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Product Development Process Modeling Based on Information Feedback and Requirement Cooperation

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Abstract: The objective of product development process modeling is to satisfy the process requirements. There exist both conflicting and cooperative relationships among the process requirements and these relationships could deeply affect the development process modeling. In this study, the macro-feedback and micro-feedback models of product development process are developed based on information feedback. By analyzing the conflicting or cooperative relationships among the process requirements, the reasoning scheme for inferring the relationships between the requirements and information, and the feedback control mechanism are developed. Using the proposed method, three reorganization activities, reorganizing the constraints, reorganizing the process, and reorganizing the structure of a designer's preference, can be carried out to transfer the balance point of the development process from one point to another or be optimized at the initial place. The case study shows that the macro-feedback and micro-feedback modeling of a product development process based on information feedback and requirement cooperation is an important method to realize lifecycle design, optimize the whole development process and product performance, capture the designer's preferences, and satisfy the process requirements.

Key Words: process modeling, dynamic model, requirement cooperation, information feedback, quality function deployment (QFD), fuzzy logic.

1. Introduction

Requirements are the kernel of product development process modeling. In essence, process requirements include two parts that come from subjective and objective aspects, respectively. The subjective requirement is presented by the consumer to adapt to a change in market environment. The objective requirement is the function requirement that the product itself should have to satisfy the customer's requirement. It is necessary to develop an effective and logical development process model to realize the process requirements.

From the product development one can see that it is not only a process of resource moving, but also a complex evolution process subject to development constraints [1]. In this process, the design information is transformed and accumulated. The programming and modeling of the development process are very important for developing a good product that has a stronger market competence. By doing so effectively, the development process can be optimized and the design information can be accumulated well. This can also improve the concurrent degree, improve product quality, and cut development cost and time. However, in a practical development process, because of dynamic uncertainty, time overlapping, constraint coupling of product development process, and imperfection and fuzziness of design information [2], the resource moving is slow and information accumulation may stop, thus hampering the process flow.

From the structure of product development, it can be seen that the product development process resembles a network (process net), where processes are highly interconnected, including feedback-loops and interactions on different hierarchical levels. The typical characteristics that can be used to describe the development process are: creative and innovative, dynamic, interdisciplinary, strongly interrelated, strongly parallel, iterative, communication intensive, anticipatory, planning intensive, uncertain, and risky [3].

In order to emphasize the dynamic characteristics of the product development process and the important influence of information interaction, some design

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theories and methods, such as dynamics of concurrent engineering [4], manufacturing informatics [5], information theory of engineering [6], intelligent real design [7], and so on, were studied. Ren [4] established the dynamic system model of concurrent engineering, and presented the approximate solutions of the dynamic model. Ren [4] also analyzed some reasons that result in the instability of the product development process. Wood and Agogino [6] presented the concept of IRTD (intelligent real-time design) based on the theory of expected value of information. The IRTD emphasizes the real-time and dynamic design, and can make the designers pay attention to gathering the design information, by which the uncertainty that has the most important influence on the design objectives in the design process can be reduced. Wood and Agogino [6] pointed out that the uncertainty in the design process could come from design constraints, design intentions, design parameters, evaluation models, and customer's preferences. Therefore, the designer can reduce the uncertainty by renewing the preference function, design models, and design parameters. Zhang [5] developed manufacturing informatics, and studied manufacturing information deeply. Negele et al. [3] developed a method to map and interconnect the processes of all different engineering disciplines, and pointed out that development processes behave like process nets, including manifold interrelations and feedback-loops. Feng et al. [8] developed a fuzzy mapping mechanism of requirements onto functions in detail. Kusiak et al. [9] pointed out that the design process could be adjusted or reorganized by adjusting or reorganizing the design structure matrix and design constraints. Fu [10] studied the concurrent schedule and cooperation of the product development process, and presented the integrated schedule theory architecture and model about the product development process.

The objective of this study is to develop an interactive development process model based on feedback-control theory and requirement collaboration. The conflicting or cooperative relationships among the process requirements, the feedback-control mechanism of design information, and the effect of design information on these conflicting or cooperative relationships are analyzed in detail. The model for realizing the process requirements was developed from two aspects, namely, macro-process and micro-process. The application of this model shows that this is an important method to realizing the lifecycle design and optimizing the whole development process and product performance.

This article is organized as follows. First, the feedback-control theory in the product development process is introduced in Section 2. Second, the macro-feedback and micro-feedback models of the product development process are developed in Sections 3 and 4, respectively. Third, the recognition of the requirement relationships and the reasoning scheme for inferring the relationships between requirements and information are discussed in Section 5. An illustrative case is given in Section 6. Finally, conclusions comprise Section 7.

2. Feedback Control in the Product Development Process

An important method for enhancing the stability of a system and improving the quality of a system is to improve the feedback process and make the feedback prompt and reasonable, as shown in Figure 1.

There are two methods to improve the feedback process [4]. One is to simplify the development process and delete redundant processes that add no value to the system output (object). The other is to emphasize the feedback and control of both the output (object) and each subprocess (state).

In order to make the system output change according to the designer's expected output, all the states in the system should be controlled well. There are two necessary and sufficient conditions that should be satisfied [4].

