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Performance modelling based on value analysis for improving product development process architecture

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A B S T R A C T

Improving the architecture of product development process (PDP) is an effective approach to improve PDP performance. However, performance is difficult to model because the criterion of performance such as development cost, time and product quality are usually contradictory. The objective of this paper is to use process value as the evaluation indicator of PDP performance. The process value of PDP, as well as the ratio of process function and process cost, is discussed and its quantitative method is proposed. The process function is defined as the process effectiveness which considers the importance of each activity of PDP, and its evaluation methods based on rework theory and quality function deployment (QFD) are given. The simulation method is used to illustrate the proposed model and analyze the relation between architecture and process value of PDP, and an optimization model for PDP architecture is provided. With the model, we can get a suitable PDP architecture to balance the cost and product function during product development.

A R T I C L E I N F O

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1. Introduction

Product development process (PDP) refers to the entire set of activities to convert customers' needs into a technical and commercial solution [1, 2]. The activities and their relationships are described by the process architecture (or network). Analyzing and optimizing the architecture is helpful to build a PDP with high performance, which implies low development cost, short lead time and high product quality [3, 4]. However, these criterions are usually contradictory. For example, higher product quality may mean that the development time is longer or cost is higher. In addition, high performance is an elusive notion [5].

There have been relevant studies on performance measurement in PDP. Huang and Fu [6] proposed a quantitative model based on signal flow graphs (SFG), assessing process from the aspects of time, cost, quality and robustness. Pun et al. [7] proposed a self-assessment model of new product development performance (NPD) using analytical hierarchy process (AHP). Syamil et al. [8] researched the relationships between product development process and process performance, and provided a model of process performance at project level. The cost estimating [9], development quality [10], product performance [11], feasibility [12] and uncertainty [13] etc. have also been studied by some other researchers, which can reflect or affect the performance of PDP. So many measures and evaluation methods for PDP performance lead to an ambiguous definition of performance in above literatures. In addition most works focused on performance at project or program level.

O'Donnell and Duffy [14] considered that the overall performance in design is determined both by performance of the design solution (related to the product design parameters or product quality), and the performance of the process (related to the duration or cost). In their model, efficiency and effectiveness are as fundamental elements of performance. Efficiency is seen as the relationship between the knowledge that an activity gained and the used resources; while effectiveness is related to the degree how the outputs of knowledge meet the goals of activities. The model provides an improved perception of performance measurement, but the relationship between efficiency and effectiveness is not direct, because their focuses (efficiency focuses on process, and effectiveness focuses on solution or product) are different. Accordingly in some cases it is difficult to achieve combination of the two variables.

With successful application and good effects in manufacturing process, lean thinking has been gradually extended to development field in enterprises. Many works have been reported recently [15-17]. Value is the core concept in lean product development (LPD). The essential of value is to guide improvement processes [18]. Some scholars have tried to improve the performance of PDP through the value analysis method [19] or value stream method [20, 21]. Browning [22] pointed out that value is a function of both the product recipe and the process that produces it. That is to say both the effectiveness of the product and the efficiency of the process affect value.

However, there are two types of value in product development, product value and process value according to Chase [23]. Unfortunately, most of researches in this field have ignored the difference between them, and mainly focused on product value. Different from the product value which is defined as a capability provided to a customer at the right time at an appropriate price, process value is defined as the ability to perform with maximum quality at minimum cost. The quality is related to effectiveness, while the cost is related to efficiency, and waste in PDP can be understood as inefficiency and ineffectiveness [18], so the process value provides a new way to evaluate and improve the performance of PDP.

This paper is concerned with performance modelling by building the evaluation method of process value. The proposed model that describes the process value of PDP integrates the performance parameters, such as development time, process cost and product quality or function. It involves the factors such as process structure, rework constraints, customer requirements and so on. In the model, we extend O'Donnell and Duffy's [14] concept of effectiveness. In our work, the process effectiveness of one activity is evaluated by its rework. The rework evaluation method based on Design Structure Matrix (DSM) and the creation goal evaluation method based on Quality Function Deployment (QFD) are introduced to the model. Through the optimization of the process value, PDP can be improved from different aspects, such as resource allocation, process architecture improvement, requirement optimization, etc. In this study we focus on improving PDP from the aspect of process architecture improvement.

The remainder of this paper is organized as follows. Section 2 discusses the process value and its quantitative method. In section 3 the relationship between architecture and performance of PDP is verified by simulation based on a sample, and a new optimization model for PDP architecture is proposed. An example and some discussions are given in section 4. Finally, the conclusions and some extended research are presented in section 5.

