPj) | FRi \in \Omega_1, DPj \in \Omega_2, DPj = R(FRi), FRi = R(DPj)\}, \quad i, j = 1,2,\cdots,n \tag{19}$$

where $\Omega_1 \circ \Omega_2$ is directed product of Ω_1 and Ω_2, and it reflects the relationship between the two sub-sets. Mapping matrix A is the direct representation of this relationship, and this relationship also reflects the concept of input-output pair described in the process state equation.

5.2 Mapping Relationship between Physical Domain and Process Domain

The same as the mapping relationship between the function domain and the physical domain, the selection of design parameter DP depends on the configuring of process variable PV. Let PV be the process variable set, $PV = (PV1 \quad PV2 \quad \cdots \quad PVk)$. The mapping activity between the physical domain and the process domain is to realize the configuring of design parameters in the physical domain by the configuration of process variables in the process domain. That is to realize the following mapping

$$g : PV^k \rightarrow DP^m \tag{20}$$

Design parameter DP is the function of process variable PV, and can be expressed as follows:

$$DP = B \cdot PV \tag{21}$$

where DP, B, PV are matrix of design parameters, matrix of mapping, matrix of process variables, respectively.

Similarly, DP is a multi-variable function of PV, and can be denoted as follows:

$$g_j(PV1, PV2, \cdots, PVk) = DP_j, \quad (j = 1,2,\cdots,m) \tag{22}$$

The mapping matrix B is obtained by differentiation of design parameter expression. Thus

$$B=\begin{pmatrix} B_{11} & \cdots & B_{1j} & \cdots & B_{1k} \\ \vdots & & \vdots & & \vdots \\ B_{i1} & \cdots & B_{ij} & \cdots & B_{ik} \\ \vdots & & \vdots & & \vdots \\ B_{m1} & \cdots & B_{mj} & \cdots & B_{mk} \end{pmatrix}=\frac{\partial(g_1,g_2,\cdots,g_m)}{\partial(PV1,PV2,\cdots,PVk)} \tag{23}$$

Mapping matrix B reflects the influence degree of process variables PV to design parameters DP.

5.3 Mapping Relationships among Function Domain, Physical Domain and Process Domain

There exists mapping relationship between the function domain and the physical domain as follows.

$$f: DP^m \to FR^n$$

The mapping relationship between the physical domain and the process domain is as follows:

$$g: PV^k \to DP^m$$

Therefore, the mapping relationship between function domain and process domain is as follows:

$$h: PV^k \to FR^n \tag{24}$$

where $h = f \circ g$ is the composite mapping relationship.

From the analysis above we can see that the configuration of process variables has important influence on the realization of functional requirements. Therefore, function requirements FR is the composite function of process variables PV. The function can be expressed as follows:

$$FR = C \cdot PV \tag{25}$$

where FR, C, PV are matrices of functional requirement, matrix of composite mapping, matrix of process variable, respectively.

The mapping matrix C can be obtained by differentiation of composite function above.

$$\Delta(f \circ g)=\frac{\partial(f_1,f_2,\cdots,f_n)}{\partial(DP1,DP2,\cdots,DPm)}\cdot\frac{\partial(g_1,g_2,\cdots,g_m)}{\partial(PV1,PV2,\cdots,PVk)}\Delta PV \tag{26}$$

$$C=\frac{\partial(f_1,f_2,\cdots,f_n)}{\partial(DP1,DP2,\cdots,DPm)}\cdot\frac{\partial(g_1,g_2,\cdots,g_m)}{\partial(PV1,PV2,\cdots,PVk)}=A \circ B \tag{27}$$

6. CASE STUDY

The development of an excavator is used as an example to illustrate the design method proposed above. By analyzing the market requirements and the functional requirements, the general function of the excavator was identified and the function decomposition table was established as shown in Table 1. Based on the axiomatic design theory, the function-physical mapping table of an excavator was established as shown in Table 2. Thus, we can get many conceptual design solutions.

Considering the special requirements of power, energy transferring and distribution, the physical elements, such as gasoline engine, electromotor, chain drive, strip drive, couldn't satisfy the operation requirements of excavator, and they should be deleted from the function-physical mapping table. Thus, the total number of solutions is reduced more.

After detailed analysis, two design concepts are decided.