1. System output can affect all the states in the system.
2. All the information in the system should be obtained.

The feedback in a system can be classified into positive feedback, negative feedback, complete feedback, and local feedback. The negative feedback reduces the environmental effect on the object, and maintains the system at the initial balance point. The positive feedback deflects the initial balance point of the system and transfers it from one balance point to another.

Product development itself is a complex, dynamic, and uncertain system. The feedback-control theory is very important in product development process modeling. A change in the outer environment could have some influence on the entire development process, which may not necessarily be harmful to product development. Since the disturbance of the outer environment can break the balance of the system and push the system to make fast response to outer

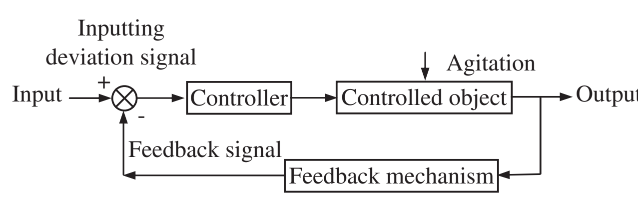

Figure 1. Feedback control system.

change so as to avoid disturbance, it can make the system reach a new balance point. This new balance point may be better than the older one, and may have a stronger market life-force and competition-force. For example, when the conditions of the outer market change, or new customer requirements or new technologies appear, in order to ensure that the product has a stronger market life-force and competition-force, the new information should be fed back into the entire development process promptly to improve or reorganize the system. It is the positive feedback process that deflects the initial balance point of the complex development process and finds a new balance point to adapt to the new environment. Therefore, in product development process modeling, the positive feedback process is often used to complete the spiral evolution of development process step-by-step.

3. Macro-feedback Model of Product Development Process

The limitation of people's cognition and the complexity of the design cause many uncertain factors in each developmental stage of a product. These uncertain factors disturb the development system to some extent and make the system unstable. For this reason, the development process may be stopped or suspended. Such an instability in the development process can affect the product quality, prolong the development time, and increase the development cost. Information interaction and feedback in the dynamic system helps the system maintain a dynamic balance. Therefore, in order to reduce the instability, product development is viewed as a dynamic system. A macro-feedback model of the product development process has been established and is described in Figure 2 [1].

From Figure 2 it can be seen, that the model can be divided into two parts by the diagonal. The upper right part describes the proceeding state of the development process. The black points in the figure represent constraint evaluation points. The satisfaction state to constraint evaluation points can decide the proceeding modes of the development process (i.e., serial mode and parallel mode) and the process flow. However, it should be pointed out that the satisfaction of constraint evaluation points is a necessary condition to decide the process flow but not the sufficient condition [1].

The feedback state of process can be depicted by the bottom left part of Figure 2. Let $X = (X_{i-2}, X_{i-1}, X_i, X_{i+1}, X_{i+2})$ be the state vector of the dynamic system. The state vector could not only be the state that the designer masters the customer's requirements or the customers understand and express their requirements, or the state that the designer masters the design technology related to the product in the design process, but could also be the manufacturing state in the development, or the state that the product satisfies the customer's requirements after it was checked and tried out. The state vector has a time characteristic, and its dimension depends on the complexity of the system. Moreover, the state vector is a fuzzy concept. The ideal state can be expressed as 1, and the most ambiguous state can be expressed as 0 [1].