2. Performance modelling based on value analysis

2.1 Process value

The importance of one activity in PDP describes the role that the activity plays during developing product, which can be considered as the process creation goal of the activity divided from the overall process creation goal of PDP. We use g to denote the creation goal of an activity and G to denote the overall process creation goal of PDP. The relationship between them can be expressed as Eq. 1.

$$G = \sum_{i=1}^{n} g_i \tag{1}$$

Here n indicates the number of activities. Whether an activity is able to achieve its goals or play its role in PDP depends on the effectiveness of the activity. In our method, the process effectiveness refers to the degree of the relevance between the creation and the goal of the process or activity. The effectiveness of the activity is denoted by e, while the effectiveness of the PDP is denoted by E. The process function can be considered as the actual creation of activity or PDP. The process function of an activity denoted by f and the process function of PDP denoted by F can be calculated as Eq. 2 and Eq. 3.

$$f = g \cdot e \tag{2}$$

$$F = G \cdot E \tag{3}$$

In addition, f and F have the following relationship:

$$F = \sum_{i=1}^{n} f_i \tag{4}$$

In our model the process value is defined as the capability to achieve the process creation goal under appropriate cost. The process value of an activity represented by the letter v, and the process value of the PDP represented by the symbol V^{proc}, are formulated as Eq. 5 and Eq. 6.

$$v = \frac{g \cdot e}{c} \tag{5}$$

$$V^{proc} = \frac{G}{\alpha_1 \cdot C + \alpha_2 \cdot T} \cdot E \tag{6}$$

The cost of PDP includes both resource consumption C and time consumption T. In Eq. 6, α_1 and α_2 respectively represent the weight of the cost and development time. The performance model of PDP with effectiveness and process value is expressed in Fig. 1.

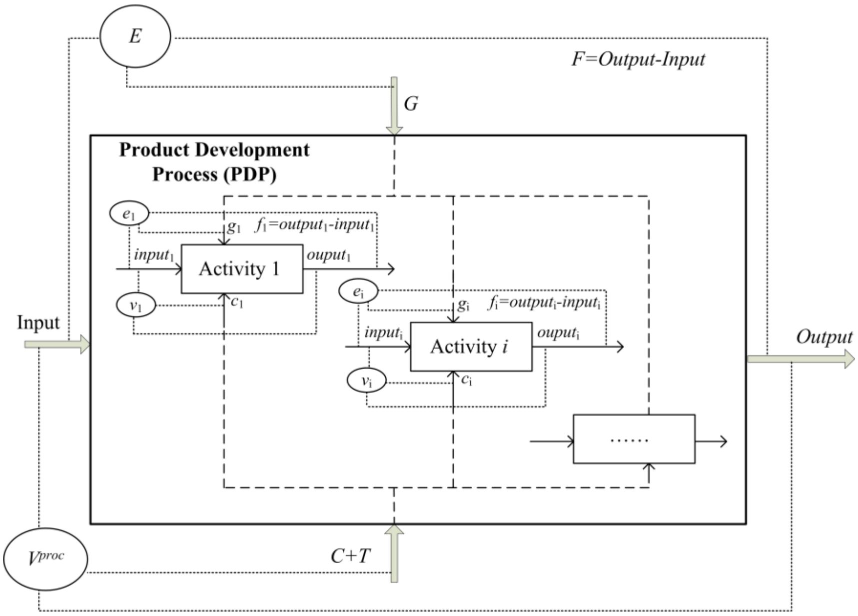


Fig. 1 Effectiveness and process value

The first part $\frac{G}{\alpha_1 \cdot C + \alpha_2 \cdot T}$ reflects the different development modes and development methods. The second part E reflects the uncertainties in a PDP, such as the different architectures, reworks and so on. So we can select suitable product development type and improve the architecture of PDP according to Eq. 6. This paper only studies the improvement of architecture under a fixed product development type. The parameters G and C can be considered as the static information, which can be obtained through prediction. Non-dimensional treatment for them is produced in analysis process. The cost C is the accumulation of the cost of all activities in PDP in normal executing case. It is the expected cost, rather than the actual cost of execution, and can be calculated according to Eq. 7.

$$C = \sum_{i=1}^{n} (c_i \cdot d_i) \tag{7}$$

Here c_i is the expected cost of unit time of activity i, and d_i is the expected working time of activity i. Generally, coefficient of C is 1.

The development time T is affected by the development process architecture. Assume that the development time on critical path of a PDP is T_{min}, the coefficient of T can be calculated by Eq. 8.

$$T = \frac{T_{min}}{T_{expected}} \tag{8}$$

Here $T_{expected}$ is the expected time of the product development project, and can be considered as a constant.