Composition 1: Positive-bucket excavator with pedrail

Its physical solution is: A1+B1+C2+D2+E1+F1+G1+H2+I2

Composition 2: Positive-bucket excavator with tyre

Its physical solution is: A3+B1+C1+D2+E2+F1+G2+H1+I3

Table 1. The function decomposition of an excavator

The general function of an excavator (FR)	Driving (FR1)	Energy transforming (FR11)	
		Energy transferring and distribution (FR12)	
	Operation (FR2)	Excavating (FR21)	Bucket (FR211)
			Push and press (FR212)
		Lifting (FR22)	
		Rotating (FR23)	
	Moving (FR3)		
	Controlling (FR4)	Staring and braking (FR41)	
		Shifting (FR42)	
		Display of meter (FR43)	

Table 2. The function-physical mapping table of an excavator

Function elements \ Physical elements		No.			
		1	2	3	4
A	Push and press	Rack	Wire rope	Oil cylinder	
B	Bucket	Positive bucket	Reverse bucket	grab bucket	
C	Lifting	Hydraulic cylinder	Wire rope	Gear-rack	
D	Rotating	Inner gear transmission	Outer gear transmission	Hydraulic wheel	
E	Moving	Pedrail mode	Tyre mode	Step by step mode	Track- wheel
F	Energy transforming	Diesel engine	Gasoline engine	Electromotor	
G	Energy transferring and distribution	Gear box	Oil pump	Chain drive	Strip drive
H	Shifting	Hydraulic mode	Gear mode	Hydraulic- gear	Electric mode
I	Staring and braking	Strip	Break	Pad break	Conic

After the design concept was identified, the concept should be designed in detail. However, because the complexity of development and the different development environment, many detail design solutions can be gotten. The evaluation index C (or C') can be used to evaluate and select design solutions.

It is supposed that the development process has four sub-processes, such as design, manufacturing, assembling and disassembling. The development process is denoted as follows.

$$P=(p_1,p_2,p_3,p_4)=(\text{design, manufacturing, assembling, disassembling}) \tag{28}$$

Each sub-process has different influences on the whole development process. The weights of sub-processes are given as follows by experts.

$$w=(w_1,w_2,w_3,w_4)=(0.4,0.3,0.2,0.1) \tag{29}$$

The factors, such as excavating force, speed, noise, vibration, convenience of operation, safety, and so on, are selected as influence factors. So, the evaluation vector can be denoted as

$$\begin{aligned} U &= (u_1,u_2,u_3,u_4,u_5,u_6) \\ &= (\text{excavatingforce,speed,noise,vibration, convenience of operation,safety}) \end{aligned} \tag{30}$$

Each evaluation factor has different influences on the whole performance. The weights of evaluation factors are obtained as follows by the fuzzy comprehensive evaluation.

$$v=(v_1,v_2,v_3,v_4,v_5,v_6)=(0.25,0.25,0.1,0.1,0.15,0.15) \tag{31}$$

According to Eq. (8), the influence of every evaluation factor on the whole process are denoted by

$$e_i=\sum_{j=1}^{4} w_j u_{ij}\ , \quad i=1,2,\cdots,6 \tag{32}$$

where u_{ij} is the influence degree of the ith evaluation factor on the jth process.

We hope that the excavating force is as big as possible, speed as fast as possible, noise as small as possible, convenience of operation as good as possible, and safety as high as possible. That is to say that the excavator should have the biggest satisfactory degree. According to Eq. (11), the evaluation index of the whole process can be given as follows.

$$C' = \sum_{i=1}^{6} v_i e_i \tag{33}$$

The higher the value of C', the better the performance of the excavator is.

It is assumed that we have two design concepts, the satisfactory degree of their evaluation factors are obtained as follows respectively.

$$C_1 = (C_{11}, C_{12}, C_{13}, C_{14}, C_{15}, C_{16}) = \begin{pmatrix} 0.95 & 0.90 & 0.80 & 0.50 \\ 0.88 & 0.80 & 0.80 & 0.20 \\ 0.70 & 0.85 & 0.85 & 0.20 \\ 0.85 & 0.80 & 0.75 & 0.20 \\ 0.85 & 0.80 & 0.70 & 0.70 \\ 0.90 & 0.85 & 0.80 & 0.40 \end{pmatrix}$$

$$C_2 = (C_{21}, C_{22}, C_{23}, C_{24}, C_{25}, C_{26}) = \begin{pmatrix} 0.95 & 0.95 & 0.80 & 0.50 \\ 0.98 & 0.90 & 0.85 & 0.30 \\ 0.70 & 0.85 & 0.80 & 0.20 \\ 0.87 & 0.76 & 0.83 & 0.20 \\ 0.80 & 0.80 & 0.70 & 0.65 \\ 0.88 & 0.83 & 0.80 & 0.70 \end{pmatrix}$$

According to Eq. (4), the total evaluation index of every evaluation factor in the whole development process can be given as follows respectively.

$$C_1 = (C_{11}, C_{12}, C_{13}, C_{14}, C_{15}, C_{16}) = (0.860, 0.772, 0.725, 0.750, 0.790, 0.815)$$
$$C_2 = (C_{21}, C_{22}, C_{23}, C_{24}, C_{25}, C_{26}) = (0.875, 0.862, 0.715, 0.762, 0.765, 0.831)$$

According to Eq. (33), the evaluation index (i.e. satisfactory degree) of each design concept was obtained as follows respectively.

$$C_1' = 0.7963, \quad C_2' = 0.8214, \quad C_1' < C_2'$$

It is concluded that the design concept 2 is better than concept 1.

