A Modular Approach for Lean Product Development (LPD) Based on System Engineering

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Abstract. Metallurgical equipment belongs to the discrete manufacturing industry, in which large-scale equipment is common, and has feature of high level of customization, large variety, single and small batch. Under the model of design to order, R&D staff have to modify or redesign according to each order, leading to longer product development cycle and higher cost. This paper presents w-model of system engineering framework to solve the R&D cross sectoral collaborative problem. Top-down functional decomposition integrated with bottom-up component clustering is suggested by the author to form module for design knowledge reuse. In the end, this paper takes an illustrative example of lean metallurgical equipment development to demonstrate the feasibility and technical advantage of the approach.

Keywords: Lean product development · Product development value stream mapping · System engineering · Modular approach · Metallurgical equipment development

1 Introduction

Nowadays, the discrete manufacturing industry in China are facing product development problem, such as unclear R&D target, unclear personnel responsibility, unreasonable project planning, poor collaborative ability and so on. On the other hand, it is difficult to identify customer requirement which is more than ever and changes rapidly. Engineers have to design components with similar functions repeatedly. As a result, it calls for modular approach to eliminate unnecessary waste and reuse design knowledge. The poor cross-department collaboration and the lack of closed-loop feedback make it ineffective to meet customer needs. So it is necessary to consider the whole lifecycle of product development process in the view of system engineering [1].

Product development value stream mapping is a tool for process improvement, offering a visual way for people to observe the waste in the process more easily. The

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data, inventory state and other information in the information flow help to visualize the current state of the process and provide basic data for determining improvement goals [2].

Value stream mapping is the first step for lean product development. It helps to analyze the problem existing in product development and identify waste, working as a reference for development process reengineering implementation plan. Then the system engineering method helps to consider the relationship between different phases at each level, like design, manufacturing, assembly and maintenance. Modular approach is based on system engineering, because both modular decomposition and component clustering are related to levels. The aim of modular approach based on system engineering is to improve product development process and make the process lean [3].

2 Status Review for Lean Product Development (LPD)

Most scholars use concurrent engineering, Stage-Gate, IDEF models, ASME method, Fig role, Petri nets and other methods of production in the field of business process reengineering, only a few scholars have used value stream mapping method. Junfen [4] compared four kinds of methods. Based on her results, the author add value streaming mapping into the comparison. The scale is defined by four levels (poor, normal, good and excellent). For example, value stream mapping is easier for understanding than other method, we define the comprehensibility "excellent". So the comparison of approaches for LPD process reengineering is shown as the table below (Table 1).

Table 1. Comparison of approaches for Lean Product Development process reengineering

Attributes		Modeling method				
		Flowchart	Role behavior diagram	IDEF0	Petri net	Value stream mapping
Formalization	Comprehensibility	Good	Normal	Normal	Normal	Excellent
	Graphical representation	Good	Good	Good	Good	Good
	Computerization	Good	Normal	Normal	Normal	Normal
Completeness	Abstract mechanism	None	None	Exist	Exist	Exist
	Semantic rule	Poor	Poor	Exist	Exist	Exist
	Event trigger mechanism	Exist	None	None	Exist	Exist
Expression	Organization	none	Exist	Exist	Not good	Exist
	Function	Exist	Exist	Exist	Exist	Exist
	Data	Exist	None	None	None	Exist
	People	None	Exist	Exist	None	Exist
Extension	Cross functional process modeling	Support	No	Normal	Poor	Support
	Process simulation support	Not	Not	Not	Support	Support
	Dynamic modeling support	Not	Not	Not	Support	Support
	Assistant tool	Exist	None	Exist	None	None
	Business process reengineering support	Normal	Normal	Normal	Normal	Support

By comparison, Value Stream Mapping method can be seen in the superiority of the degree of formalization, completeness, modeling skills, model extension and other aspects. So in this paper, it is chosen for lean product development business process modeling analysis.

3 A System Engineering-Based Framework for LPD

3.1 Traditional V-Model of System Engineering

The pillars of traditional V-model of system engineering include systems thinking, concurrent engineering, teamwork, target-driven design, reusability, reliability, package and vehicle attribute focus. Figure 1 depicts the system using a diagram shaped like a "V". As the requirements are cascaded, system, sub-system and component level requirements are defined. Once the final plan is established, the design and development of the vehicle is continued and verified up the right side of the "V" until the product is ready for launch [1]. But V-model of system engineering does not emphasize the point of product lifecycle. So that is why the author propose the concept of W-model of system engineering.