In Fig. 1 input and output of activity or PDP are indeterminate and difficult to evaluate, so in the next section we will explore the decomposition of G and evaluate E.

2.2 Decomposing of process creation goal

G of PDP is the performance or function of product that must be created. As a broad concept, it reflects the extent of how much the product to meet the customer requirements, including technical parameters, quality and other attributes. So that is to say, it is based on the customer requirements and will not be changed during development. In other words, it can be seen as a constant. However, g of an activity is decomposed from G of PDP based on its importance during the development, and difficult to quantify. The coefficient of activity (COA) is used to express the importance of an activity during development.

Customer requirement is the start to evaluate process. On referring to Quality Function Deployment (QFD) method, which considers that meeting customer requirement is the ultimate goal of product development, this paper establishes the mapping matrix from customer requirement to product function, and the mapping matrix from product function to activities. Through these matrices the COA can be evaluated.

Because the QFD has been quite mature, it is assumed that the customer requirements and all of the mapping matrices are able to be estimated or set by experienced engineers. The customer requirements can be expressed by $CR = [CR_1, CR_2, \dots, CR_l]$, where l is the total number of customer requirements, and $\sum_{k=1}^{l} CR_k = 1$.

The mapping matrix from product requirements to product function is

$$RF = \begin{bmatrix} rf_{11} & \cdots & rf_{1m} \\ \vdots & \ddots & \vdots \\ rf_{l1} & \cdots & rf_{lm} \end{bmatrix},$$

where rf_{ks} indicates the importance coefficient of product function s to realize the customer requirement k. The sum of every row in RF is 1. The weight of product functions W is expressed by $[W_1, W_2, \dots, W_m]$. So the evaluation coefficient of product functions (COF) expressed by vector $[COF_1, COF_2, \dots, COF_m]$ can be calculated with Eq. 9.

$$COF = (CR \cdot RF) \times W \tag{9}$$

Similarly, the matrix

$$FA = \begin{bmatrix} fa_{11} & \cdots & fa_{1m} \\ \vdots & \ddots & \vdots \\ fa_{n1} & \cdots & fa_{nm} \end{bmatrix},$$

with sum of every column being 1, expresses the mapping matrix from product function to development process, and fa_{is} indicates the importance coefficient of activity i to realize the product function s. So the evaluation coefficient of product function target of activities (COA) expressed by vector $[COA_1, COA_2, \dots, COA_n]$, can be calculated with Eq. 10.

$$COA = COF \cdot FA^{\mathrm{T}} \tag{10}$$

Then the decomposing formula of G is given as Eq. 11.

$$g_i = G \times COA_i \tag{11}$$

2.3 Effectiveness evaluating based on R-DSM

The effectiveness reflects the degree of completing the process creation goal. If the creation goal cannot be fully completed by the PDP or the activity, the part that has not been completed can be considered as ineffective, which should be retrieved by rework process. So we can evaluate the effectiveness of activity through its rework.

We suppose that the completion degree of the process function of the activity is related to the cost and time the activity consumed. As shown in Fig. 2, if the consumed time and cost is c and the process creation goal is g, it will get the process function $f = g \cdot e$. In other words, there will be $g - f$ process function left to be reworked, which is expressed as rg. Similarly, in order to get the process creation goal $g - f$ function which can be the process creation goal of the rework, the consumed time and cost (rc) will be $\frac{(g-f)\cdot c}{g}$, which is the rework effort. So the rework rate of an activity can be calculated as $r = \frac{g-g\cdot e}{g} = 1 - e$. Therefore the activity effectiveness can be represented and calculated simply by the rework rate of activity as Eq. 12.

$$e = 1 - r \tag{12}$$

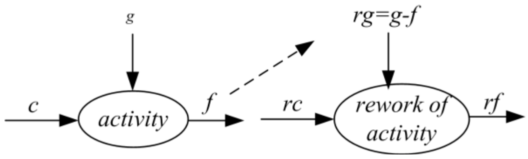


Fig. 2 Example of rework

Reworks can improve product quality or functions, but probably it will increase the development cost and time. We explain the rework probability, rework impact and rework workload using design structure matrix (DSM) method, which is similar with Browning and Eppinger's [24].

Rework probability is a measure of uncertainty of one certain PDP architecture. Fig. 3 shows the rework probability, impact and rate through the DSM representation.

- Rework Probability Design Structure Matrix (RP-DSM): $RP(i,j)$ represents the probability that activity $i$reworks due to activity j for $i,j = 1,2,\cdots,n$ and $i \neq j$. $RP(i,j)$ represents the rework probability of the activity i due to the change of information outside the PDP, such as changes of customer requirements.

