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Optimize Variant Product Design Based on Component Interaction Graph

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1. Introduction

Dominating markets with a single product is increasingly difficult, and instead numerous industries are evolving towards mass customization, meaning the production of individually customized and highly varied products or services (Pine, 1993). This proliferation of models allows consumers to find a product that best suits their individual needs. The need for increasing product variety and shorter development time brings more complexity to the company than ever. Corporations are striving to balance customer satisfaction and cost savings, and product design is becoming essential for accomplishing this. Since developing an entirely different product is often uneconomical. A better method is to develop a product architecture that enables a company to offer highly differentiated products that share a substantial fraction of their components. Therefore, introducing product variety within a robust architecture offers one means of enhancing mass customization. Besides, an increase in product variety brings an increase in the volume of information exchanged between customers, designers and marketing department. Due to such increased information processing load, information technology is needed to tackle this problem. This chapter investigates the product variety design methodologies through the computational design optimization methods, and developing product architecture under the support of information technologies. It aims at providing product designers a rational and systematic methodology in dealing with product variety from both qualitative and quantitative viewpoints.

2. Related Literature

The issue of product variety has attracted growing research interest during recent years. In1993, Pine (1993) began discussing the need for product variety in

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increasingly competitive markets. Cohen (1995) proposed using Master House of Quality for planning product variety. Suh (1990) viewed product variety as the proper selection of design parameters that satisfy variant functional requirements. Ulrich (1995) examined the relationships between product architecture and product variety, component standardization, modularity, and product development. Erens (1996) developed product variety under functional, technology, and physical domains. Fujita and Ishii (1997) formulated the task structure of product variety design, and Martin and Ishii (1996, 1997, 2002) proposed DFV (Design for Variety), which is a series of methodologies with quantifying indices for reducing the influence of product variety on product life-cycle cost, and thus helping design teams to develop decoupled product architectures. These studies have established a basis for product variety management. However, many investigations have agreed that the key to efficiently designing and delivering multiple products is developing a good product architecture (Meyer 1993, Sawhney 1998, Ulrich& Eppinger 2000). The advantages of developing product architecture is that it enables a company to offer two or more products that are highly differentiated yet share a substantial fraction of their components. The collection of components shared by these products is called a product platform (Ulrich& Eppinger 2000). Erens (1996) defined a product platform as "An architecture concept of compromising interface definitions and key-components, addressing a market and being a base for deriving different product families." Robertson and Ulrich (1998) proposed a method of balancing distinctiveness with commonality within product architecture through identifying the importance of various factors going into this tradeoff. Fujita et al., (1998, 1999) utilized optimization techniques to identify the optimum architecture of a module combination across products in a family of aircraft. Moreover, Yu et al., (1998) defined product family architecture based on customer needs by using the target value of product features for calculating probability distributions. Additionally, Simpson, et al., (1999) used the Product Platform Concept Exploration Method (PPCEM) to design a common product platform. This platform uses the market segmentation grid to help identify suitable scale factors of the platform that are "scaled" or "stretched" to satisfy various requirements.

Although most studies focus on optimizing product structure, some studies have noticed that investigating the physical arrangement and interaction among components is the key for stable product architecture. For example, the component-based DSM (design structural matrix) method has been applied to explore alternative architectures through clustering high interactive components and arranging them in chunks (Pimmler & Eppinger 1994, Wei 2001). Moreover, Sosa et al., (2000) applied DSM to analyze the different types of interaction between modular and integrative systems, and Salhieh & Kamrani (1995) used the similarity matrix for integrating components into modules. These studies represent component relationships in terms of similarity or reciprocal interaction rather than information flows. However, during the embodiment design stage, variant designs of a single component can lead to numerous other components also requiring modification. The hierarchical structure of component interactions first must be identified, after which the influence of variety and subsequent design changes can be estimated. To deal with this problem, this chapter illustrated two methodologies via identifying component design constraint flows to build up feasible product architecture.

3. Product Design Based on Component Interaction Graph

3.1 Product design rational

Studies of product design have observed that designs are always completed through iteration. Design iteration occurs when a new requirement is inputted into the design task, resulting in the related components needing to be redesigned, and leading to the specifications of the other components that interact with the redesigned components having to change their specifications to fit the redesign. Therefore, the design process becomes iterative, and so tremendous design efforts are required. This problem becomes particularly important in planning product architectures; products must be designed to meet various customer needs, yet also share as many components as possible to minimize costs. This study attempted to solve this problem by modeling component sequential flow using ISM, interpretive structural modeling. ISM is an algebraic technique for system representation and analysis that was first introduced by Warfield (1973). ISM reduces complex system interactions to a logically oriented graph.

This study applies and modifies ISM to establish a hierarchical component interaction structure, which can help designers to determine component commonality, variety, and design priorities.

3.2 Computational procedure of ISM

Phase1: Incidence matrix construction

First, a system is decomposed into a set of components that form a square matrix. The procedure begins with paired comparisons to identify whether a direct influence exists from component *i* (row) to *j* (column). The incidence matrix $A = [a_{ij}]$ thus is defined as

$$a_{ij} = \begin{cases} 1 & \text{if a direct influence exists from component i to component j} \\ 0 & \text{otherwise} \end{cases}$$

Fig. 1(a) represents the incidence matrix of an example system containing seven components. For example, the second row of the matrix indicates that component 2 directly influences components 1, 5, and 6.

Phase 2: Reachability matrix deduction

The reachability matrix *R* is deducted from incidence matrix *A* if a Boolean *n*-multiple product of *A*+*I* uniquely converges to *R* for all integers $n > n_0$, where n_0 is an appropriate positive integer, *I* is a Boolean unity matrix, and + is addition in Boolean sense (Warfield, 1995). Matrix *R* represents all direct and indirect linkages between components. Figure 1(b) represents the reachability matrix *R* derived from matrix *A*, in which an entry $r_{ij}=1$ if component *j* is reachable by *i*, although the path length may be one or more.

$$A = \begin{array}{c} c_1 \\ c_2 \\ c_3 \\ c_4 \\ c_5 \\ c_6 \\ c_7 \end{array} \overset{\begin{array}{ccccccc} c_1 & c_2 & c_3 & c_4 & c_5 & c_6 & c_7 \end{array}}{\begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 1 & 1 & 0 \\ 1 & 0 & 0 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 1 \\ 0 & 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 \end{bmatrix}} \qquad R = \begin{array}{c} c_1 \\ c_2 \\ c_3 \\ c_4 \\ c_5 \\ c_6 \\ c_7 \end{array} \overset{\begin{array}{ccccccc} c_1 & c_2 & c_3 & c_4 & c_5 & c_6 & c_7 \end{array}}{\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 0 & 1 & 1 & 1 \\ 1 & 0 & 1 & 0 & 1 & 0 & 1 \\ 1 & 0 & 1 & 1 & 1 & 0 & 1 \\ 1 & 0 & 1 & 0 & 1 & 0 & 1 \\ 1 & 1 & 1 & 0 & 1 & 1 & 1 \\ 1 & 0 & 1 & 0 & 1 & 0 & 1 \end{bmatrix}}$$