7. CONCLUSIONS

Typical characteristics that can be used to describe product development process are: creative and innovative, dynamic, interdisciplinary, strongly interrelated, strongly parallel, interactive, planning intensive, uncertain and risky. Therefore, many factors related to a product life cycle should be taken into account when the product and its development process models are analyzed and established. In this paper, the model of integrated product and process development, the state equations and the mapping relationships among different design domains were analyzed from different perspectives. It provides not only a systematic approach to accomplish the integrated product and process development, but also an integrated decision support mechanism for the product developers. The approach developed in this paper is significant to improve product quality, cut life cycle cost, shorten development time and fully utilize the design resource.

8. ACKNOWLEDGEMENT

This research was partially supported by the National Natural Science Foundation of China under the contract number

50175010, and the National Excellent Doctoral Dissertation Special Foundation of China under the contract number 200232.

9. REFERENCES

1. Ahmadi, R., Roemer, T. A. and Wang, R. H., (2001). Structuring product development processes. European Journal of Operational Research, 130: 539-558.
2. Brunetti, G. and Golob, B., (2000). A feature-based approach towards an integrated product model including conceptual design information. Computer-Aided Design, 32: 877-887.
3. Chai, B. H. and Chan, W., (2001). Design & Control, (China Machine Press, Beijing).
4. Gayretli, A. and Abdalla, H. S., (1999). An object-oriented constraints-based system for concurrent product development. Robotics and Computer-Integrated Manufacturing, 15: 133-144.
5. Gu, Y. K. and Huang, H. Z., (2004). Fuzzy mapping between physical domain and function domain in design process. International Journal of Uncertainty, Fuzziness and Knowledge-Based Systems, 12: 7-20.
6. Harutunian, V., Nordlund, M., Tate, D. and Suh, N. P., (1996). Decision making software tools for product development based on axiomatic design theory. Annals of the CIRP, 45: 135-139.
7. Hsiao, S. W., (2002). Concurrent design method for development a new product. Industrial Ergonomics, 29: 41-55.
8. Huang, H. Z., Zhou, F. and Zu, X., (2005). Petri nets based coordination cddomponent for CSCW Environment. Journal of Mechanical Science and Technology, 19: 1123-1130.
9. Krause, K. L. and Kjellberg, F., (1993). Product modeling. Annals of the CIRP, 42: 695-706.
10. Kuo, T. C., Huang, S. H. and Zhang, H. C., (2001). Design for manufacture and design for 'X': concepts, applications, and perspectives. Computers & Industrial Engineering, 41: 241-260.
11. Lee, C. H., Sause, R. and Hong, N. K., (1998). Overview of entity-based integrated design product and process models. Advances in Engineering Software, 29: 809-823.
12. Liang, W. Y. and Grady, P. O', (1998). Design with objects: an approach to objective-oriented design. Iowa Internet Laboratory Technical Report, TR98-01 (Iowa, USA).
13. Negele, H., Fricke, E., Schrepfer, L. and Hartlein, N., (1999). Modeling of integrated product development processes. Proceeding of Annual Symposium of INCOSE (UK).
14. Smith, R. P. and Morrow, J. A., (1999). Product development process modeling. Design Studies, 20: 237-261.
15. Tang, J. S., Qin, G. S. and Peng, Y. W., (2001). State-of the art and developing trends of product life cycle integration. Manufacture Automation, 23: 1-4.
16. Vegte, W. F. V. D., Pulles, J. P. W. and Vergeest, J. S. M., (2001). Towards computer-supported inclusion and integration of life cycle processes in product conceptualization based on the processes tree. Automation in Construction, 10: 731-740.
17. Yan, P. T., Zhou, M. C. and Donald, S., (1999). An integrated product and process development methodology: concept formulation. Robotic and Computer Integrated Manufacturing, 15: 201-210.
18. Yu, J., (2002). China Mechanical Design Canon: Vol. 1, (Press of Science and Technology, Nanchang).