	1	2	…	n
1	*RP(1,1)*	*RP(1,2)*	…	*RP(1,n)*
2	*RP(2,1)*	*RP(2,2)*	…	*RP(2,n)*
…	…	…	…	…
n	*RP(n,1)*	*RP(n,2)*	…	*RP(n,n)*

(a) RP-DSM

	1	2	…	n
1	*RI(1,1)*	*RI(1,2)*	…	*RI(1,n)*
2	*RI(2,1)*	*RI(2,2)*	…	*RI(2,n)*
…	…	…	…	…
n	*RI(n,1)*	*RI(n,2)*	…	*RI(n,n)*

(b) RI-DSM

	1	2	…	n
1	*RR(1,1)*	*RR(1,2)*	…	*RR(1,n)*
2	*RR(2,1)*	*RR(2,2)*	…	*RR(2,n)*
…	…	…	…	…
n	*RR(n,1)*	*RR(n,2)*	…	*RR(n,n)*

(c) RR-DSM

Fig. 3 DSM of rework probability, impact and rate

- Rework Impact Design Structure Matrix (RI-DSM): $RI(i,j)$ represents the rework percentage of completed work of activity i when it is due to activity j or other reasons outside the PDP.
- Rework Rate Design Structure Matrix (RR-DSM): $RR(i,j)$ represents the actual rework effort of activity i affected by activity j or other reasons outside the PDP. It is product of $RP(i,j)$ and $RI(i,j)$, as Eq. 13.

$$RR(i,j) = RP(i,j) \times RI(i,j) \quad i,j = 1,2,\cdots,n \tag{13}$$

Suppose there are two activities. Activity 1 is the predecessor activity of activity 2, and the two activities have information interaction with each other. According to the architecture, activity 1 is executed without any information from activity 2, because activity 2 must be executed after activity 1. After activity 2 is completed, activity 1 would be caused to rework, and the rework rate is $RR(1,2)$. So the rework effort of activity 1 caused by activity 2 is $c_1 \cdot RR(1,2)$. In other words, the rework rate of activity 1 is $r_{1,2} = RR(1,2)$. Because activity 2 is successor activity of activity 1, and its rework is caused by the change of activity 1. The change quantity is $c_1 \cdot RR(1,2)$, therefore, the rework effort of activity 2 is $\frac{c_1 \cdot r_1}{c_1} \cdot c_2 \cdot RR(2,1)$, equivalent to $c_2 \cdot r_1 \cdot RR(2,1)$. In other words, the rework rate of activity 2 is $r_{2,1} = r_1 \cdot RR(1,2)$.

Similarly, if activity 1 and activity 2 are parallel, they will be executed without any information provided by another activity. So rework rate of activity 1 is $r_{1,2} = RR(1,2)$, while rework rate of activity 2 is $r_{2,1} = RR(2,1)$.

From the above analysis, the following conclusions can be drawn:

(1) If activity i is the upstream activity of activity j for $i,j = 1,2,\cdots,n$, the rework rate of activity i is $RR(i,j)$, and the rework rate of activity j is $r_i \cdot RR(j,i)$.
(2) If activity i and activity j are parallel, the rework rate of activity i is $RR(j,i)$, and the rework rate of activity j is $RR(j,i)$.

Use a_{ij} to show the precedence relationship between activity i and j. If activity i is the upstream activity of activity j, $a_{ij} = 1$. Otherwise, $a_{ij} = 0$. And for all $i,j = 1,2,\cdots,n$, $a_{ij} + a_{ji} \leq 1$ and $a_{ii} = 0$. So the above conclusions can be expressed as:

$$r_{i,j} = RR(i,j) \cdot (1 - a_{ji}) + r_j \cdot RR(i,j) \cdot a_{ji} \quad a_{ji} = 1 \; or \; 0 \;\&\; a_{ij} + a_{ji} \leq 1 \tag{14}$$

In addition, the RR-DSM only expresses the rework rate of one activity when it is directly affected by other activities. However, in practice an activity usually is influenced by multiple activities and some activities indirectly. Therefore, it is necessary to determine a total rework rate (r) of an activity under a specific PDP architecture.