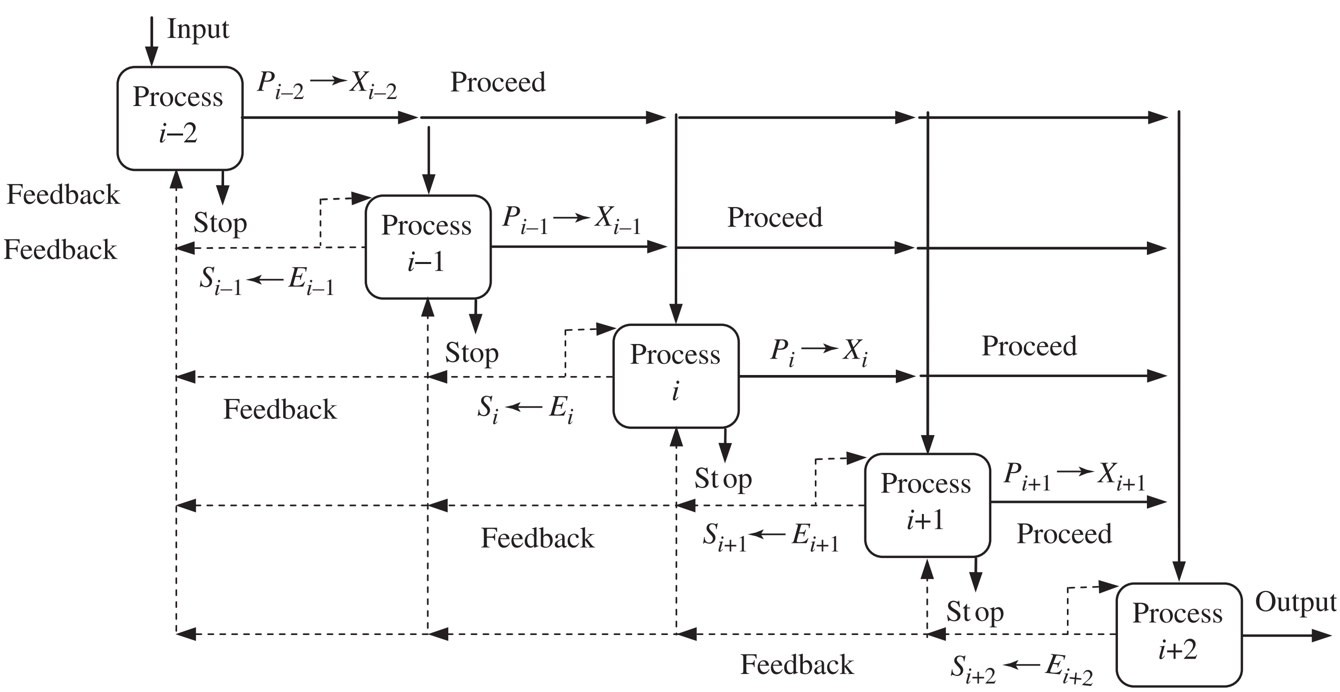

Figure 2. Development process model based on feedback control theory.

Let $P = (P_{i-2}, P_{i-1}, P_i, P_{i+1}, P_{i+2})$ be the set of state vectors of the dynamic system.

$$P_k : X_{k-1} \times \prod_{n=k}^{i+2} S_n \to X_k, \quad k = i-2, i-1, i, i+1, i+2 \tag{1}$$

Let $E = (E_{i-2}, E_{i-1}, E_i, E_{i+1}, E_{i+2})$ be the feedback state after the process is evaluated.

$$E_k : X_k \to S_k, \quad k = i-2, i-1, i, i+1, i+2 \tag{2}$$

The feedback information in the system can be classified into three categories as follows.

1. The fuzzy, stochastic, and uncertain factors in the development process.
2. The factors that should be improved to improve the requirements after the development process is evaluated.
3. The additional influence accompanied with the change in coupling factors.

State feedback is the precondition that can make the development process work successfully. As the process proceeds, the process information should be fed back to all the forward processes. From the viewpoint of control theory, this is a full-feedback model. Information feedback can make the constraints adjust in advance and make design information self-supplement, which can eliminate the influence of system perturbation and make the development process collaborative and optimal.

Theoretically speaking, the full feedback of information not only benefits the process collaboration and information interaction, but also allows the design information to be fed back completely and embodies the dynamic characteristic adequately. However, under the full-feedback state, the more feedback loops, the more difficult the operation is. Moreover, it can result in redundant feedback of design information. Redundant feedback is the main reason for making a system unstable and can result in the poor convergence of system optimization. Therefore, in order to increase the maneuverability of process programming, and also to adapt the requirements of multifunction team and working mode of multi-disciplinary, not only should the number of feedback loops be reduced, but the correct design information should also be fed back to the correct location at the right time, and also the redundant feedback of design information should be reduced.

On the basis of the dimension and the degree of complexity of the development process, the degree-of-freedom of information interaction, and the degree of information sharing, the development model based on feedback control theory can be classified as a serial feedback information model, a division and feedback process model, a concurrent process model, and a parallel process model. The advantages and disadvantages of each model are discussed in [10].

4. Micro-feedback Model of Product Development Process

The whole development process is composed of many interrelated subprocesses. Each subprocess can be viewed as an intact microcosmic subsystem in the whole macro-process. The realization process of the microcosmic subsystem is the same as that of the whole process. That is to say, it must follow four processes, including process requirement analysis, process design, process implementation, and process maintenance. In these processes, due to the uncertainty and fuzziness of process requirements, process constraints, process relationships, and process realization conditions, there exist many feedback processes. In order to eliminate the adverse influence of process feedback on process realization and performance, the information feedback and interaction should be emphasized to optimize the development process. The feedback process is shown in Figure 3. Both the plus feedback process and the minus feedback process should be strengthened to transfer or improve the balance point of the development process at the initial point. Thus, design resources and process programming can be optimized.

In the actual development process, the multistage quality function deployment (QFD) is the best tool to realize the process requirements, as shown in Figure 4 [11]. Due to many uncertain and fuzzy factors and conflicting relationships in the process, fuzzy logic was introduced into process modeling. Fuzzy logic can

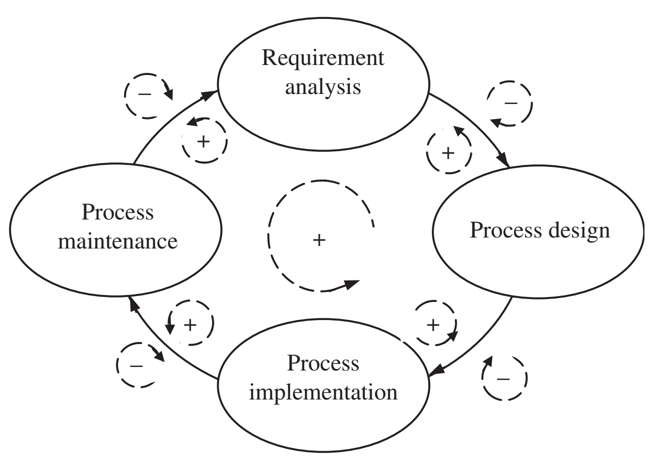

Figure 3. The realization process of process requirements.

