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A DECISION SUPPORT SYSTEM FOR PRODUCT FAMILY DESIGN

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ABSTRACT

Developing a product family under a robust platform provides a company with an important competitive advantage. The competitive benefits include reducing engineering costs and time to market, extending product portfolios and expanding market share. This study illustrated an algorithm based design methodology using two decision techniques for achieving optimal product architecture. The analytic network process (ANP) is employed to consider the relative importance of components in the response of both customer needs and the interrelationship among components. The goal programming approach that incorporates the result of ANP and cost budget limitation then is applied to determine the platform and also the variant components to be focused on redesign. A product family design example is used to illustrate the application of this methodology.

Keywords: Analytic Network Process, Product family, Product platform, Product design optimization

1 INTRODUCTION

Dominating markets with a single product is increasingly difficult, and instead numerous industries are evolving towards developing a product portfolio to better serve customers, and increases market share by widening product range. To achieve this, introducing product family offers one means of developing a product portfolio as well as improving resource utilization; for different products within a product family "share a common arrangement of elements, common mapping between function and structure, and common interactions among components, yet still retain sufficient distinctiveness to satisfy diverse market segments"[1].

This study develops a methodology that helps designers addressing the challenges of quick response to dynamic shifts in customer needs and the increasing complexity of product design. This methodology integrates the analytic network process (ANP) [2] and goal programming (GP) [3] techniques, and seeks to optimize product family architecture by balancing requests of customer needs and budgetary constraints. The operational details are illustrated using an example case.

2 RELATED LITERATURE

The issue of product family planning has attracted growing research interest during recent years. In1993, Pine [4] began discussing the need for product variety in increasingly competitive markets. Ulrich [5] examined the relationships between product architecture and product variety, component standardization, modularity, and product development. Roberson and Ulrich [6] further discussed the integration of marketing, product design, and manufacturing considerations early in the design stage when planning product platforms. Additionally, Tseng and Jiao [7] developed the PFA (product family architecture) model, in which they classified similar products into families based on product topology and functional requirements, and then devised an optimal product family architecture based on this classification scheme.

Other investigations established a basis for product family planning by solving the problem of product variety: Cohen [8] suggested using Master House of Quality for planning product variety. Fujita and Ishii [9] designed the task structure of product variety design, including design specification analysis, system structure synthesis, configuration and model instantiation. Moreover, Fujita et al [10,11] and Fujita [12] used optimization techniques to determine the optimum contents and combinations of modules in a family of aircrafts under fixed product architecture. Furthermore, Simpson, et al. [13]

used the Product Platform Concept Exploration Method (PPCEM) to design family products that are scaled around a common platform by varying one or more design parameters to realize a variety of requirements. Additionally, Gonzalez-Zugasti et al. [14,15] presented a model to account for uncertainty and real option concepts to select the most appropriate product family design from a set of alternatives, however, the interactions between design elements were not addressed when designing the product architecture. Martin and Ishii [16-18] proposed DFV (Design for Variety), which is a QFD (quality function deployment) based approach that developed product platform architectures with quantifying indices, namely the generational variety index (GVI), indicating the amount of redesign effort required for future product design; and the coupling index (CI), indicating the coupling among the product components. The design team can use these two indices to reduce the influence of product variety on product life-cycle cost, and thus helping design teams to develop product family. However, the results of the GVI and CI indices may be conflicting, and the decision process remains ambiguous.

This investigation attempts to extend the DFV method by providing an algorithm-based approach. The methodology and case study are illustrated in following sections.

3 DESIGN METHODOLOGY

3.1 Methodology Framework

The design methodology is divided into three phases. The first phase is market planning, which involved customer requirement survey, market segmentation, and identifying the desired product features in each future market. Meanwhile, during the second phase the ANP approach was performed to explicate the rating of each component regarding the changing customer needs under a network structure. Finally, during the third phase The ANP results were integrated to establish two GP models for strategically determining the platform and variant components in each market. Figure 1 shows the flow chart for solving the product family design problem.