Suppose that there are three activities 1, 2 and 3, and the rework rate of activity 1 caused by activity 2 and 3 are $r_{1,2}$ and $r_{1,3}$ respectively. Thus the rate that activity 2 doesn't cause activity 1 to rework is $1 - r_{1,2}$, while the rate that activity 3 doesn't cause activity 1 to rework is. That's to say, the rate that activity 1 doesn't rework is $(1 - r_{1,2}) \cdot (1 - r_{1,3})$. In other words, the total rework rate (r_1) of activity 1 is $1-(1-r_{1,2})\cdot(1-r_{1,3})$. So the effectiveness of activity i can be expressed as Eq. 15 and Eq. 16.

$$r_i = 1 - \prod_{j=1}^{n}(1-r_{i,j}) \quad i,j = 1,2,\cdots,n \tag{15}$$

$$e_i = \prod_{j=1}^{n}(1-r_{i,j}) \quad i,j = 1,2,\cdots,n \tag{16}$$

According to Eq. 1, Eq. 2, Eq. 3, Eq. 4 and Eq. 11, we can get the calculation process for the effectiveness of one PDP as $E=\frac{F}{G}=\frac{\sum_{i=1}^{n}f_i}{\sum_{i=1}^{n}g_i}=\frac{\sum_{i=1}^{n}(g_i\cdot e_i)}{\sum_{i=1}^{n}g_i}=\frac{\sum_{i=1}^{n}(G\cdot COA_i\cdot e_i)}{\sum_{i=1}^{n}(G\cdot COA_i)}$. Because G is a constant and $\sum_{i=1}^{n}COA_i=1$, so we can get the formula for E as Eq. 17.

$$E = \sum_{i=1}^{n}(COA_i \cdot e_i) \tag{17}$$

3. Optimization model for PDP

3.1 Computational study

An illustrative sample is presented for demonstrating the value of PDP analysis. The sample has three customer requirements, four product functions and five activities. The required input data are listed in Fig. 4. The reworks due to reasons outside of PDP are not considered. For simplicity, assume that both G and C are 1, and all the costs and process creation goals of activities are evaluated with the standardized coefficient. Both the weight of the cost and the weight of development time are 0.5. The expected lead time of the product development is 30.

Customer requirements

Requirement ID	Evaluation coefficient of requirements
CR_1	0.3
CR_2	0.5
CR_3	0.2

Mapping matrix RF

PF_1	PF_2	PF_3	PF_4
0.3	0.4	0.3	0
0.2	0	0.4	0.4
0	0.5	0.5	0

Product functions

Function ID	Weight of function
PF_1	0.1
PF_2	0.3
PF_3	0.5
PF_4	0.1

Activity information

Activity ID	Time(expected)	Cost of unit time
P_1	6	6
P_2	10	2
P_3	8	4
P_4	12	1
P_5	8	1

Mapping matrix FA

PF_1	PF_2	PF_3	PF_4
0.3	0.4	0.3	0
0.2	0	0.4	0.4
0	0.5	0.3	0
0.5	0	0	0.2
0	0.1	0	0.4

RP-DSM

P_1	P_2	P_3	P_4	P_5
0	0.5	0.8	0.2	0
0.6	0	0.4	0	0.5
0.3	0.5	0	0	0.4
0.3	0.5	0.5	0	0
0	0.6	0.2	0.4	0

RI-DSM

P_1	P_2	P_3	P_4	P_5
0	0.6	0.5	0.5	0
0.5	0	0.5	0	0.4
0.2	0.2	0	0	0.5
0.5	0.5	0.1	0	0
0	0.2	0.4	0.5	0

Fig. 4 Example of rework

All possible PDP process architectures are constructed and the process values are calculated. And the process simulations are carried out for all the architectures. Each of PDP process architectures is simulated by 1000 times, and the mean value of these simulation results is used as the final simulation of the architecture. All of the simulation programs are implemented in MATLAB 7.0.

Fig. 5 shows the simulation results of all the different process architectures. The process values are calculated by the formula (6)-(17), and the costs and duration are obtained by simulation. The figure depicts both cost and duration show decreasing trend with the increasing of process value. This concludes that the PDP architectures with high process value have better performance. So development process can be improved by optimizing the PDP architecture based on the value analysis.