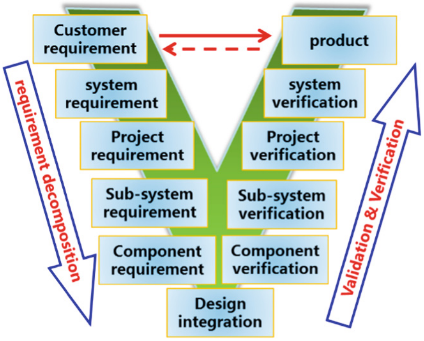

Fig. 1. V-model of system engineering

3.2 A New W-Model of System Engineering

The idea of W-model of system engineering is derived from the concept of DFX (Design for different requirements) and V-model of system engineering. From the top to the bottom, it is followed by the system level, subsystem level, component level and part level. From the left to the right, it is followed by the design phase, the manufacturing phase, assembly phase and maintenance phase (Fig. 2).

3.3 W-Model of System Engineering for LPD

On one hand, W-model of system engineering uses a cascade of targets through the vehicle. Along the cascade, system, sub-system, part, component level requirements are

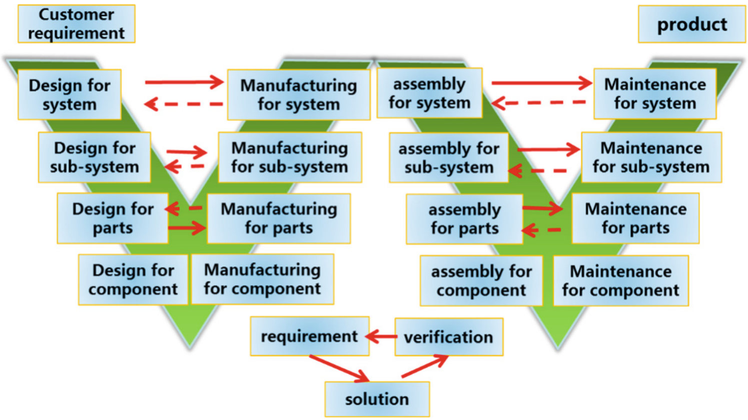

Fig. 2. W-model of system engineering

defined. On the other hand, W-model of system engineering uses the term "Design for X" to link customer requirements and quality criteria such as robustness, serviceability and others [5].

The purpose of DFM (Design for Manufacturing) is to minimize the overall component count and to optimize the remaining components so that the manufacturing costs to be reduced. DFA (Design for Assembly) focuses on the optimization of how product components can be moved, held, located and joint [6]. DFMA (Design for Maintenance) aims to lower overall life cycle costs and a product design that is optimized to its support processes.

3.4 Feasibility Analysis of the Framework

W-model of system engineering combine product lifecycle with system level form horizontal and vertical aspects. During the design phase, the designers need to consider the criteria and rules of manufacturing, assembly and maintenance, they will look some components as a module, which will help to reduce the number of components, simplify the process of assembly and improve the quality of repairing accordingly.

4 Modular Approach for Improvement in Lean Product Development

DFX is to minimize the overall component number, modular approach can reduce the number of components. Each level of W-model of system engineering calls for modular approach. And modular approach for different phases has different advantage. It can reduce design complexity for design, reduce manufacturing costs for manufacturing phase, improve the relative movement between one part and another for assembly and improve product maintainability for maintenance.

4.1 Module Decomposition

Module decomposition is determined by the requirement, principles, function, performance, structure, precision machining, assembly, cost, supply chain and other factors. Figure 3 shows module decomposition in accordance with function. Finally, module can be divided into five kinds, fundamental module, special module, auxiliary module, adaptive module and customized module. In this paper, functional decomposition and component clustering are integrated. Functional decomposition suits for conceptual design phase, while component clustering is mainly applied for engineering change phase.

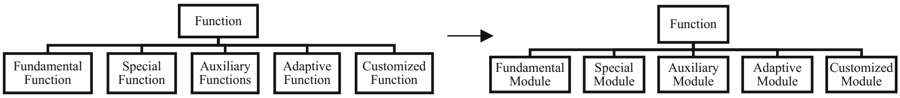

Fig. 3. The relationship between function decomposition and function module

4.2 Module Clustering

Module decomposition is top-down method, on the contrary, module clustering is bottom-up approach. Clustering analysis is based on the correlation of parts and components. The steps of clustering are shown in Fig. 4.