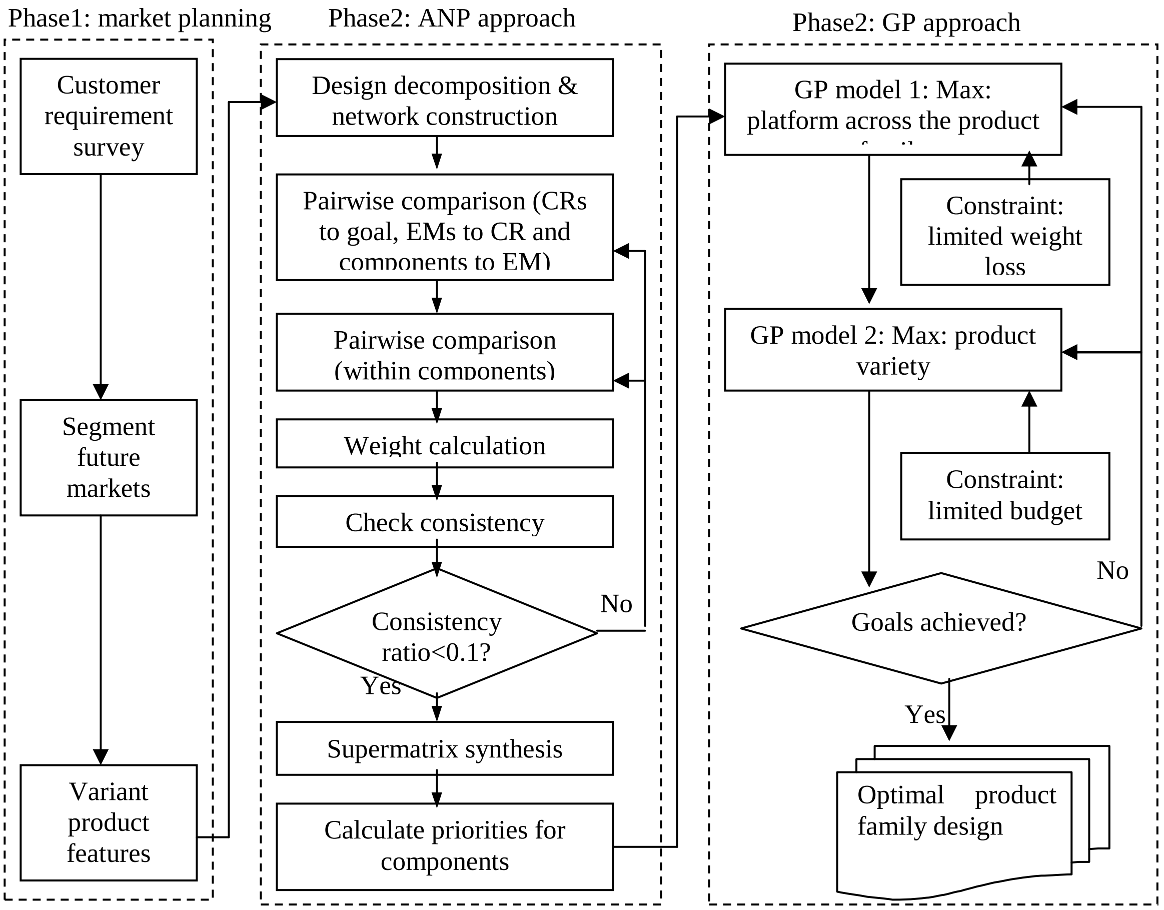

Figure 1. Methodology framwork for optimum product family design.

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

ANP is a general form of the widespread multi-criteria decision technique, AHP (analytic hierarchy process) [19]. 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 GP 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. 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.

3.3 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 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:

$$\begin{array}{r|cccc|} & \text{G} & \text{CRs} & \text{ECs} & \text{C} \\ \text{Goal(G)} & 0 & 0 & 0 & 0 \\ \text{Customer Requirements(CRs)} & W1 & 0 & 0 & 0 \\ \text{Engineering Characteristics(ECs)} & 0 & W2 & 0 & 0 \\ \text{Components (C)} & 0 & 0 & W3 & W4 \end{array} \qquad (1)$$

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*.

4 CASE STUDY

This section presented an illustrative example of a water cooler family design [18]. The proposed methodology was further demonstrated using a stepwise form.

4.1 Survey customer requirements and segment the future markets

Product variety planning begins with surveying customer requirements. Figure 2 illustrated three future markets defined by the design team, along with the desired product features in these envisioned markets.

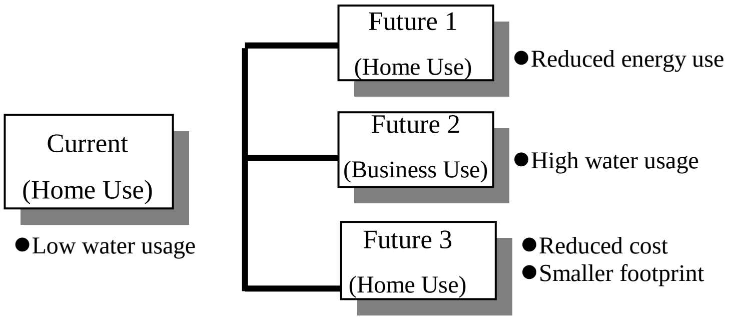

Figure2. Market planning of the water cooler for three envisioned markets.

4.2 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. According to the desired product features depicted in Fig.2, the design team estimated the range of changes of the CRs for each market using Saaty's 1-9 scales [19] pairwise comparisons as shown in Table 1. To avoid comparison inconsistencies, a consistency ratio measured the probability that the 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. (2).

$$W1=\begin{array}{c}\begin{array}{ccc}M1 & M2 & M3\end{array}\\ \left[\begin{array}{ccc}0.071 & 0.300 & 0.045\\ 0.071 & 0.300 & 0.045\\ 0.643 & 0.033 & 0.045\\ 0.071 & 0.033 & 0.409\\ 0.071 & 0.300 & 0.045\\ 0.071 & 0.033 & 0.409\end{array}\right]\end{array}\begin{array}{c}\\ \text{Fast cooldown}\\ \text{High capacity}\\ \text{Low energy use}\\ \text{Compact}\\ \text{Rapid pouring}\\ \text{Low cost}\end{array} \qquad (2)$$

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

Table 1. Pairwise comparison matrix of CRs for the goal of Market 3.