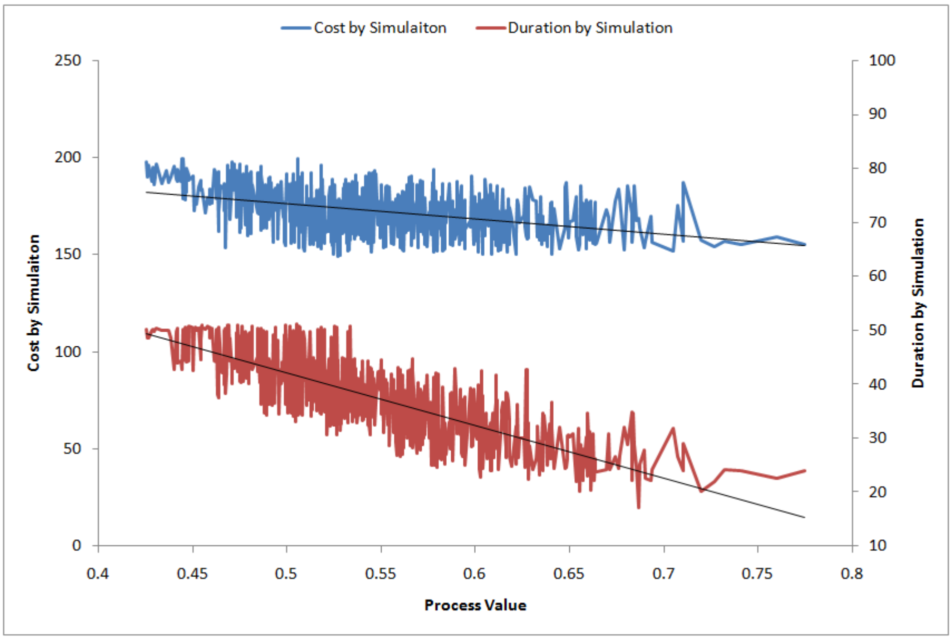


Fig. 5 Simulation results analysis of the computational study

3.2 Optimization model for PDP

Based on the elements discussed above, we propose the optimization model for PDP architecture as follows:

$$\max: V^{proc} = \frac{G}{\alpha_1 \cdot C + \alpha_2 \cdot T} \sum_{i=1}^{n} (COA_i \cdot e_i) \tag{18}$$

subject to Eq. 8, Eq. 9, Eq. 10, Eq. 13, Eq. 14, Eq. 15, Eq. 16 and

$$a_{ij} + a_{ji} \leq 1 \quad i,j = 1,2,\cdots,n \tag{19}$$

$$a_{ji} = 1 \; or \; 0 \quad i,j = 1,2,\cdots,n \tag{20}$$

The optimization model focuses on the effects of PDP architecture on the process value which can express the performance of PDP. In the model, the resource requirements are assumed static and unlimited, and the customer requirements, process goals, rework probability and activity duration can be estimated. The optimization variables are a_{ij}, for all $i,j = 1,2,\cdots,n$ and $i \neq j$. All parameters are summarized in Table 1. Eq. 19 shows that there is no circuit in the network of PDP.

4. Example application

In order to verify the feasibility of the proposed optimization model, the development process of a refrigerator is studied as an example. The PDP of the refrigerator has 18 activities and its detailed information is given in Fig. 6. Through analysis, we sorted out the customer requirements and the product functions, shown in Fig. 7. Fig. 8(a) gives the initial architecture of the PDP. With the increasing of competitive pressure it is necessary to shorten the development cycle and reduce the cost. The expected lead time is 200 days.

Table 1 Model parameters

Parameters	Definition and Description
V^{proc}	Process value of PDP
G	Overall process creation goal of PDP, which can be decomposed into the process creation goals of activities (g). If g_i is evaluated with the standardized coefficient, G would be 1.
C	Expected total cost of PDP, which is the sum of the cost of each activity (c). If c_i is evaluated with the standardized coefficient, C would be 1.
T	Development time that expressed with the standardized coefficient.
T_{min}	The development time on critical path of a PDP.
$T_{expected}$	The expected lead time of the product development project.
α_1	The weight of PDP cost.
α_2	The weight of PDP duration.
E	Effectiveness of the PDP, which is the degree to what the creation during the process relates to the overall process creation goal of the PDP.
F	Process function of the PDP, which is the actual creation of the PDP.
COF_s	The evaluation coefficient of product functions s.
CR_k	The evaluation coefficient of customer requirement k
W_s	The weight of product function s.
COA_i	The coefficient of activity i which is used to express the importance of an activity.
RF	The mapping matrix from product requirements to product function.
FA	The mapping matrix from product function to development process.
g_i	Creation goal of the activity i and evaluated with the standardized coefficient.
c_i	Cost of the activity i. Sometimes it can be evaluated with the standardized coefficient.
d_i	Duration of activity i.
e_i	Effectiveness of activity i
f_i	Process function of activity i, which is the actual creation and calculated using $e_i \cdot g_i$.
$RR(i,j)$	The actual rework effort of activity i affected by activity j for $i,j = 1,2,\cdots,n$.
$RP(i,j)$	If $i \neq j$, it is the probability that activity i is reworked affected by activity j for $i,j = 1,2,\cdots,n$, and else it is the rework probability of the activity i caused by the change of information outside the PDP.
$RI(i,j)$	The rework percentage of completed work of activity i, when activity i is reworked affected by activity j, or other reasons outside the PDP.
r_i	The total rework rate of activity i under a specific PDP architecture.
$r_{i,j}$	The rework rate of activity i affected by activity j or other reasons outside under a specific PDP architecture.
m	Total number of activities.
n	Total number of product functions.
l	Total number of requirement.