(a) Original incidence matrix *A* (b) Reachability matrix *R*

Figure 1 a-b. Stepwise procedure of ISM

Phase 3: Cluster retrieval

A technique for cluster retrieval is inserted in the ISM process to identify components that influence one another and form a loop (Roberts, 1997). The reachability matrix *R* multiplies the transposed matrix of *R*, say R^t; thus in $R \bullet R^t$, components *i* and *j* mutually interact if $r_{ij}\, r_{ji} = 1$. Figure 1(c) displays the output matrix of $R \bullet R^t$, in which clusters of components can be identified easily by rearranging component order. Figure 1(d) reveals four clusters in the system, namely: {1}, {2,6}, {3,5,7}, and {4}.

$$
R \bullet R^t = \begin{array}{c} \\ c_1 \\ c_2 \\ c_3 \\ c_4 \\ c_5 \\ c_6 \\ c_7 \end{array}
\begin{array}{c} \begin{array}{ccccccc} c_1 & c_2 & c_3 & c_4 & c_5 & c_6 & c_7 \end{array} \\
\begin{bmatrix}
1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 1 & 0 & 1 & 0 & 1 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 1 & 0 & 1 \\
0 & 1 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 1 & 0 & 1 & 0 & 1
\end{bmatrix} \end{array}
$$

(c) Output matrix of $R \bullet R^t$

$$
R \bullet R^t = \begin{array}{c} \\ c_1 \\ c_2 \\ c_6 \\ c_3 \\ c_5 \\ c_7 \\ c_4 \end{array}
\begin{array}{c} \begin{array}{ccccccc} c_1 & c_2 & c_6 & c_3 & c_5 & c_7 & c_4 \end{array} \\
\begin{bmatrix}
1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 1 & 0 & 0 & 0 & 0 \\
0 & 1 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 1 & 1 & 0 \\
0 & 0 & 0 & 1 & 1 & 1 & 0 \\
0 & 0 & 0 & 1 & 1 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1
\end{bmatrix} \end{array}
$$

(d) Retrieval of clusters

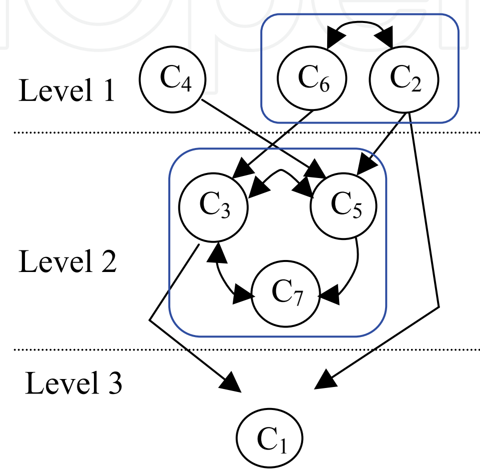
Figure 1 c-d. Stepwise procedure of ISM

Phase 4: Obtained hierarchy graph

Following cluster retrieval, the order of reachability matrix *R* is rearranged (as shown in Fig. 1(e)), and the clustered components are integrated and treated as a single entity. The hierarchy graph then is obtained by identifying a set of components in matrix *R* that cannot reach or be reached by other components outside the set itself, removing the set from the original matrix *R*, and then repeating this process for remaining matrix until a unique set of nodes that no other nodes can reach is obtained. For example, in Fig. 1(e), c_1 first is identified as an "exit", since it can not reach to other components; meanwhile, {c_2, c_6} and c_4 were separated as "entrances", because they can not be reached by other nodes. In this example, three levels of nodes were obtained (illustrated in Fig.1 (f)). The oriented links then connected the nodes from source to sink one based on the incidence matrix. Notably, the rounded rectangles in Fig.1 (f) indicate the retrieved clusters, in which the information flow forms a loop.

$$R = \begin{array}{c} \\ c_1 \\ c_2 \\ c_6 \\ c_3 \\ c_5 \\ c_7 \\ c_4 \end{array} \begin{array}{ccccccc} c_1 & c_2 & c_6 & c_3 & c_5 & c_7 & c_4 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 & 1 & 1 & 0 \\ 1 & 1 & 1 & 1 & 1 & 1 & 0 \\ 1 & 0 & 0 & 1 & 1 & 1 & 0 \\ 1 & 0 & 0 & 1 & 1 & 1 & 0 \\ 1 & 0 & 0 & 1 & 1 & 1 & 0 \\ 1 & 0 & 0 & 1 & 1 & 1 & 1 \end{array}$$

(e) Rearranged matrix *R*



(f) Hierarchical interaction graph of the system

Figure 1 e-f. Stepwise procedure of ISM

3.3 Analysis procedure

The Analysis procedure comprises three main phases: market planning, QFD and the ISM approach. Figure 2 presents the flow diagram for linking these phases. The first phase begins with product market planning which clarifies the various requirements of different markets. The second phase involves the QFD analysis, during which the variant requirements are related to physical components with specific values to identify relationship degree, yielding the relative importance of each component towards the market variations. Finally, the inner interactions between physical components are further examined via ISM analysis, with component design priority being represented using a hierarchical graph. The result obtained from QFD is incorporated into the hierarchical graph to identify the component to be redesigned in the influential path, deriving new products that satisfy market niches by redesigning finite components.

4. Case Study for Variant Design Based on Component Interaction Graph

4.1 Case background

This study illustrated the design of a family of 1.5-liter automatic drip coffee makers from an electronic appliances manufacturer (Company X). Ninety-five percent of the products of this company are original design manufactured (ODM), and are mainly exported to America, Europe, and Japan. Company X aims to provide product varieties to simultaneously meet the requirements of each segmented market, as well as to develop product architectures in mass customization. Components of the original product are listed in Table 1.

4.2 Analysis procedure

Phase 1 : Market Planning

The market planning aims at two different markets (spatial variety) with two different launch times (temporal variety), concurrently developing four products, as illustrated in Fig. 3. The launch time of the “current” products is planned for after three months, while that of “future” products is planned for after eight months.

Phase 2: Identify the exterior drivers of variation

To emphasize market differentiation, the QFD matrix lists the differences in customer requirements rather than common requirements. In the case, how to maintain coffee temperature is the key driver for spatial market differentiation, because the weather in Market 2 is much colder than that of Market 1. Table 1 illustrates the mapping from requirements into components, in which the values 9, 5, 3, 1, and 0 indicate the mapping relationships ranging from very strong, through to strong, ordinary, weak, and none, respectively. Table 1 demonstrates that the most important component for Keeping coffee temperature is the Carafe. Furthermore, the key drivers for temporal market differentiation are Ease of cleaning, Comfortable to use, and Fashionable style. These requirements are listed in Table 2, along with their relative importance. The critical components for these requirements include the Housing, Top cover, and Carafe. The QFD results are input into the product design, as described in Section *4.3*.