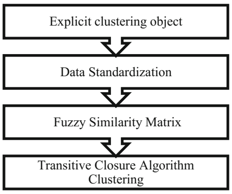

Fig. 4. Steps of fuzzy clustering analysis

Step 1 is to explicit clustering object. Imagine that the number of component is n, each component has m kinds of features. Finally, we get a $n \times m$ matrix.

$$X = \begin{bmatrix} x_{11} & x_{12} & \dots & x_{1m} \\ x_{21} & x_{22} & \dots & x_{2m} \\ \vdots & \vdots & \dots & \vdots \\ x_{n1} & x_{n2} & \dots & x_{nm} \end{bmatrix} \quad (1)$$

Step 2 is to standardize the data to avoid a large magnitude indicators highlight the neglect of magnitude smaller index. Each index is transferred into interval $[-1, 1]$.

$$x'_{ik} = \frac{x_{ik} - \frac{1}{n}\sum_{i=1}^{n} x_{ik}}{\sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(x_{ik} - \frac{1}{n}\sum_{i=1}^{n} x_{ik}\right)^2}} (\mathrm{i} = 1, 2, \ldots, \mathrm{n}; \mathrm{k} = 1, 2, \ldots, \mathrm{m}) \tag{2}$$

$A = \min\{x'_{ik}\}$, $B = \max\{x'_{ik}\}$,

$$\mathrm{y}_{ik} = \frac{x'_{ik} - A}{B - A},\ 0 \le \mathrm{y}_{ik} \le 1 \tag{3}$$

Step 3 is to build up fuzzy similarity matrix $\tilde{R}$. $Y = [y_{ik}]_{n \times m}$, r_{ij} means the degree of similarity between y_i and y_j.

$$\tilde{R} = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & & \vdots \\ r_{n1} & r_{n2} & \cdots & r_{nm} \end{bmatrix} \tag{4}$$

Step 4 is to get the clustering result by using transitive closure algorithm clustering. According to transitive closure algorithm, there is min k to make $\tilde{R}^k$ a fuzzy equivalent matrix.

$$\mathrm{t}\left(\tilde{R}\right) = \tilde{R}^k = \underbrace{\tilde{R} \circ \tilde{R} \circ \cdots \circ \tilde{R}}_{k} \quad (\text{“} \circ \text{” means} \left(\wedge, \vee\right)) \tag{5}$$

4.3 Module Generation

The bigger the confidence level λ (λ is between 0 and 1) is, the bigger number of module and more sort of module, which is good for product modification. But this does harm to assembly. So, after the generation of module, there comes a multi-objective optimization model [7]. The constraints are design complexity A_D^Y, ease of manufacture A_F^Y, assembly complexity A_A^Y and ease of maintenance A_M^Y. Module size is defined as $\mathrm{a} = \frac{1}{\lambda}$. The bigger the size is, the smaller the number of module is.

$$A_D^Y = -\frac{1}{\mathrm{k}_a}\sum_{i=1}^{n}\left[d_i \ln d_i + (1 - d_i)\, ln(1 - d_i)\right] \tag{6}$$

K_{a} means module number corresponding with module size “*a*”. *di* stands for degree of certainty of the function *i* in design phase.

$$A_F^Y = -\frac{1}{\mathrm{k}_a}\sum_{i=1}^{n}\left[f_i \ln f_i + (1-f_i)\,ln(1-f_i)\right] \tag{7}$$

f_i stands for degree of certainty of the function i in manufacturing phase.

$$A_A^Y = -\frac{1}{\mathrm{a}}\sum_{j=1}^{k_a}\frac{n_t(j)}{n}\ln\frac{n_t(j)}{n} \tag{8}$$

n_t (j) stands for the number of function module of module j.

$$A_M^Y = -\frac{1}{\mathrm{k}_a}\sum_{i=1}^{n}\left[\eta_i \ln \eta_i + (1-\eta_i)\,ln(1-\eta_i)\right] \tag{9}$$