It can be seen from Fig. 6, some activities interact with each other. There are two main coupling activities groups, one is (5,6,10,14), and the other is (4,9,13). The mapping matrix FAs of them shown in Fig. 9 are obtained by Analytic Hierarchy Process (AHP). The optimization models are established for the two coupled activities groups, and the improved architectures shown in Fig. 8(b) is obtained.

Using the given parameters, the process simulation for the architectures before and after the improvement is performed. The simulation runs 1000 times for each architecture. The simulation results are given in Table 2.

Activity information

Activity ID	Activity description	Activity duration	Cost of unit time
1	General Design	7	17.1
2	Appearance Preliminary Design	14	7.8
3	Technical Specifications Determine	14	7.1
4	Body Preliminary Design	5	14
5	Appearance Modeling	10	14
6	Body Detailed Design	20	11
7	Body Trial-produce	25	25.6
8	Body Test	30	13
9	Refrigerating System Preliminary Design	10	9
10	Refrigerating System Detailed Design	30	10
11	Refrigerating System Trial-produce	40	16.5
12	Refrigerating System Test	35	12
13	Control System Preliminary Design	10	10
14	Control System Detailed Design	25	16
15	Control System Trial-produce	56	15
16	Control System Test	35	13.7
17	Assembling	21	12.9
18	Assembly Test	14	15.7

RP-DSM

Activity ID	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	1	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	1	0	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	1	1	0.3	0	0	0	0	0.6	0	0	0	0.7	0	0	0	0	0
5	0	0	0	1	0.2	0.8	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0.3	0.3	0	0	0	0.6	0	0	0	0.6	0	0	0	0
7	0	0	0	0	0	1	0.2	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	1	0.3	0	0	0	0	0	0	0	0	0	0
9	0	1	1	0.5	0	0	0	0	0.3	0	0	0	0.6	0	0	0	0	0
10	0	0	0	0	0	0.8	0	0	1	0.3	0	0	0	0.5	0	0	0	0
11	0	0	0	0	0	0	0	0	0	1	0.3	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	1	0.2	0	0	0	0	0	0
13	0	1	1	0.4	0	0	0	0	0.8	0	0	0	0.2	0	0	0	0	0
14	0	0	0	0	0	0.4	0	0	0	0.8	0	0	1	0.7	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0.3	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0.4	0	0
17	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	1	0.3	0
18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0.3

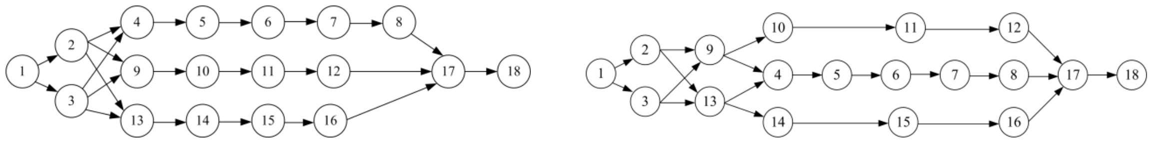
RI-DSM

Activity ID	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	0.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0.5	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0.5	0	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0.6	0.4	0.5	0	0	0	0	0.5	0	0	0	0.6	0	0	0	0	0
5	0	0	0	0.6	0.7	0.6	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0.3	0.6	0	0	0	0.7	0	0	0	0.6	0	0	0	0
7	0	0	0	0	0	0.4	0.6	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0.5	0.5	0	0	0	0	0	0	0	0	0	0
9	0	0.4	0.5	0.6	0	0	0	0	0.6	0	0	0	0.5	0	0	0	0	0
10	0	0	0	0	0	0.6	0	0	0.5	0.7	0	0	0	0.5	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0.6	0.7	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0.4	0.5	0	0	0	0	0	0
13	0	0.3	0.2	0.5	0	0	0	0	0.5	0	0	0	0.5	0	0	0	0	0
14	0	0	0	0	0	0.5	0	0	0	0.5	0	0	0.6	0.7	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0.7	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.6	0.6	0	0
17	0	0	0	0	0	0	0	0.5	0	0	0	0.4	0	0	0	0.3	0.8	0
18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.7	0.9