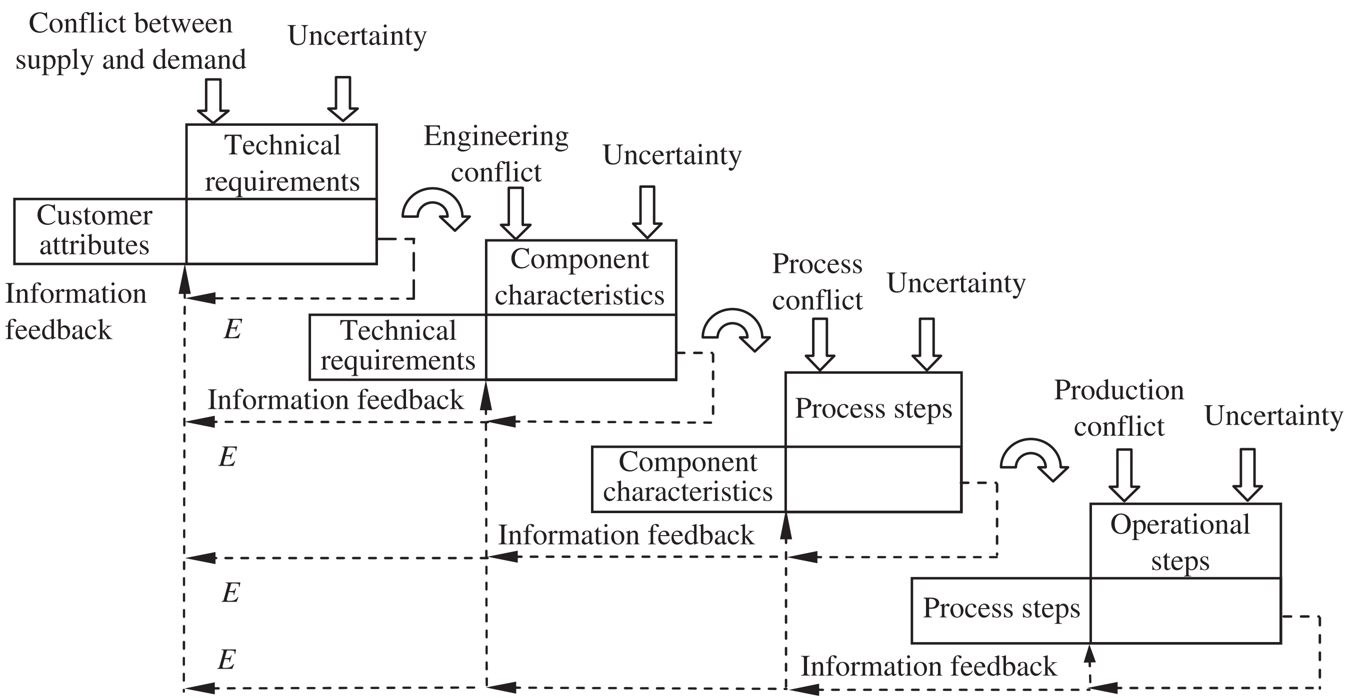

Figure 4. Multistage QFD for realizing process requirements based on information feedback.

handle inexact information and linguistic variables in a mathematically well-defined way that simulates the processing of information in natural language communication. By doing so, fuzzy multistage QFD is developed to realize the process requirements. By adopting multistage QFD, the balance point of QFD can be transferred from one point to another, which makes the development process respond to the change in market environment, technology, and requirements.

5. Relationships between Information Feedback and Process Requirements

Temponi et al. [12] pointed out that the identification of relationships between requirements is often time-consuming. Sometimes, it is difficult to arrive at a consentaneous point on a particular relationship between requirements. To address this issue, Temponi et al. developed a fuzzy logic-based extension of QFD to capture the imprecise requirements to both facilitate communication among team members and have a formal representation of the requirements. In this part, two reasoning schemes are also developed, one to infer the relationships between requirements, the other to infer the relationships between requirements and feedback information.

5.1 Requirement Relation Recognition

Process requirements can be described in many modes. For example, one simple requirement is that the cost for developing the product should be low, or the reliability of the product should be high. However, some process requirements are coupled, e.g., one coupled requirement can be described as that the development cost should be low and the manufacturing quality should be high. Also, the environment influence should be good. In this case, the coupled requirement should be decoupled to facilitate analysis. The coupled requirement can be divided into three simple requirements, i.e., low development cost, high manufacturing quality, and good environment influence.

Let R be the process requirement and R^n be the requirement space $R \subseteq R^n$, $R = \langle R_1, R_2, \ldots, R_n \rangle$. Process requirement can be classified into two categories: qualitative requirement and quantitative requirement. The effectiveness degree of information on quantitative requirement can be identified by its differential coefficient but on qualitative requirement can only be judged by the fuzzy relationship between design information and requirement. Qualitative requirements are usually expressed in natural language which is vague and ambiguous in nature. However, during the design process, it is still desirable to express the requirements using linguistic terms because it facilitates communication among different parties. Fuzzy logic has been well-known for its capability of formally representing the semantics of linguistic terms. Hence, fuzzy logic has been adopted to represent the requirements.

In the design process, some requirements impose constraints on the development processes such as the cost for the construction of the system and the resources that could be consumed in the development process. Some requirements impose constraints on the realization of a system and describe the desired features of a product, such as consistency and reliability. Generally, there exist two relationships among the requirements, i.e., dependent and independent of each other.