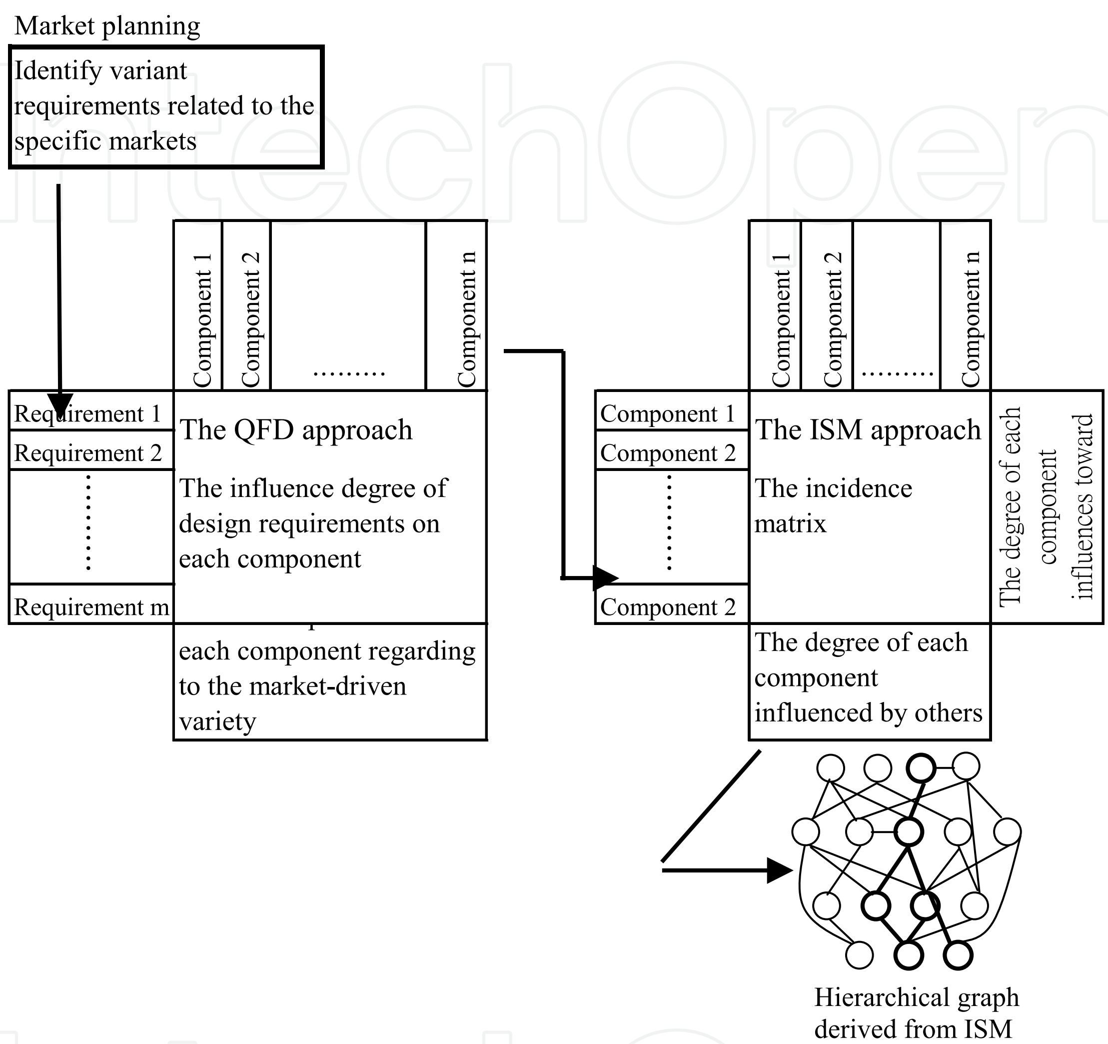


Figure 2. Flow diagram of the analysis phases

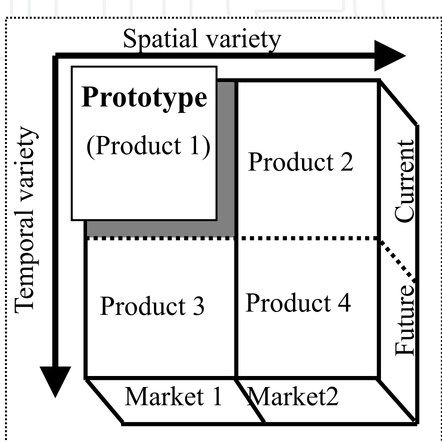


Figure 3. Market planning of the coffee maker

Spatial differentiation requirement \ Component	top Cover	top Cover base	spout	spout seat	top cover base	water tank cover	water tank	base	silicone ring	water outlet pipe	pipe connection seat	base cover	packing valve	heating element	switch	hot plate ring	hot plate	cup bank	carafe handle cover	carafe handle	carafe	carafe cover	housing	filter holder packing valve	filter holder
	1	2	3	4	5	6	8	11	12	13	14	15	16	18	19	20	21	22	23	24	25	26	27	28	30
Keep coffee temperature	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	1	3	0	0	0	**9**	3	0	0	0

Table 1. QFD matrix of the spatially differential requirements

Temporal differentiation requirement \ Component No.	1	2	3	4	5	6	8	11	12	13	14	15	16	18	19	20	21	22	23	24	25	26	27	28	30	Rwlative Weight
Ease of cleaning	**1**	3	0	0	3	1	3	0	0	0	0	0	0	0	0	0	0	0	1	0	**5**	1	**1**	0	5	3
Comfortable to use	**9**	0	1	1	1	3	0	0	0	0	0	0	0	0	3	0	0	0	1	3	**3**	1	**9**	0	3	5
Fashionable style	**3**	0	0	0	0	1	3	3	0	0	0	0	0	0	1	0	0	0	3	3	**9**	1	**5**	0	0	2
Total	**54**	9	5	5	14	20	15	6	0	0	0	0	0	0	17	0	0	0	14	21	**48**	10	**58**	0	30	

Table 2. QFD matrix of the temporally differential requirements

Phase 3: Identify the interior hierarchical interactions

In this approach, senior design engineers of company X perform the incidence matrix by investigating the relationships between each pair of components. Table 3 lists the original incidence matrix. The cells in the incidence matrix are marked with "1" if the components in rows constraint the specifications of the components in columns. The related design constraints are documented in the form *d (i, j)*, where *i* denotes the source component providing a constraint to component *j*. For example, *d (4, 5)* indicates that the Top Cover Base (component 5) should fit the diameter of the Spout Seat (component 4). This incidence matrix is then manipulated through the ISM procedures illustrated in Section 3.2. Fig.4 shows the hierarchical graph of the design constraint flow derived through ISM. In this graph, the circles represent components, the oriented lines are design constraints provided by the source components, and the rounded rectangles indicate that a set of mutually interactive components, which are integrated as a module. These modules and other components then are further grouped into chunks according to the frequency of their interactions. Table 4 lists the incidence matrix after appropriate rearrangement of the order. Four chunks are formed in the product, namely C1 housing chunk, C2 water tank chunk, C3 base chunk, and C4 carafe chunk. The precedence of the four chunks is determined by the inter-chunk interactions.

Part Name	No.	1	2	3	4	5	6	8	11	12	13	14	15	16	18	19	20	21	22	23	24	25	26	27	28	30
top cover	1		1																							
top cover set	2	1																								
spout	3		1		1																					1
spout seat	4			1		1																				
top cover base	5	1																						1		1
water tank cover	6							1																		
water tank	8						1																			
base	11							1					1			1	1	1						1		
silicone ring	12								1		1	1														
water outlet pipe	13								1	1		1														
pipe connection seat	14									1	1			1												
base cover	15								1																	
packing valve	16											1														
heating element	18															1		1								
switch	19								1																	
hot plate ring	20																	1								
hot plate	21																1									
cup bank	22																				1					
carafe handle cover	23																				1					
carafe handle	24																		1	1			1			
carafe	25																	1	1		1		1	1		
carafe cover	26																				1					
housing	27					1																				
filter holder packing valve	28																									1
filter holder	30					1																		1		

Table 3. The original incidence matrix of coffee maker components

4.3 Design procedure

The results of the analysis illustrated in previous section are applied in the product design; four products were designed concurrently to satisfy requests of different markets. The design procedure is demonstrated in the following paragraphs.