η_i stands for failure rate of module i. Finally, module clustering optimum solution depends on $B(Y)$

$$B(Y) = \min\left\{\tilde{A}_D^Y + \tilde{A}_F^Y + \tilde{A}_A^Y + \tilde{A}_M^Y\right\} \tag{10}$$

$$\tilde{A}_D^Y = \frac{A_D^Y}{\sum_{i=1}^{N} A_D^Y}, \tilde{A}_F^Y = \frac{A_F^Y}{\sum_{i=1}^{N} A_F^Y}, \tilde{A}_A^Y = \frac{A_A^Y}{\sum_{i=1}^{N} A_A^Y}, \tilde{A}_M^Y = \frac{A_M^Y}{\sum_{i=1}^{N} A_M^Y} \tag{11}$$

4.4 Technical Advantage of Modular Approach

Top-down module decomposition and bottom-up module clustering work together to avoid designing repeatedly, reduce waiting time, improve R&D efficiency and eliminate waste in product development. The multi-objective optimization process of module generation can avoid the impact of a single factor and improve the accuracy of the clustering results.

5 Illustrative Example of Lean Metallurgical Equipment Development

5.1 Current State of VSM for Metallurgical Equipment Development

Aluminum electrolytic multifunction machine is the key equipment for large-scale pre-baked anode aluminum electrolysis production. It can replace manual operations to complete the process of electrolytic crust, replacing the anode, the anode pit cleaning, feeding, and metering of aluminum, anode bus adapter, cell repair, lifting and other operations.

Pot tending machine consists of cart, tool cart, trolley car, hydraulic system, pneumatic system and electric control system. The product development can be divided into two parts from the aspect of structure, one is mechanical part and the other is electrical part. The product development process is shown in Fig. 5.

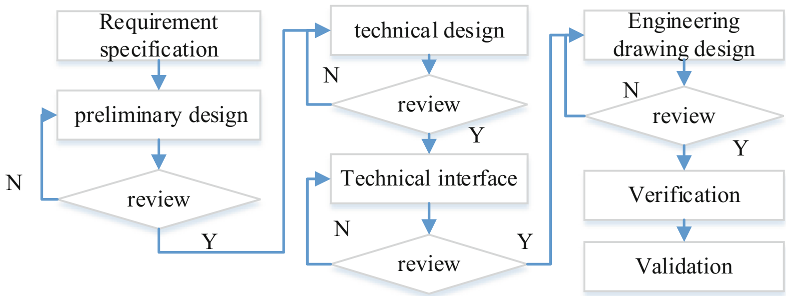

Fig. 5. The product development process of pot tending machine

Based on the product development process, with data and information being gathered, including process time, waiting time and talk time, the current state of value stream mapping of product development process of pot tending machine comes out as shown in Fig. 6 [8–11].

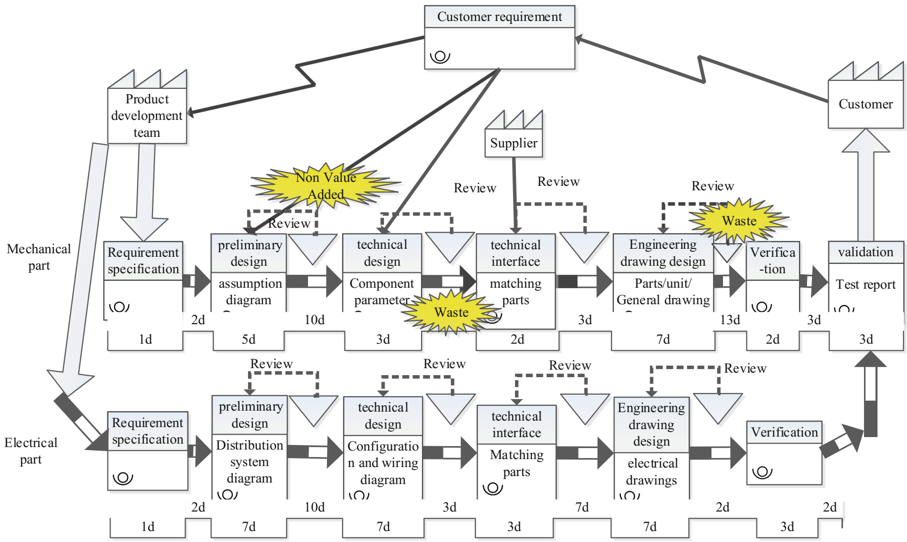

Fig. 6. The current state of value stream mapping of product development process of pot tending machine

5.2 Root Cause Analysis for Metallurgical Equipment Development

Figure 7 depicts eight kinds of waste in product development, including waiting, over process, over production, information defect, transmission, knowledge lost, moving and inventory. The cause of waste was analyzed via fishbone diagram. The root cause is the lack of systematic modular design methods, leading the product development target to be unclear, project planning unreasonable.