The dependent or independent relationship can be defined as the different impacts on the satisfaction degree of a requirement. Let R_1 and R_2 be two different requirements in the same process:

1. *Independent of each other*. The satisfaction of one requirement does not have any impact on the satisfaction of the other requirement. That is, any change in the satisfaction of one requirement will not affect the satisfaction of the other requirement. It can be denoted as $R_1 \bigcirc R_2$.
2. *Directly dependent*. Any change in the satisfaction of one requirement will affect the satisfaction of the other requirement (partially or completely). It can be denoted as $R_1 \circledcirc R_2$.

The dependent relationship can be further classified into the following two categories.

- *R_1 and R_2 are conflicting*. The directions of increase R_1 and R_2 are opposite. An increase in the satisfaction degree of one requirement decreases the satisfaction degree of the other. It can be denoted as $R_1 \ominus R_2$. The conflicting degree can be expressed by $Conf(R_1, R_2)$.

$$Conf(R_1, R_2) = \mu_{\tilde{C}}(R_1, R_2) \tag{3}$$

where $\tilde{C}$ is a fuzzy set. The conflicting degree can be linguistically expressed as 'strong', 'medium', and 'weak'. $\mu_{\tilde{C}}(R_1, R_2)$ is the membership grade and can be used to express the conflicting degree.

- *R_1 and R_2 are cooperative*. The increase directions of R_1 and R_2 are consistent with each other. An increase in the satisfaction degree of one requirement will result in the increase of the satisfaction degree of the other. It can be denoted as $R_1 \oplus R_2$. The cooperative degree can be expressed by $Coop(R_1, R_2)$.

$$Coop(R_1, R_2) = \mu_{\tilde{C}}(R_1, R_2) \tag{4}$$

where $\tilde{C}$ is a fuzzy set. The cooperative degree can be linguistically expressed as 'strong', 'medium', and 'weak'. $\mu_{\tilde{C}}(R_1,R_2)$ is the membership grade, and can be used to express the cooperative degree.

5.2 Recognition of Conflicting and Cooperative Relationships Between Requirements

Let R_1 and R_2 be two different requirements of a process p. Under a process state i, the satisfaction degrees of R_1 and R_2 are $Sat_{R_1}(p^i)$ and $Sat_{R_2}(p^i)$, respectively. Under a process state j, the satisfaction degrees of R_1 and R_2 are $Sat_{R_1}(p^j)$ and $Sat_{R_2}(p^j)$, respectively. If

$$\left(Sat_{R_1}(p^i) - Sat_{R_1}(p^j)\right) \times \left(Sat_{R_2}(p^i) - Sat_{R_2}(p^j)\right) < 0 \tag{5}$$

then one can say R_1 and R_2 are conflicting, and can be denoted as $R_1 \ominus R_2$. If

$$\left(Sat_{R_1}(p^i) - Sat_{R_1}(p^j)\right) \times \left(Sat_{R_2}(p^i) - Sat_{R_2}(p^j)\right) > 0 \tag{6}$$

then one can say R_1 and R_2 are cooperative, and can be denoted as $R_1 \oplus R_2$.

5.3 The Influence of Feedback Information on Process Requirements

R_1, R_2, and R_3 are three different process requirements of one process. E is the feedback information. The following reasoning scheme is used to infer the requirements and information relationships.

1. If $R_1 \bigcirc R_2$, $R_2 \bigcirc R_3$, then $R_1 \bigcirc R_3$; If E can change the satisfaction degree of R_1, it does not have any impact on that of R_2 and R_3.
2. If $R_1 \oplus R_2$ and $R_2 \oplus R_3$, then $R_1 \oplus R_3$; If E can improve the satisfaction degree of R_1, then E can improve the satisfaction degree of R_2 and R_3, too.
3. If $R_1 \oplus R_2$ and $R_2 \ominus R_3$, then $R_1 \ominus R_3$; If E can improve the satisfaction degree of R_1, then E can improve the satisfaction degree of R_2, but decrease that of R_3.
4. If $R_1 \ominus R_2$ and $R_2 \ominus R_3$, then $R_1 \oplus R_3$; If E can improve the satisfaction degree of R_1, then E can decrease the satisfaction degree of R_2, but improve that of R_3.

That is to say, the conflicting or cooperative relationships between the requirements, and the impact of information on requirements have transitivity and reflexivity. The improvement scope of process requirement is dependent on their conflicting or cooperative degrees. Let $\bigoplus$ and $\circleddash$ denote the conflicting or cooperative degree, such as strong, medium, and weak. The following reasoning scheme is used to infer the requirements improvement.

Table 1. Rules to infer cooperative relationships and information influence from identified cooperative relationships.

	Coop(R_1, R_2) $E \rightarrow$Sat(R_1) (↑)		
Coop(R_1, R_3)$E \rightarrow$ Sat(R_3) (↑)	**Strong**	**Medium**	**Weak**
Coop(R_2, R_3) $E \rightarrow$Sat(R_2) (↑)			
Strong	Strong	Medium	Weak
Medium	Medium	Medium	Weak
Weak	Weak	Weak	Weak

Table 2. Rules to infer conflicting relationships and information influence.