Chunk	module/component	No.	1	2	3	4	28	30	5	27	8	6	11	15	19	21	20	14	12	13	16	18	22	23	24	26	25
C 1	Top cover module	1		1																							
		2	1																								
	Spout module	3		1		1		1																			
		4			1				1																		
	holder packing valve	28						1																			
	Filter module	30							1	1																	
		5	1					1		1																	
		27							1																		
C 2	Tank module	8										1															
		6									1																
C 3	Base module	11								1	1			1	1	1	1										
		15											1														
		19											1														
	Heating plate module	21															1										
		20														1											
	Water pipe module	14																	1	1	1						
		12											1					1		1							
		13											1					1	1								
		16																1									
	Heating element	18													1	1											
C 4	Carafe outfit module	22																							1		
		23																							1		
		24																					1	1		1	
		26																							1		
	Carafe	25								1						1							1		1	1	

Note: Grayed cells indicate the inter-chunk interactions.

Table 4. Incidence matrix after appropriate rearranging the order

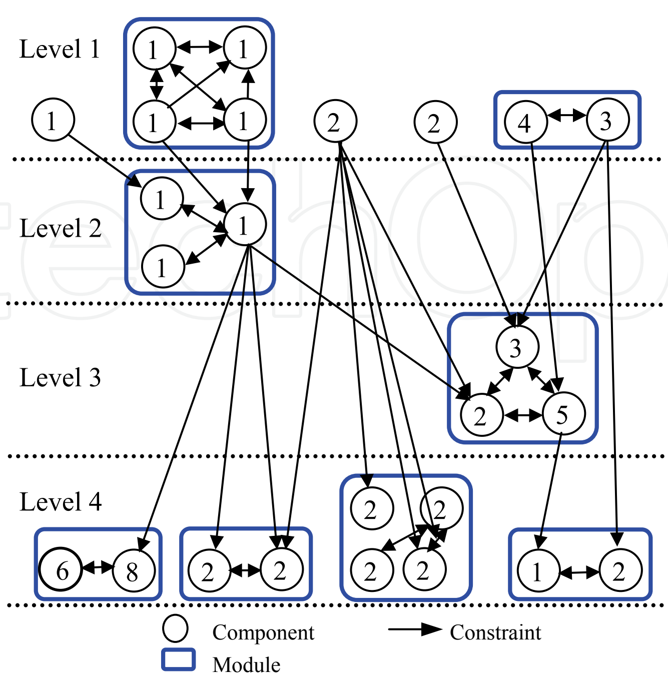


Figure 4. Hierarchical graph of component interaction

Phase 1: Design for spatial variety

Table 1 indicates that Carafe (part No.25) design is essential for maintaining coffee temperature. Therefore, the Carafe is redesigned to meet the requirement: the wall should be thickened and use heat insulation material, the shape slenderized and the top narrowed to reduce heat loss. To identify the influence of the new Carafe design, Fig.5 (extracted from Fig.4) shows the incidence diagram of the Carafe. In this figure, the design constraints the Carafe exports to the sink nodes are listed below:

***d*(25, 21)**: The Heating Plate module should fit the diameter of Carafe base (fixed).

***d*(25, 22)**: The Cup Bank should fit the diameter of Carafe body (changed).

***d*(25, 24)**: The Carafe Handle should fit the arc and weight of Carafe body (changed).

***d*(25, 26)**: The Carafe Cover should fit the diameter of Carafe rim, and the re quested thermal condition (changed).

***d*(25, 27)**: The Filter Module should fit the Carafe height (changed).

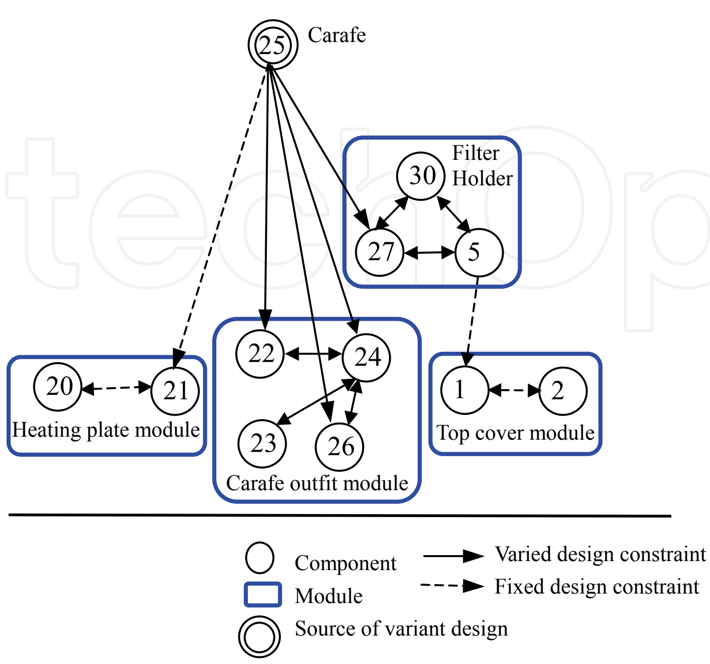


Figure 5. Incidence diagram of carafe (component 25)

The constraint of *d(25, 21)* is fixed (represented as dotted line in Fig.5), and thus parts 20, 21 are left unchanged. However, constraints *d(25, 22)*, *d(25, 24)*, *d(25, 26)*, and *d(25, 27)* are changed (represented as solid lines in Fig. 5) owing to the new carafe specification, resulting in the design of the Filter Module and Carafe Outfit Module having to be changed to match the altered conditions. In the Carafe Outfit Module, the components are redesigned to fit the new Carafe. However, the design change of the Filter Module must refer not only to the Carafe, but also to other components that provide constraints on the Filter Module, as shown in Fig.6. Thus in redesigning the Filter Module, the constraint from the Carafe becomes the source of variant design (represented as solid line in Fig.6), while the others are fixed constraints (represented as dotted lines in Fig. 6) listed below:

***d(11, 27)*:** The Housing should fit the Base.

***d(28, 30)*:** The Filter Holder should fit the Filter Holder Packing Valve diameter.

***d(4, 5)*:** The Top Cover Base should fit the Spout Seat diameter.

***d(3, 30)*:** The Filter Holder should fit the Spout shape.

Under these constraints, the design of Filter Module (parts 27, 5, and 30) is changed from V-shaped to U-shaped to fit the new Carafe design.
Furthermore, constraint from the Filter Module is:

***d(5, 1)*:** The Top Cover should fit the Basket Holder rim diameter.

Since the specification of the Basket Holder rim is fixed, component 1 and 2 need not change their design. Consequently, Table 5 lists the design solution driven by spatial market differentiation.