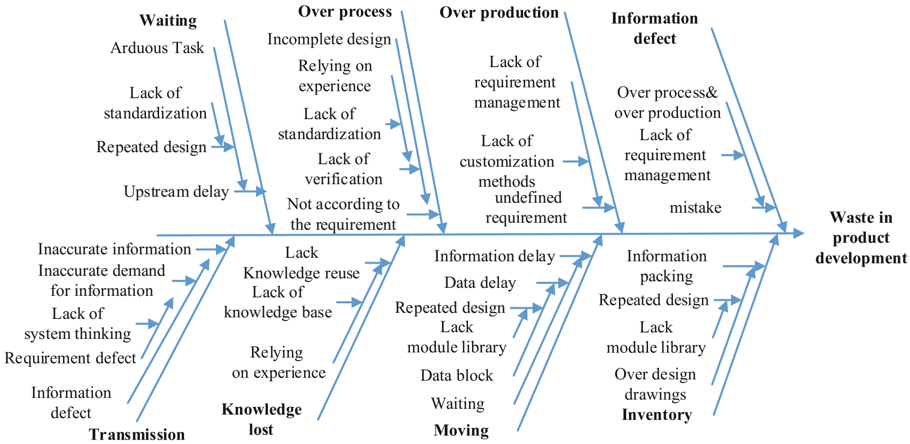

Fig. 7. Fishbone diagram of root cause analysis in product development waste

5.3 Improvements for Metallurgical Equipment Development

Crust breaker is an example of W-model of system engineering applied to improve the development. Crust breaker needs to ensure a certain angle, in order to make the fight against the hammer to hit the seam position. So oblique cylinder mounting and position should be considered in design phase. Further more, the influence of hydraulic cylinder piston rod length change in manufacturing phase, the interference of cylinder installation position after adjusting for connecting racks in assembly phase, the hammer blow strength and maintenance programs in maintenance phase should also be traded off in design phase. From the system engineering point of view, modular division of crust breaker is shown as below (Fig. 8).

As for modular approach, take tool cart as an example. The principle of function decomposition of tool cart module is similar to that of crust breaker depicted above. When engineering change occurs, modular clustering plays an important role. The Tool cart running device main components bill of material is shown in Table 2 as below.

According to Eqs. (1), (2), (3) and (4), components fuzzy matrix $\tilde{R}_{10\times 10}$ is shown in Table 3.

According to Eqs. (5)–(11), the clustering result is shown in Table 4.

From Table 4, the minimum value of B(Y) is 0.2023, so solution 2 is the optimum solution. The module generation result is four groups.

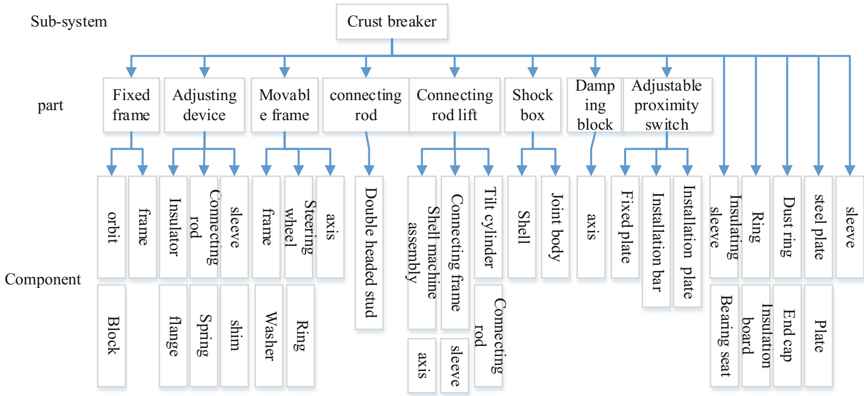

Fig. 8. Crust breaker modular hierarchy

Table 2. Tool cart running device main components bill of material

No.	Name	No.	Name	No.	Name
1	Active wheel group	5	Track brush	9	Ground wheel device
2	End beamI	6	End beamII	10	Beam
3	Driven wheel group	7	Upper horizontal wheel		
4	Track brush holder	8	Ground wheel bracket		