	Coop(R_1, R_2) $E \rightarrow$Sat(R_1) (↑)		
Conf(R_1, R_3) $E \rightarrow$Sat(R_3) (↓)	**Strong**	**Medium**	**Weak**
Conf(R_2, R_3) $E \rightarrow$Sat(R_2) (↑)			
Strong	Strong	Medium	Weak
Medium	Medium	Medium	Weak
Weak	Weak	Weak	Weak

Table 3. Rules for inferring cooperative relationships and information influence from identified conflicting relationships.

	Conf(R_1, R_2) $E \rightarrow$Sat(R_1) (↑)		
Coop(R_1, R_3) $E \rightarrow$Sat(R_3) (↑)	**Strong**	**Medium**	**Weak**
Conf(R_2, R_3) $E \rightarrow$Sat(R_2) (↓)			
Strong	Strong	Medium	Weak
Medium	Medium	Medium	Weak
Weak	Weak	Weak	Weak

1. If $R_1 \oplus R_2$ and $R_2 \oplus R_3$, then $R_1 \oplus R_3$; If E can greatly increase the satisfaction degree of R_1, then it can also greatly increase that of R_2 and R_3.
2. If $R_1 \oplus R_2$ and $R_2 \ominus R_3$, then $R_1 \ominus R_3$; If E can greatly increase the satisfaction degree of R_1, then it can also greatly increase that of R_2, but greatly decrease that of R_3.
3. If $R_1 \ominus R_2$ and $R_2 \ominus R_3$, then $R_1 \oplus R_3$; If E can greatly increase the satisfaction degree of R_1, then it can greatly decrease that of R_2, but also greatly increase that of R_3.

Thus, the rules to infer cooperative or conflicting relationships among R_1, R_2, and R_3 can be developed, as shown in Tables 1–3.

From the relationships above, one can see that the degree of influence of the design information on conflicting or cooperative relationships between requirements is parallel to the conflicting or cooperative relationships. These relationships are very important for the development of the relationship matrix in multistage QFD.

In product development, there exist many requirements at the same time, and the conflicting and cooperative relationships between requirements are coexistent. However, the complexity of product development itself restricts the possibility of total satisfaction of all process requirements at the same time. A repeat of the material flow process is not allowed in the product development process. Therefore, the interaction and feedback of information flow should be emphasized to ensure that the process requirements are satisfied. Moreover, it is very important to arrange the feedback process, feedback information flow, and information quantity of development process so as to satisfy all the process requirements. In this process, the designer's preference and the relative important degree of process requirement should be taken into account.

5.4 Reorganization Activities Accompanied with Information Feedback

After the feedback information was fed back, the multifunction design team carried out three reorganization activities, based on the practicable development environment to optimize the development process, as follows.

1. *Reorganizing constraints*. Owing to the identity of a design resource, there exist constraint relations among the design parameters. Based on the feedback information, the constraint relations can be adjusted or changed to optimize the process structure.
2. *Reorganizing process*. The process structure can be modified by adjusting the time or logic relation of the process. Thus, the process that can happen only under the sufficient and necessary condition could happen under sufficient or necessary condition.
3. *Reorganizing the structure of designer's preference*. A designer's preference can, to a great extent, decide the relations among design processes. If the satisfactory design cannot be achieved under the initial preference structure, and it is difficult to change the rigid constraints, the designer's preference should be looser to satisfy the requirements of optimization design by adjusting the boundary value of ranges of the preference function.

6. Case Study

Take the multistage QFD of a reducer's concept design as an example to illustrate the model developed above. The primary multistage QFD model was developed as shown in Figure 5. Because of the fuzziness

(a)

CR			Idegree	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}
				Technical requirements (TR)									
CR	C_1	C_{11}	4	◎		○							
		C_{12}	5		◎								
		C_{13}	9	△		◎							
		C_{14}	5				◎						
	C_2	C_{21}	8		△	△		△		◎	○	△	○
		C_{22}	6						○		◎		
	C_3	C_{31}	8		△			△	△	△		◎	○
		C_{32}	9		△			△	△	○		○	◎
	C_4	C_{41}	7		○								
Object value				< 500 150 350	Good	550kN	± 3	60 dB	Good	< 1500 yuan	> 96%	> 99%	6 years
Idegree of TR				45	83	101	45	25	35	98	78	98	129

Relationships:
◎ Strong
○ Medium
△ Weak

(b)

		Object value	Idegree	F_{11}	F_{12}	F_{21}	F_{22}	F_{31}	F_{32}	F_{41}	F_{42}	F_{43}	F_{51}	F_{52}
				Features of key parts (FKP)										
				F_1		F_2		F_3		F_4			F_5	
TR	TR1	99%	7.5				◎	○			◎	◎	○	◎
	TR2	6 years	8				◎	○			○	○		
	TR3	<1500	7.9	○	◎	○	○	◎	◎	○		○	○	◎
Weight				24	72	24	163	118	72	24	92	115	46	139

(c)

	Process flow (P)	P_1	P_2		P_3		P_4	P_5	P_6	P_7		P_8			P_9		P_{10}
	Process feature (PF)	PF_{11}	PF_{21}	PF_{22}	PF_{31}	PF_{32}	PF_{41}	PF_{51}	PF_{61}	PF_{71}	PF_{72}	PF_{81}	PF_{82}	PF_{83}	PF_{91}	PF_{92}	PF_{10}
FKP	Criterion																
FKP_1	240 HB		○	○						◎	◎						
FKP_2			◎	◎			○			○	○				◎	○	
FKP_3	7-8 grade																
FKP_4					○	◎	○	○	○			○	◎	○		○	
Process criterion		Different process criterion based on actual environment															

Figure 5. Initial multistage QFD for realizing process requirements. (a) Product planning matrix of the reducer, (b) parts deployment matrix of the reducer, and (c) process planning matrix of the reducer.

and complexity of the design process, and because of the variety of requirements and market, the primary scheme cannot satisfy the designer's expected requirements. Therefore, the primary QFD model should be modified and the information feedback among all the design stages should be speeded up. The physical meanings of symbols in Figure 5 are listed in Tables 4–6. The feedback information is listed in Table 7.