No.	Redesigned component
25*	Thermal carafe
22*	Cup bank of thermal carafe
23*	Handle cover of thermal ca-
24*	Handle of thermal carafe
26*	Cover of thermal carafe
27*	U-shaped housing
5*	U-shaped cover base
30*	U-shaped filter baseket

Table 5. List of variant components for Market 2

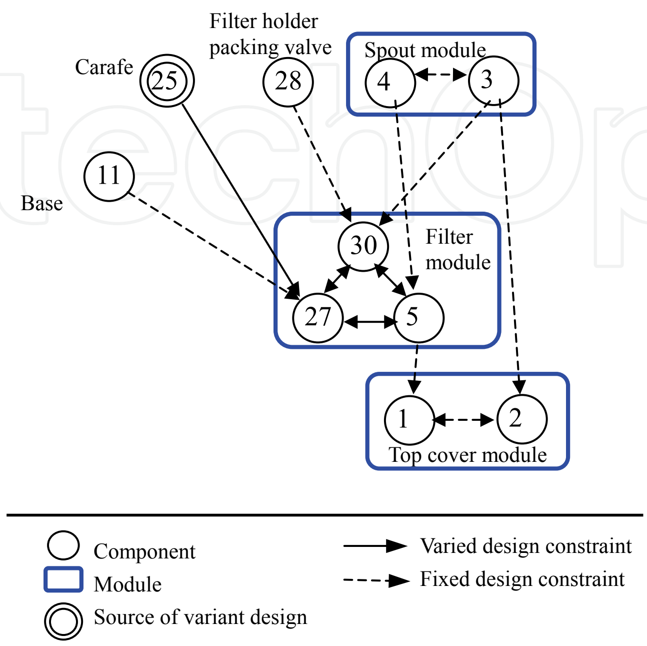


Figure 6. Constraint flow diagram of the filter module

Phase 2: Design for temporal variety

Table 2 indicates that the critical components for realizing temporal variety are the Housing (part 27), Top Cover (part 1), and Carafe (part 25). According to the hierarchical graph in Fig. 4, for these three components, the Carafe occupies the upper level in the interaction hierarchy. This arrangement means that the Carafe design should be addressed first, followed by that of the Housing and finally, the Cover. However, the incidence and costs involved in carafe redesign are quite high. The strategy of Company X thus is to "over design" this component; that is, to improve the quality of the current specifications capable of handling future market requests. Therefore, the Carafe is upgraded for easy cleaning, pouring and dishwasher-safe in both the "current" and "future" versions. Therefore, according to the design priority, the product variety should focus on redesigning the Housing (part 27). To facilitate usability, the design team tends to substitute swing-out housing for the fixed housing. This change divides the component into two new parts; namely, the Swing-out Filter Housing and the Support. The Swing-out Filter Housing is further differentiated into either U-shaped or V-shaped. The original design constraints of the Housing are laid on the two new parts, respectively (see Fig. 7). Thus the shape of the Swing-out Housing must fit the Carafe; and the design of the Support must

fit the Base. The variant design of the Housing directly influences the Top Cover (part 1); meanwhile, for convenient to use, the Top Cover is changed from a lift up to a fixed design.
Finally, Table 6 lists the variant design driven by temporal market differentiation.

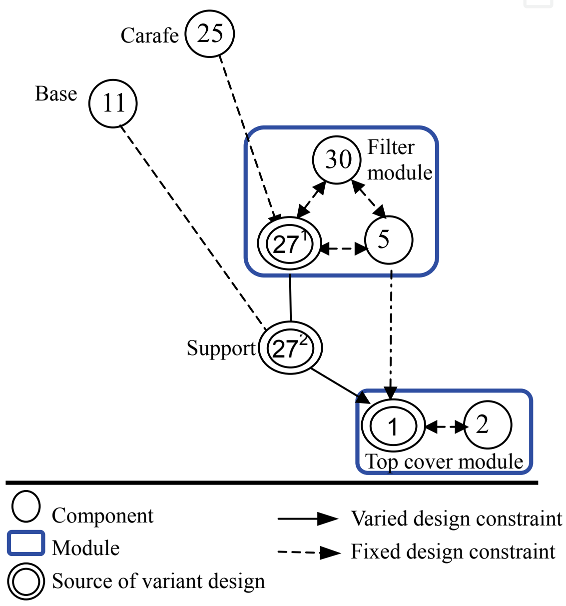


Figure 7. Constraint flow diagram of the new design

No.	Redesigned component
27*[1]	Swing out filter basket
27*[2]	Support
1*	Fixed top cover

Table 6. List of variant components for Future market

4.4 Result

Table 7 lists the components of the four products derived via the proposed methodology. Among these components, most of the variety occurs in chunks 1 and 4, while chunks 2 and 3 remain virtually unchanged, and thus are considered "platforms" of this product architecture. Moreover, the design team further suggested that components of the upper levels of chunk 3, including Water Pipe Module, Heating Element, Base Module, and Heating Plate Module, should be standardized to reduce the redesign effort and production cost.

Chunk	Component	No.	Product 1	Product 2	Product 3	Product 4
	Fastened top cover	1	V	V		
	Lifted-up cover	1*			V	V
	Top Cover base	2	V	V	V	V
	Spout	3	V	V	V	V
	Spout seat	4	V	V	V	V
	Filter holder packing valve	28	V	V	V	V
	V-shaped filter holder	5	V		V	
	U-shaped filter holder	5*		V		V
	V-shaped filter basket	30	V		V	
	U-shaped filter basket	30*		V		V
	V-shaped fixed housing	27	V			
	U-shaped fixed housing	27*		V		
	V-shaped swing out filter housing	27*			V	
	U-shaped swing out filter housing	27*				V
C1	Support	27*			V	V
	Water tank cover	6	V	V	V	V
C2	Water tank	8	V	V	V	V
	Silicone ring	12	V	V	V	V
	Water outlet pipe	13	V	V	V	V
	Pipe connection seat	14	V	V	V	V
	Packing valve	16	V	V	V	V
	Heating element	18	V	V	V	V
	Base	11	V	V	V	V
	Base cover	15	V	V	V	V
	Switch	19	V	V	V	V
	Hot plate ring	20	V	V	V	V
C3	hot plate	21	V	V	V	V
	Glass carafe	25	V		V	
	Thermal carafe	25*		V		V
	Cup bank of glass carafe	22	V		V	
	Cup bank of thermal carafe	22*		V		V
	Handle cover of glass carafe	23	V		V	
	Handle cover of thermal carafe	23*		V		V
	Handle of glass carafe	24	V		V	
	Handle of thermal carafe	24*		V		V
	Cover of glass carafe	26	V		V	
C4	Cover of thermal carafe	26*		V		V

Table 7. Components list of the product family

4.5 Comparison of existing and proposed designs

A team of engineers and managers of Company X estimated the sales volume, marketing, variable (raw material/ production prices) and fixed (engineering/ injection mold) costs for the proposed designs, and compared these estimates to those for products designed independently. Table 8 lists the comparison.

The profit is calculated using the following function:

$$P_i = S_i(PR_i - VC_i) - FC_i - MC_i \qquad (1)$$

Where P_i, S_i, PR_i, VC_i, FC_i, MC_i are the profit, sales volume, price, variable cost, fixed cost, and marketing cost of product i, respectively.

Table 8 illustrates that the primary cost difference between the two design strategies lies in the fixed cost. The proposed designs significantly reduced the fixed cost for developing new products through sharing most components. The second row from the bottom shows that the profits associated with independently developing products 2 and 4 is minus 73% and 65% of current product, respectively. Therefore, the best decision seems to be not to develop any product in Market 2. However, the proposed designs generate a total profit 127% in current markets and 541% in future markets higher than if product 1 was the only product launched. The result shows the potential savings and profit available using this methodology.

