Fuzzy Logic Evaluation Approach for Modular Product Development

Chung-Shing Wang*, Teng-Ruey Chang, Chung-Chuan Wang***, Huei-Hua Hsiao******

** Department of Industrial Design, Tung-Hai University, Taichung, Taiwan. E-mail: cswang@thu.edu.tw*
*** Department of Industrial Management, Nan-Kai University of Technology, Nan-Tou, Taiwan.*
E-mail: t237@nkut.edu.tw
**** Department of Multimedia and Game Science, Chung-Chou University, Chung-Hwa, Taiwan.*
E-mail: ccwang@dragon.ccut.edu.tw
***** Department of Industrial Design, National Cheng-Kung University, Tainan, Taiwan.*
E-mail: whshiao@gmail.com

Abstract: Modular product development not only can increase the products in variety, it also enhances the competition in the coming market. This research was based on the fuzzy logic approach in configuration sorting of modular product. The algorithms of fuzzy synthetic evaluation (FSE), fuzzy interpretive structural model (FISM) and fuzzy clustering analysis (FCA) were proposed for the planning of components in product. Fuzzy synthetic evaluation transforms unclear product data to evaluated factors of the products. The fuzzy interpretive structural model was more useful in deciding the priority of components in production than traditional decomposition method. By using fuzzy clustering analysis, the assessed values of parts indicated the joint constrained in components was included for its classification. It made the sorting process easier and quickly in finding out the key components of the modular products. Multi-speed drive hub in bicycle was as the case study to verify the application of fuzzy logic evaluation in product modular configuration.

Key words: Modular Product Development, Fuzzy Synthetic Evaluation, Interpretive Structural Model, Fuzzy Clustering Analysis, Product Decomposition.

1. Introduction

Based on the need of variety and flexibility in product development, the derivative of the modular design concept is introduced. During the process of modular design, there are three important stages: the configuration structure between the components, the engineering design of the product components and the analysis of the manufacturing process. Essentially, the first stage in configuration decomposition and the linked constraints among components is the crucial issue in product development. This research focused on the deconstruction of the front-end components analysis. We induced the fuzzy logic evaluation to the concepts of the linked constraints in the components. By constructing three kinds of fuzzy logic methods - fuzzy synthetic evaluation (FSE), fuzzy interpretive structural modeling (FISM), and fuzzy clustering analysis (FCA), the product's modular design and planning application can be achieved.

Related literature in this research, Victor analyzed the interactive matrix of product features and physical arrangement, assembly, and geometric relationships in the product [1]. Gu considered the product life cycle assessment for the evaluation of the components. Finally, the modular design of parts can be achieved after assessment [2]. Tseng considered the parameters of the green modular design engineering attributes added. It used the group genetic algorithm (GGA) and identified the best module solution [3]. Kuo & Chen used fuzzy synthetic evaluation to find the best products to help consumers' decisions. Mobile phone was as an example for implementation [4]. Tsai & Hsiao proposed analytic hierarchy process (AHP) to define the order of importance of the customer needs. Then, it used fuzzy inference model to build customer demand model. The concept of fuzzy synthetic evaluation can be induced for looking for the best alternative components. Stroller was used as an example to verify this idea [5]. Mitchell & Jiao illustrated the concept of cluster analysis in electronic module classification to construct the related matrix and finished the parts clustering planning product modules [6].

In this study, multi-speed drive hub in bicycle is as the direction to investigate and verify. Normally, multi-speed drive hub is about six months to a year needed to do maintenance. This study attempts within the transmission components as a modular design and planning case study.

2. Methodology

In this study, the main research methods in fuzzy logic algorithms include fuzzy synthetic evaluation (FSE), fuzzy interpretive structural model (FISM) and fuzzy clustering analysis (FCA). The aim of the research is to build the modular configuration decomposition for the components. Applying these three algorithms, the methodology can be divided into two categories: (1) To construct the hierarchical structure of the modular components: The concept of fuzzy synthetic evaluation combined with interpretive structural modeling is introduced to identify the parts appropriate classification. Furthermore, by explicit fuzzy synthetic evaluation of the weights, the target for part planning can be reached. (2) To consider the linked constraints strength between the components: Using fuzzy clustering method to produce part assessments, this process assisted in finding out the key parts.