Table 3. Components fuzzy matrix table

	1	2	3	4	5	6	7	8	9	10
1	1	0.112	0.914	0.106	0.206	0.11	0.563	0.105	0.211	0.132
2	0.112	1	0.115	0.324	0.216	0.923	0.104	0.413	0.363	0.863
3	0.914	0.115	1	0.113	0.504	0.123	0.602	0.126	0.221	0.241
4	0.106	0.324	0.113	1	0.679	0.245	0.263	0.789	0.563	0.421
5	0.206	0.216	0.504	0.679	1	0.382	0.253	0.452	0.327	0.124
6	0.11	0.923	0.123	0.245	0.382	1	0.127	0.436	0.365	0.843
7	0.563	0.104	0.602	0.263	0.253	0.127	1	0.114	0.108	0.254
8	0.105	0.413	0.126	0.789	0.452	0.436	0.114	1	0.857	0.321
9	0.211	0.363	0.321	0.563	0.327	0.365	0.108	0.857	1	0.131
10	0.132	0.863	0.221	0.421	0.124	0.843	0.254	0.321	0.131	1

5.4 Future State of VSM for Metallurgical Equipment Development

Figure 6 shows where the waste and non-value added lie in. Then the root cause analysis in product development waste helps us find the key factors. By using W-model of system engineering framework for LPD and modular approach for improvement in Lean Product Development, the waste is reduce to a degree, as shown in Fig. 9.

Table 4. Clustering result

Solution	λ	Group division	Size	$B(Y)$
1	0.7	{1,3},{2,6,10},{8,9},4,5,7	6	0.2137
2	0.5	{1,3,7},{2,6,10},{4,5},{8,9}	4	0.2023
3	0.3	{1,3,7},{2,4,5,6,8,9,10}	2	0.2216

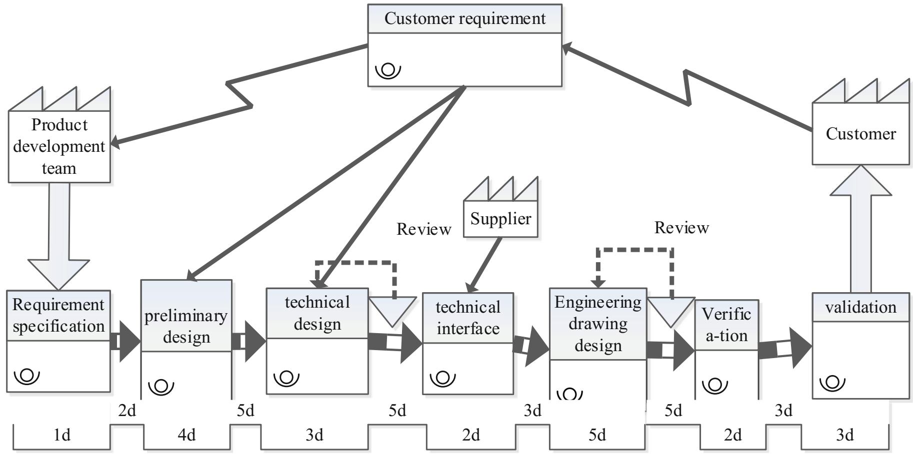

Fig. 9. The future state of value stream mapping of product development process of pot tending machine

5.5 Potential Industrial Benefits

W-model of system engineering can solve the problem about cross sectoral collaboration and shorten the waiting time in a rate of 29.5%.

Modular method based on top-down functional decomposition and the bottom-up modular clustering can improve the reusability of components and reduce development cost in a rate of 2%.

6 Conclusion and Future Perspectives

Product development is the lifeline of the development of an enterprise. Design process is not just the business of the R&D department personnel, but should be the enterprise participation. Waste should be eliminated in order to respond to customer needs rapidly, improve the design efficiency and save the cost of R&D. By describing the current status of development process, drawing the corresponding current value flow chart, the waste and non-value added links in the process are identified. W-model emphasizes the coordination of design, manufacturing, assembly and maintenance. Modular approach introduces the process of module partition, module clustering and module generation. The future perspectives are as below, Specific quantitative relationship between the levels of system, sub-system, component and parts needs deeper research. Modular configuration and product configuration are worth studying in the future, including configuration rules, configuration approach, configuration model and configuration processes.

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