	No product family design				Product family design using this methodology			
% of current product	Product 1	Product 2	Product 3	Product 4	Product 1	Product 2	Product 3	Product 4
Sales volume	100	80	100	80	100	80	100	80
Price	100	120	115	130	100	120	115	130
VC	100	145	105	145	100	140	100	140
FC	100	100	100	100	100	40	10	10
MC	100	200	100	100	100	200	100	100
Profit	100	-73	208	-65	100	27	334	207
Total profit	current=	27	future=	143	current=	127	future=	541

Note: VC, FC, MC are the variable, fixed and marketing costs, respectively.

Table 8. Comparison of independently developed and the proposed designs

4.6 Design strategies based on the component interaction graph approach

The hierarchical graph could optimize variant design in the following design strategies:

1. Design strategies for the source components:

- a: Differentiated customer requirements directly drive design variation of these components. And since the incidence and effort for the design changes are relative huge, this variation must be obvious and valuable to customers. To achieve stable product architecture, "over-design" of dominant components might be unavoidable for extending component lifecycle.
- b: If the components are remained unchanged, they should be considered to be standardized or fixed specification, and become core platform of the product family.

2. Designs of the sink components are more likely to change to comply with both the altered design constraints and the requests of customer requirements. However, the cost and incidence of altering these components is relatively low. Furthermore, the redesign should incorporate the constraints provided by the source components.

3. Components that with their specification flow forms an interaction loop are likely to be further modularized or integrated.

5. Product Design Based on Analytic Network Process

5.1 The rational for using the ANP approach for optimizing product design

The approach in sections 3 and 4 illustrated a product variety design based on the component relationship structure graph. The graph forms design constraint flows from source components to the sink ones. However, in some ill-structured product architectures, the component relationships may form a complicated network, and the ISM approach may not be applied successfully. Therefore, we developed an integrated approach via analytic network process (ANP) (Saaty, 1996) technique to fix this problem. The differences between ISM and ANP are that (1). ANP treats component relationship as relative importance (from 0 to 1) rather than binary; (2).ANP mathematically copes with the network structure well, while the ISM, hierarchical structure.

ANP is a general form of the widespread multi-criteria decision technique, AHP (analytic hierarchy process) (Saaty, 1990). AHP employs unidirectional hierarchical relationship among levels, while ANP enables consideration of the interrelationships among the decision levels and attributes. The distinguishing features of ANP make it suitable for dealing with the hierarchical mappings as well as component coupling problems in determining the influence of variety on each design element. In this approach, the analysis result of ANP is then input to the goal programming (GP, Dantzig 1963) models for determining the standardized and variant parts of product architecture. The GP model handles multiple objectives and minimizes deviation from desired goals, and thus provides a feasible and consistent solution for optimizing product family design. Although many researchers use mathematic models, such as (Reiter & Rice 1966, Ringuest & Graves 1989) most methodologies are assumed independent among design alternatives. In this study, we integrated ANP and GP approaches for accommodating interdependence among design alternatives that is first applied in the product variety optimization problem.

5.2 Computational procedure of the ANP

The procedure of optimizing design variety via the ANP was summarized as follows: The first step was to estimate the qualitative changes in customer requirements (CRs) in each future market compared to the current product. The importance of the CRs were compared and calculated, corresponding to the first step of the matrix manipulation concept of ANP. The CRs were then deployed into engineering characteristics (ECs) by comparing the ECs with respect to each CR. The ECs were further deployed into components by comparing the relative contributions of components to each EC. Finally, the interdependence priorities of the components were further examined by analyzing the couplings among components. The supermatrix utilized to model the procedure in matrix notation, which is formed from four submatrices, is constructed as follows:

$$\begin{array}{r} \\ \text{Goal(G)} \\ \text{Customer Requirements(CRs)} \\ \text{Engineering Characteristics(ECs)} \\ \text{Components (C)} \end{array} \begin{array}{c} \begin{array}{cccc} \text{G} & \text{CRs} & \text{ECs} & \text{C} \end{array} \\ \begin{bmatrix} 0 & 0 & 0 & 0 \\ W1 & 0 & 0 & 0 \\ 0 & W2 & 0 & 0 \\ 0 & 0 & W3 & W4 \end{bmatrix} \end{array} \qquad (2)$$

where W1 denotes a matrix representing the relative importance of CRs for satisfying each specified market goal; W2 represents the mappings of the CRs to each ECs, W3 representing the impact of ECs to each component, and W4 denoting the coupling relationship among components.

Using the above notations, the priorities of the components (Wc) were calculated by multiplying W4 and W3. The overall priorities of the components (W^{ANP}) that reflect the degree of required changes of components in response to the niche of each market, then were calculated by multiplying Wc, W2, and W1.

6. Case Study for Optimizing Product Variety Using the ANP Approach

This section presented an illustrative example of a water cooler family design (Martin & Ishii, 2002). The proposed methodology was further demonstrated using a stepwise form.

6.1. Survey customer requirements and segment the future markets

Product variety planning begins with surveying customer requirements. Figure 8 illustrated three future markets defined by the design team, along with the desired product features in these envisioned markets.

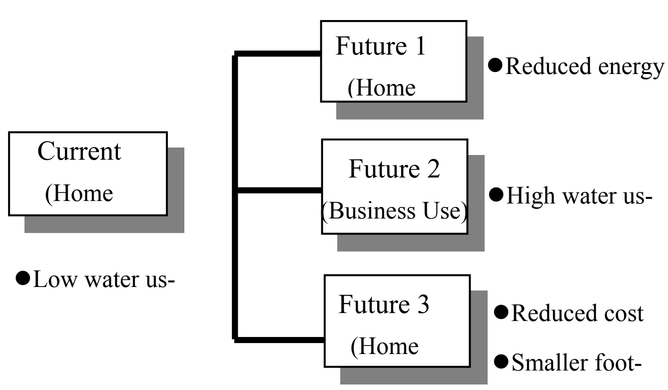


Figure 8. Market planning of the water cooler for three envisioned markets.

6.2 The ANP approach

Phase 1. Estimate relative importance of CRs in each market

For this water cooler example, the main CRs were Fast Cooldown, High Capacity, Low Energy Consumption, Compact, Rapid Pouring, and Low Cost. Figure 8 depicts the desired product features for each market. According to the planning, the design team estimated the range of changes of the CRs for each market using using Saaty's 1-9 scales (Saaty, 1990) pairwise comparisons as shown in Table 9. To avoid comparison inconsistencies, a consistency ratio measured the probability that the pairwise comparison matrix was randomly filled. The upper limit for the consistency ratio was 0.1, which signified that up to 10% chance was tolerable for the comparison conducted in random manner. The procedure was applied in each market. The resulting relative weights of CRs compose W1, as shown in Eq. (3).

$$W1 = \begin{array}{c} \begin{matrix} \text{M1} & \text{M2} & \text{M3} \end{matrix} \\ \begin{bmatrix} 0.071 & 0.300 & 0.045 \\ 0.071 & 0.300 & 0.045 \\ 0.643 & 0.033 & 0.045 \\ 0.071 & 0.033 & 0.409 \\ 0.071 & 0.300 & 0.045 \\ 0.071 & 0.033 & 0.409 \end{bmatrix} \end{array} \begin{array}{c} \\ \text{Fast cooldown} \\ \text{High capacity} \\ \text{Low energy use} \\ \text{Compact} \\ \text{Rapid pouring} \\ \text{Low cost} \end{array} \tag{3}$$

where M1, M2, M3 represent Markets 1, 2, and 3, respectively.