In the stage of developing a product programming matrix, new technical requirements ⟨fast replacement⟩ and new customer requirements ⟨low noise⟩ appear. The

Table 4. The physical meanings of symbols in Figure 5(a).

Symbol	Meaning	Symbol	Meaning	Symbol	Meaning
TR	Technical requirement	T_9	Reliability	C_{21}	Sound price
T_1	Dimension	T_{10}	Lifetime	C_{22}	High transmission efficiency
T_2	Seal	CR	Customer requirement	C_3	Reliability
T_3	Carrying capacity	C_1	Function requirement	C_{31}	Safety
T_4	Range of velocity	C_{11}	Dimension	C_{32}	Longtime
T_5	Maximal noise	C_{12}	Good seal	C_4	Maintainability
T_6	Lubrication	C_{13}	Big carrying capacity	C_{41}	Fast replacement
T_7	Price	C_{14}	Low speed variety	Idegree	Important degree
T_8	Transmission efficiency	C_2	Economics		

Table 5. The physical meanings of symbols in Figure 5(b).

Symbol	Meaning	Symbol	Meaning	Symbol	Meaning
FKP	Features of key parts	F_3	Bearing	F_5	Lubrication oil
F_1	Electromotor	F_{31}	Style	F_{51}	Style
F_{11}	Power	F_{32}	Precision	F_{52}	Viscosity
F_{12}	Rotating speed	F_4	Gear	TR	Technical requirement
F_2	Axis	F_{41}	Material	TR_1	Reliability
F_{21}	Material	F_{42}	Surface hardness	TR_2	Lifetime
F_{22}	Strength	F_{43}	Strength	TR_3	Price

Table 6. The physical meanings of symbols in Figure 5(c).

Symbol	Meaning	Symbol	Meaning	Symbol	Meaning
P	Process flow	PF	Process feature	PF_{81}	Wear of grinding wheel
P_1	Checking blank	PF_{11}	Checking blank according to rules	PF_{82}	Grinding depth
P_2	Normalizing	PF_{21}	Time of temperature-holding	PF_{83}	Feed-in degree
P_3	Cutting blank	PF_{22}	Temperature of temperature-holding	PF_{91}	Gear honing precision
P_4	Hobbing gear	PF_{31}	Feed-in degree	PF_{92}	Mesh speed
P_5	Machining groove	PF_{32}	Cutting depth	PF_{10}	Storing according to rules
P_6	Shaving gear	PF_{41}	Wear of hobs	FKP	Features of key parts
P_7	High frequency quenching	PF_{51}	Wear of tools	FKP_1	Gear hardness
P_8	Internal grinding	PF_{61}	Wear of shaving cutter	FKP_2	Gear strength
P_9	Honing gear	PF_{71}	Electric current frequency	FKP_3	Gear precision
P_{10}	Storage	PF_{72}	Electric current quantity	FKP_4	Gear material

Table 7. Feedback information.

E	Feedback information
E_1	
E_{11}	Appearing new technical requirement: fast replacement
E_{12}	Appearing new customer requirement: low noise
E_{13}	New market orientation: emphasizing product price
E_{14}	Changing object value: the maximal noise: 55 dB
E_{15}	Changing the correlative relationships and the important degree of customer requirements to avoid priority transferring of technical requirements
E_2	
E_{21}	Changing technical requirement: emphasizing transmission efficiency
E_{22}	Changing the object value of technical requirements and its important degree
E_{23}	Changing the feature of key part: emphasizing process precision of gear
E_3	
E_{31}	Changing process flow: testing machining precision before the product is stored
E_{32}	Changing process features: emphasizing the precision of gear indexing movement devices or appearing new process features
E_{33}	Changing the features of key parts
E_{34}	Changing the criterion of part features

(a)

Relationships: ◎ Strong ○ Medium △ Weak

CR			Idegree	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}	T_{11}
CR	C_1	C_{11}	4	◎		○								
		C_{12}	5		◎									○
		C_{13}	9	△		◎								
		C_{14}	5				◎		△					
		C_{15}	6				○	◎	○	○	△			
	C_2	C_{21}	9		○	○		△		◎	○	△	○	
		C_{22}	6						◎		◎			
	C_3	C_{31}	8		△			△	△	△		◎	○	
		C_{32}	8		△			△	△	○		○	◎	
	C_4	C_{41}	7		○									◎
Object value				<500,150,350	Good	550kN	±3%	55dB	Good	<1500 yuan	> 96%	> 99%	6 years	Good
Idegree of TR				45	109	120	63	79	111	158	87	105	123	78