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= 1.6023E-09

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 2 maps the relations between CRs and ECs. For example, In column 5 of Table 2, two ECs (Width and Depth) specify the request of Compact specification of equal importance, thus, their weighted values were both 0.5.

Table 2. Matrix W2, the mappings of CRs to the relative ECs.

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

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 3. In which the zeros were assigned to the cells if the EC had no effect on the components.

Table 3. Aggregation of relative importance for components in each EC

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

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 4 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 5. The matrix indicated the inner dependence among components, in which zeros indicated the eigenvectors of the unrelated components.

Table 4. Pairwise comparison matrix with the Fan as controlling component.

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 5. Aggregation interdependence matrix among components

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

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Phase 5. Synthesis the overall priorities of components

According to Eq.(1), the interdependent priority of the components, W_c, was calculated as

$$Wc = W4 \times W3 \tag{3}$$

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

$$W^{ANP} = W_c \times W2 \times W1 = \begin{array}{c} \begin{array}{ccc} \text{M1} & \text{M2} & \text{M3} \end{array} \\ \left[\begin{array}{ccc} 0.082 & 0.042 & 0.089 \\ 0.056 & 0.059 & 0.077 \\ 0.216 & 0.064 & 0.032 \\ 0.244 & 0.035 & 0.078 \\ 0.107 & 0.150 & 0.231 \\ 0.067 & 0.241 & 0.100 \\ 0.113 & 0.249 & 0.153 \\ 0.040 & 0.076 & 0.039 \\ 0.074 & 0.082 & 0.198 \end{array}\right] \end{array} \begin{array}{l} \\ \text{Fan} \\ \text{Heat sink} \\ \text{TEC} \\ \text{Power Supply} \\ \text{Chassis} \\ \text{Plumbing} \\ \text{Reservoir} \\ \text{Insulation} \\ \text{Fascia} \end{array} \tag{4}$$

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.

4.3 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 [20] 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 [21], 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

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

$$\sum_{i=1}^{n}\sum_{j=1}^{m} \sigma_j w_{ij}^{ANP} x_i + d_2^- - d_2^+ = \lambda, \tag{5}$$

$$\sum_{j=1}^{m} \sigma_j = 1,\ x_i \in \{0,1\},\ \mathbf{i=1,2,\ldots n; j=1,2,\ldots m;}\ d_1^-, d_1^+, d_2^-, d_2^+ \ge 0, ; \lambda \le 1$$

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

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

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

$$x_k \in \{0,1\},\ d_1^-, d_1^+, d_2^-, d_2^+ \ge 0,\ \ j=1,2,\ldots m;\ k=1,2,\ldots n \qquad (6)$$

$k \neq i$ 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.

4.4 Result

The third column of Table 6 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 6. 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.(6) was applied for selecting the redesign components in the three envisioned markets , yielding the result listed in Table 7, 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.

Table 6. Platform components selected under variant weight loss (λ).

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 7. Components selected for redesign in three markets.

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

5 DISCUSSION

In comparison the approaches of DFV [16-18], the advantages of this approach were illustrated as follows.

1. The GVI of a component in DFV method was calculated by summing up the scores of the component relating to the engineering matrix, while that in the AHP/ANP method, the importance of a component was calculated with the geometric mean of the scores for pairwise comparison.
2. The ANP approach calculated different request of CRs as well as relative importance of each market, which were not addressed in GVI. Therefore, GVI was invalid in selecting the redesigned components in a specific market.
3. The coupling relation among components was addressed in the ANP via a matrix, and integrated into the decision system to adjust the priorities of components. In practical design, the design team first selected components requiring redesigned, then, considered the coupling relations of other components interacting with the redesigned components. Therefore, considering all the receiving/ supplying information (CI-R/ CI-S) of a component is impractical. Rather, only the coupling relations interacting with the redesigned components should be addressed.
4. The indices of GVI, CI-S, and CI-R lacked coherence. Therefore, designers have difficulty determining product architecture when these indices contradicted one another. This approach provided a coherent and effective decision support system for designing an optimal product family architecture.

6 CONCLUSION

To deal with the growing variety of customer requirements and the demand of faster responses, corporations strive to balance customer satisfaction and cost savings, and product family design is becoming essential for accomplishing this. In product family design, it is very important to consider the interdependent relationship among product elements as well as the changes of customer requirements, while traditional methods stressed on only one side or provided conflictingly ambiguous solutions.

Developing a systematic decision algorithm for aiding designers in developing a product family is a difficult problem. We introduce a novel method of solution through a case example using ANP and GP techniques. The hierarchical and 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 economic implication of this approach for marketing and engineering is to reduce design expenses and enhance efficiency through reusing component designs and extending product portfolio. The application of the decision procedure presented in this study can easily be extended to include additional decision criteria, such as manufacturability, sustainability, and maintainability. Moreover, the interdependencies as well as feedbacks among customer needs and engineering metrics can also be contained in the decision algorithm. Subsequent research will address these points.

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