Future Market 3		Fast cooldown	High capacity	LEC	Compact	Rapid pouring	Low cost	Relative weight
Fast cooldown		1	1	1	1/9	1	1/9	0.045
High capacity			1	1	1/9	1	1/9	0.045
Low energy consumption (LEC)				1	1/9	1	1/9	0.045
Compact					1	9	1	0.409
Rapid pouring						1	1/9	0.045
Low cost							1	0.409
Consistency Ratio=	1.60228E-09							

Table 9. Pairwise comparison matrix of CRs for the goal of Market 3.

Phase 2. Translating CRs into ECs

The ECs used in the product design include Cool Down Time (min), Cool Water Volume (gal), Power Consumption (W), Width, Depth (in), Volume Flow Rate (gal/min), and Cost ($). If a CR was fulfilled via two or more ECs, the design team was required to conduct a pairwise comparison to assess the relative importance of the ECs with respect to the CR. Table 10 maps the relations between CRs and ECs. For example, In column 5 of Table 10, two ECs (Width and Depth) specify the request of Compact specification of equal importance, thus, their weighted values were both 0.5.

W2	Fast cooldown	High capacity	LEC	Compact	Rapid pouring	Low cost
Cool down time(min)	1.000	0.000	0.000	0.000	0.000	0.000
Cold water volume(gal)	0.000	1.000	0.000	0.000	0.000	0.000
Power consumption(W)	0.000	0.000	1.000	0.000	0.000	0.000
Width(in)	0.000	0.000	0.000	0.500	0.000	0.000
Depth(in)	0.000	0.000	0.000	0.500	0.000	0.000
Volume flow rate(gal/min)	0.000	0.000	0.000	0.000	1.000	0.000
Cost($)	0.000	0.000	0.000	0.000	0.000	1.000

Table 10. Matrix W2, the mappings of CRs to the relative ECs.

Phase 3. Deploying the ECs to product components

Again, the design team performed AHP to evaluate the relative importance of the components' contribution to each EC, and the aggregation of relative importance weights for components in each EC formed matrix W3, as shown in Table 11. In which the zeros were assigned to the cells if the EC had no effect on the components.

Phase 4. Examining inner dependences among components

In this case, the components are seriously coupled. The degree of the coupling relations between components was identified using a series of pairwise comparisons. Table 12 displays the inner dependence matrix of components with the Fan as controlling component, in which Plumbing and Insulation were excluded because of not impacting the Fan. The schema was performed in each component, and obtained the resulting eigenvectors as shown in Table 13. The matrix indicated the inner dependence among components, in which zeros indicated the eigenvectors of the unrelated components.

W3	Cool down time	Cold water volume	Power consumption	Width	Depth	Volume flow rate	Cost
Fan	0.115	0.000	0.143	0.000	0.000	0.000	0.000
Heat Sink	0.231	0.000	0.000	0.000	0.000	0.000	0.071
TEC	0.115	0.000	0.429	0.000	0.000	0.000	0.000
Power Supply	0.038	0.000	0.429	0.000	0.000	0.000	0.071
Chassis	0.000	0.000	0.000	0.500	0.500	0.000	0.214
Plumbing	0.000	0.000	0.000	0.000	0.000	0.900	0.000
Reservoir	0.231	1.000	0.000	0.000	0.000	0.100	0.214
Insulation	0.038	0.000	0.000	0.000	0.000	0.000	0.000
Fascia	0.231	0.000	0.000	0.500	0.500	0.000	0.429

Table 11. Aggregation of relative importance for components in each EC

Fan	Fan	HS	TEC	PS	Chassis	Reservoir	Fascia	Relative Weights
Fan	1	4	9	6	4	9	9	0.477
Heat Sink(HS)		1	3	3/2	1	5	5	0.154
TEC			1	1/2	1/3	3/2	1	0.048
Power Supply (PS)				1	2/3	3	5/2	0.096
Chassis					1	5	4	0.148
Reservoir						1	4/3	0.034
Fascia							1	0.042
Consistency Ratio=	0.013							

Table 12. Pairwise comparison matrix with the Fan as controlling component.

W4	Fan	HS	TEC	PS	Chassis	Plumbing	Reservoir	Insulation	Fascia
Fan	0.477	0.087	0.000	0.059	0.097	0.000	0.000	0.066	0.125
Heat Sink	0.154	0.498	0.064	0.000	0.145	0.000	0.021	0.000	0.021
TEC	0.048	0.086	0.625	0.092	0.000	0.000	0.056	0.038	0.000
Power Supply	0.096	0.000	0.125	0.673	0.074	0.000	0.000	0.000	0.048
Chassis	0.148	0.167	0.000	0.093	0.276	0.000	0.239	0.000	0.262
Plumbing	0.000	0.000	0.000	0.000	0.000	0.664	0.118	0.000	0.142
Reservoir	0.034	0.067	0.121	0.000	0.253	0.165	0.448	0.373	0.000
Insulation	0.000	0.035	0.064	0.000	0.026	0.050	0.118	0.523	0.021
Fascia	0.042	0.061	0.000	0.082	0.129	0.121	0.000	0.000	0.381

Table 13. Aggregation interdependence matrix among components.

Phase 5. Synthesis the overall priorities of components

According to Eq.(2), the interdependent priority of the components, W_c, was calculated as

$$Wc = W4 \times W3 \qquad (4)$$

The overall priorities of the components regarding the goals of the three markets were calculated as follows:

$$W^{ANP} = W_c \times W2 \times W1 = \begin{array}{c} \\ \end{array}\begin{array}{ccc} M1 & M2 & M3 \\ \left[\begin{array}{ccc} 0.082 & 0.042 & 0.089 \\ 0.056 & 0.059 & 0.077 \\ 0.216 & 0.064 & 0.032 \\ 0.244 & 0.035 & 0.078 \\ 0.107 & 0.150 & 0.231 \\ 0.067 & 0.241 & 0.100 \\ 0.113 & 0.249 & 0.153 \\ 0.040 & 0.076 & 0.039 \\ 0.074 & 0.082 & 0.198 \end{array}\right. \end{array}\left.\begin{array}{l} \text{Fan} \\ \text{Heat sink} \\ \text{TEC} \\ \text{Power Supply} \\ \text{Chassis} \\ \text{Plumbing} \\ \text{Reservoir} \\ \text{Insulation} \\ \text{Fascia} \end{array}\right. \quad (5)$$

where M1, M2, M3 represent Markets 1, 2, and 3, respectively.
The ANP result revealed the priority for redesigning components to satisfy market goals. For example, in Market 1, the first component requiring redesign was Power Supply, with a relative importance value of 0.244, whereas Reservoir and Chassis were identified as the most important components in Markets 2 and 3 with relative importance values of 0.249 and 0.231, respectively.

6.3 Optimization

The optimization of the product architecture is to achieve a stable product platform that enable variant products to be highly differentiated yet share as many substantial portions of their components as possible, thus reducing the manufacturing and design costs.