Technical requirements (TR)

Feedback

Information feedback $E_1 = < E_{11}, E_{12}, E_{13}, E_{14}, E_{15} >$

(b)

Features of key parts (FKP)

TR		Object Value	Idegree	F_{11}	F_{12}	F_{21}	F_{22}	F_{31}	F_{32}	F_{41}	F_{42}	F_{43}	F_{44}	F_{51}	F_{52}
				F_1		F_2		F_3		F_4				F_5	
TR	TR_1	99%	8				◎	○			◎	◎		○	○
	TR_2	6years	8				◎	○			○	○			
	TR_3	<1450	9	○	◎	○	○	◎		○		○	○	○	○
	TR_4	>96%	6					○	◎		○		◎	○	◎
Weight				27	81	35	171	147	54	27	114	123	81	69	105

Feedback

Information feedback $E_2 = < E_{21}, E_{22}, E_{23} >$

(c)

Process flow (P)		P_1	P_2		P_3		P_4		P_5	P_6	P_7		P_8			P_9		P_{10}	P_{11}
Process feature (PF)		PF_{11}	PF_{21}	PF_{22}	PF_{31}	PF_{32}	PF_{41}	PF_{42}	PF_{51}	PF_{61}	PF_{71}	PF_{72}	PF_{81}	PF_{82}	PF_{83}	PF_{91}	PF_{92}	PF_{10}	PF_{111}
FKP	Criterion																		
FKP_1	260 HB		○	○							◎	◎							
FKP_2			◎	◎			◎	○			○	○							
FKP_3	7-8 grade										○					◎	○	○	
Process criterion		Different process criterion based on actual environment																	

Feedback

Information feedback $E_3 = < E_{31}, E_{32}, E_{33} >$

Figure 6. Multistage QFD for realizing process requirements based on information feedback. (a) Product planning matrix of the reducer, (b) parts deployment matrix of the reducer, and (c) process planning matrix of the reducer.

relationship between ⟨fast replacement⟩ and ⟨good seal⟩ is strongly conflicting. There exist cooperative relationships between ⟨low noise⟩ and other customer requirements, such as ⟨low speed variety⟩ and ⟨good lubrication⟩, but the relationship between ⟨low noise⟩ and ⟨low product price⟩ is conflicting. Because new market orientation emphasizes that the product price is paramount, the importance of price should be improved, which will lead to the priority of some technologies being changed. Because there exist correlative relationships (conflicting or cooperative) between ⟨low noise⟩ and other customer requirements, such as ⟨low speed variety⟩, ⟨good lubrication⟩, and ⟨low price⟩, if the expected value of ⟨maximal noise⟩ is changed, the correlative degree among customer requirements will also be changed. Due to the inadequate estimation of the importance of requirement and to correlative relationships between requirements and technologies, the priority of technology requirements will be changed locally. Therefore, all the relationships above should be modified through information feedback.

In the stage of developing the part deployment matrix, due to the new change of work condition, the transmission efficiency is emphasized. The new technical requirement ⟨transmission efficiency⟩ is added to the part deployment matrix. Because there exist correlative relationships between ⟨transmission efficiency⟩ and ⟨electromotor⟩, ⟨axis⟩, ⟨bearing⟩, ⟨gear⟩, and ⟨lubrication⟩, the new technical requirement will lead to the change of weight and priority of key part features. Moreover, the change of both object value of technology requirements and their importance not only affects the weight and priority of key part features, but also affects the object values and degrees of importance of customer requirements and technology requirements in the product planning matrix. The change of key part features, such as gear precision, will also affect the weight values and priority of part features.

In the developmental stage of the process planning matrix, the change in process flow or process feature (for example, it is necessary to test machining precision before the product is stored, or the precision of gear indexing movement devices is improved) will result in a change in gear precision, strength, process flow, and process feature. Some new process features accompanying the change of process flow will also change. Moreover, the change of part features and its criterion will result in the change of gear precision, strength, and the importance of process features.

According to the information feedback model and the reasoning scheme of requirement relationships developed above, the multistage QFD is improved as shown in Figure 6.

7. Conclusions

The material flow in a product development process is prohibited from repetition. That is to say, the resource movement is not an alternating process. It is the feedback and interaction of information that should be emphasized and used to ensure a successful development process. However, because of the incompletion and fuzziness of design information, and because of the limitation of human recognition, it makes the dynamic modeling of the product development process become very important. By analyzing the conflicting and cooperative relationships among process requirements, macro-feedback and micro-feedback models of the product development process based on information feedback, and the multistage QFD model were developed to satisfy the process requirements. The balance point of the development process can be optimized at the initial place or transferred from the initial balance point to another balance point. Using the proposed method, the spiral evolution of product development can be completed. The results of the case study show that macro-feedback and micro-feedback modeling of the product development process based on information feedback is an important method to realize lifecycle design, optimize the whole development process and product performance, capture designer's preferences, and satisfy the process requirements from both subjective and objective perspectives.

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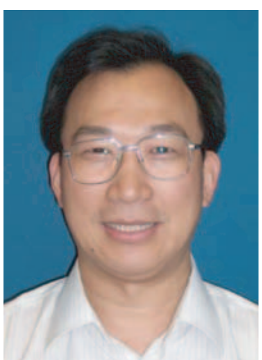

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