Fig. 6 Detailed information of the refrigerator development

Customer requirements			Mapping matrix RF								Product functions		
Requirement ID	Requirement description	Evaluation coefficient of requirements	PF_1	PF_2	PF_3	PF_4	PF_5	PF_6	PF_7	PF_8	Function ID	Function description	Weight of function
CR_1	Fast Refrigeration Speed	0.176	1	0	0	0	0	0	0	0	PF_1	Refrigerating Capacity	0.07
CR_2	Low Energy Consumption	0.118	0	0.28	0	0.28	0	0.1	0.1	0.26	PF_2	Energy Consumption	0.124
CR_3	Small Noise	0.118	0	0.17	0.5	0.17	0	0	0.2	0	PF_3	Noise Level	0.093
CR_4	Environmental	0.176	0	0.2	0.2	0	0	0	0.6	0	PF_4	Thickness of Insulation Layer	0.109
CR_5	Appearance Style	0.059	0	0	0	0.1	0.9	0	0	0	PF_5	Dimension of Body	0.07
CR_6	Multi-function	0.118	0	0	0	0	0	0	0	1	PF_6	Temperature Control Method	0.116
CR_7	Low Price	0.118	0	0.06	0	0.06	0	0.2	0.2	0.52	PF_7	Cooling Method	0.209
CR_8	Simple Operation	0.118	0	0	0	0	0	0.5	0.5	0	PF_8	Input Power	0.209

Fig. 7 Customer requirements and the product functions



(a) Initial architecture (b) improved architecture

Fig. 8 Architectures of PDP

Activity ID	PF_1	PF_2	PF_3	PF_4	PF_5	PF_6	PF_7	PF_8
5	0.06	0.14	0.14	0.22	0.32	0.06	0.05	0.09
6	0.22	0.18	0.18	0.49	0.54	0.10	0.15	0.26
10	0.59	0.35	0.35	0.25	0.09	0.34	0.59	0.53
14	0.13	0.33	0.33	0.04	0.05	0.50	0.21	0.12

Activity ID	PF_1	PF_2	PF_3	PF_4	PF_5	PF_6	PF_7	PF_8
4	0.24	0.48	0.16	0.69	0.77	0.09	0.14	0.53
9	0.68	0.47	0.58	0.22	0.16	0.32	0.57	0.33
13	0.08	0.05	0.26	0.09	0.07	0.59	0.29	0.14

Fig. 9 Mapping matrix FAs of the two coupling activities groups

Table 2 Simulation results

Item	Initial scheme	Improved scheme
Process value	0.748	0.793
Cost by simulation	9,099	8,730
Duration by simulation	210	194

Compared with the initial scheme, the cost of the improved scheme is reduced by 369,000 RMB (1 US \$ = 6.86 RMB), and the development time is shortened by 16 days.

The performance of PDP and the value concept have received considerable attention in the previous literatures. However, no one has studied these two together. This study concludes that the PDP with maximum process value has good performance because of its lower cost and shorter development period. The V^{proc} as a comprehensive indicator is not only related to the process cost, process time and product quality, but also related to the customer requirement, rework probability and the product development process architecture. Under the goal of maximizing process value, we can improve PDP from different aspects by different optimization variables.

The proposed model is suitable for improving PDP of products like refrigerator from the process architecture aspect. These products have strong market characteristics, and have mature and stable development technology. Their development process goals are certain, and their development resources are relatively fixed. The customer requirements can be obtained through market research, while the rework probability and impact between activities can be obtained through statistical analysis based on historical data. Enterprises that produce these products must develop and launch new products rapidly in order to occupy the market, and also need to implement low-cost strategy in order to maximize profitability.

The optimization model can also be used to solve other improvement problem by adjusting constrains and optimization variables. For example, in the engineering to order (ETO) enterprises like mould enterprises, shipyards, etc., multiple products usually are being developed simultaneously, and this causes competition of sharing resource. In such situation, the optimization goal is still maximizing the process value, but the variables and constraints should be changed. Variables that represent resource allocation will be added to the model as an optimization variable, and the variables represent process architecture (a_{ij}) will be used as constraints. Thus, the changed model can be used to solve the resource allocation problem.

5. Conclusion

The research studies the performance modelling of PDP based on value analysis. The proposed process value of PDP used to express process performance is a comprehensive indicator of cost, time and function. In the specific quantitative method of the process value, process function is evaluated by process creation goal and effectiveness. To estimate the effectiveness of activities, an evaluation method of rework is introduced, and to estimate the process creation goal of activities, a method referring to QFD is used. We demonstrate the analyzing procedure of process value and verify the relationship between architecture and value of PDP by simulation method based on an example. The simulation results show that the PDP architectures with high process value, have low development cost and short development time. To improve the PDP architecture, an optimization model is provided. Through the model, we improve a refrigerator development process.

Although studies such as this paper have led to a deeper thinking and understand of the process value and performance of PDP, the empirical research of the value evaluation method and optimization model should be carried out, and simulation and genetic algorithm should be further studied in the future.

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