Phase 1: Platform component selection

There are two considerations in selecting the platform components. First, components with high engineering costs should be the initial focus. Second, a product platform stresses on component commonality; therefore, the components with low W^{ANP} factors -which are less sensitive and more stable in response to the changing environment, are suitable as platform items. Therefore, a weighted GP (Schniederjans, 1995) algorithm is utilized for selecting platform components that satisfy two goals: (1) high engineering cost, and (2) control the W^{ANP} weight loss under a tolerable ratio. Furthermore, to consider the relative importance of different markets and to regulate the possible incommensurability problem of different goals (Ringuest & Graves, 1989), the general GP is as follows:

$$\min \quad \omega_1^{\cos t}\left(\frac{d_1^-}{\sum_{i=1}^{n} c_i}\right)+\omega_2^{ANP}\left(\frac{d_2^+}{\lambda}\right)$$

subject to

$$\sum_{i=1}^{n} c_i x_i + d_1^- - d_1^+ = \sum_{i=1}^{n} c_i, \qquad (6)$$

$$\sum_{i=1}^{n}\sum_{j=1}^{m} \sigma_j w_{ij}^{ANP} x_i + d_2^- - d_2^+ = \lambda,$$

$$\sum_{j=1}^{m} \sigma_j = 1,\ x_i \in \{0,1\},\ \boldsymbol{i=1,2,\ldots n;}$$

$$\boldsymbol{j=1,2,\ldots m}\ d_1^-, d_1^+, d_2^-, d_2^+ \geq 0, ;\ \lambda \leq 1;$$

where $\omega_1^{\cos t}$, ω_2^{ANP} denote the importance weights, d_1^-, d_1^+, d_2^- and d_2^+ denote the negative and positive deviation variables of the goals, respectively; x_i is the binary variable representing whether the *i*th component is assigned as a platform item (if x_i =1) or not (when x_i =0), c_i denotes the engineering cost of the *i*th components, σ_j denotes the relative importance of market *j*, w_{ij}^{ANP} represents the *i*th component weight in the *j*th market, and λ is a controllable variable indicating the tolerable ratio of weight loss.

Phase 2: Variant component selection

This phase considered the distinctiveness of each product for satisfying specific market needs. Therefore, certain components were selected redesigned achieve the distinctiveness under limited design budget. Therefore, the GP was employed to satisfy two goals: (1) select the components with high W^{ANP} factors, and (2) control the cost under a budget. Following the same principle of regulation incommensurability, the general GP is as follows:

To select the redesigned components for market *j*:

$$\min \quad \omega_1^{ANP}\left(\frac{d_1^-}{\sum_{k=1}^{n} w_{jk}^{ANP}}\right)+\omega_2^{budget}\left(\frac{d_2^+}{B_j}\right)$$

subject to

$$\sum_{k=1}^{n} w_{jk}^{ANP} x_k + d_1^- - d_1^+ = \sum_{k=1}^{n} w_{jk}^{ANP}, \qquad (7)$$

$$\sum_{k=1}^{n} c_k x_k + d_2^- - d_2^+ = B_j,$$

$$x_k \in \{0,1\},\ d_1^-, d_1^+, d_2^-, d_2^+ \geq 0,\ \ j=1,2,\ldots m;\ k=1,2,\ldots n$$

$k \neq i$ if the ith component has been assigned as a platform item

where ω_1^{ANP} and ω_2^{budget} denote the importance weights, and d_1^-, d_1^+, d_2^- and d_2^+ represent the negative and positive deviation variables of the first and second goals, respectively; x_k represents a binary variable representing whether the kth component is assigned as a redesigned item (if x_k =1) or not (x_k =0). Notably, the variable x_k should not contain components that have been determined as platform items. w_{jk}^{ANP} is priority rating of the kth component in the jth market, c_k denotes engineering cost of the kth component, and B_j represents design budget of the jth market.

6.4 Result

Table 14 lists the engineering cost for redesigning each component. The data and the W^{ANP} weight in Eq.(5) is input into the GP models via LINDO software. The platform components selected by the GP under variant weight loss (variable λ) are shown in Table 14. After examining the solutions, the design team strategically set the weight loss at 20%, yielding Fan, Heat Sink, and Insulation as the components shared across the product family. Furthermore, the GP model of Eq.(7) was applied for selecting the redesign components in the three envisioned markets , yielding the result listed in Table 15, in which the GP solutions identified the focuses for redesign as being TEC, Power Supply, Plumbing and Reservoir in Market 1; Chassis, Plumbing and Reservoir in Market 2; and Power Supply, Chassis, Plumbing and Fascia in Market 3.

Variable	Component	Redesign cost$	GP solutions				
x_1	Fan	10,000		V	V	V	V
x_2	Heat Sink	200,000	V	V	V	V	V
x_3	TEC	20,000			V	V	V
x_4	Power Supply	3,000					
x_5	Chassis	1,000				V	V
x_6	Plumbing	2,000					
x_7	Reservoir	10,000					
x_8	Insulation	3,000		V	V		V
x_9	Fascia	2,000					
λ			10%	20%	30%	40%	50%

Table 14. Platform components selected under variant weight loss (λ).

Variable	Component	GP Solutions		
		Market 1	Market 2	Market 3
x_3	TEC	V		
x_4	Power Supply	V		V
x_5	Chassis		V	V
x_6	Plumbing	V	V	V
x_7	Reservoir	V	V	
x_9	Fascia			V

Table 15. Components selected for redesign in three markets.

7. Conclusion

This chapter illustrates the authors' current studies on managing product variety in different degrees of product architecture maturity (Liu & Hsiao 2005, Hsiao & Liu 2005). We suggested that the occasion in implementing the first approach (sections 3, 4) is when product architecture is under constructed; the interactions of components have not been investigated. Applications of the approach to product architecture provide the hierarchical graph of component interactions. Furthermore, the methodology provides the following advantages for developing product family:

1. The methodology clarifies the specification flow between components rather than merely symmetric relationship "similarity" or "correlation". Thus the necessary information is provided for determining not only clustering but also precedence among components.

   The incidence matrix with the documented design constraints provides a computable way for design knowledge representation.

2. The hierarchical graphical diagram provides designers with a user-friendly display for clarifying the influence of each component variation.

3. The hierarchical structure along with the QFD analysis helps product family developers to identify whether the components should be standardized, altered, or modularized.

Furthermore, the occasion in implementing the second approach (sections 5, 6) is when component interactions have been clearly defined and formed complicated networks, a flexible and comprehensive decision support system is needed in trading off the product variety, standardization, and resource utilization. In the approach, The interdependent nature inherent in the product design process was considered using the ANP approach. The use of ANP weights, and resource limitations in the multi-objective goal programming provided feasible and more consistent solutions, thus yielding the optimal solutions in determining the platform component as well as the variant components focused on during the redesign phases. The application of the methodologies presented in this chapter can easily be extended to include additional decision criteria, such as the manufacturability, sustainability, and assembly in designing product families. Subsequent research will address these points.

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The primary goal of this book is to cover the state-of-the-art development and future directions in modern manufacturing systems. This interdisciplinary and comprehensive volume, consisting of 30 chapters, covers a survey of trends in distributed manufacturing, modern manufacturing equipment, product design process, rapid prototyping, quality assurance, from technological and organisational point of view and aspects of supply chain management.

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