Based on these two classification methods with each other as a modular product design planning, the modular components of the front-end design configuration decomposition process can be completely classified as well as the assessment of key components. To verify this study, a case study of bicycle multi-speed drive hub is introduced to apply the planning and design of the front end in the modular decomposition classification techniques. Research flowchart is shown in Figure 1.

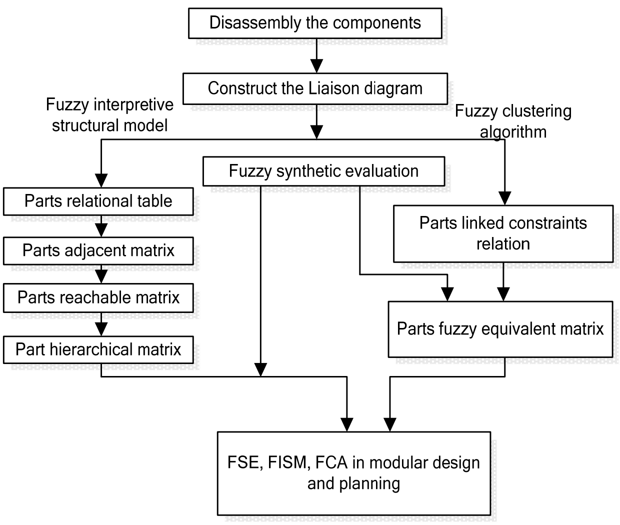

Figure 1 Research flowchart

2.1 Fuzzy synthetic evaluation

The main function of fuzzy synthetic evaluation is to do an objective judgment on the decision making. It builds the evaluation according to multiple indicators about the events. Using formula (1) via fuzzy relations operation, we can get fuzzy synthetic matrix. By multiplying assessment scale scores in formula (2), we find the fuzzy synthetic evaluation scores.

$$\widetilde{A}=\left[\widetilde{a}_1,\widetilde{a}_2,\ldots\widetilde{a}_n\right]=W\circ B \text{ ....} \quad (1)$$

$$\widetilde{N}=\widetilde{A}\times V \text{ ....} \quad . (2)$$

$\widetilde{A}$: fuzzy synthetic evaluation matrix; *n*: number of fuzzy synthetic evaluation; *W*: weights for all events; *B*: influence factor matrix; $\widetilde{N}$: fuzzy evaluation score; *V*: evaluation scale; The operator between *W* and *B* used maximum-minimum operation.

2.2 Fuzzy interpretive structural model

Fuzzy interpretive structural model is a method to find the relationship among all the components in assembly part. Interpretive structural modeling with the concept of fuzzy synthetic evaluation is the basis for fuzzy interpretation in this study. The concept of interpretive structural model is based on the relationship matrix in finding the shortest path among the parts which is a basis for components clustering. The steps are as follows [7]:

1. Disassemble the parts and build the parts relationship diagram.
2. To convert the parts relationship diagram into matrix and put the diagonal to 1, it is called adjacent matrix. This is the directed arc in graph theory.
3. By self-multiplying to the adjacent matrix, until there are no changes in increasing new nodes, we can make sure that the matrix has been to the reachable matrix.
4. By using the redefined conversion rules, the reachable matrix can convert into hierarchical matrix for parts. This hierarchy presentation stands for the FISM.
5. To put the fuzzy synthetic scores to FISM diagram, it can help designers to determine a group of parts and planning.

2.3 Fuzzy clustering analysis

The fuzzy clustering analysis classification concept is to establish the relationship between the constraints in parts. This study linked the strength of the relationship between the values of parts, as the association between parts. Combined with fuzzy synthetic evaluation, it is easier and faster for design classification. Its mode of operation, as described below:

1. Establish fuzzy equivalent matrix：By finding the fuzzy synthetic evaluation scores. Respectively, multiplied by the link strength of the relationship between the two parts. That is to get fuzzy similarity relation between two parts R_{ij}. The fuzzy equivalent matrix can be constructed.
2. Fuzzy Clustering: Use the largest tree method of fuzzy clustering to sort all the components. The maximum tree is the method which links the elements by lines with the value in order in the fuzzy equivalent matrix. Finally, by experience in accordance with the disassemble process, the appropriate fuzzy relationship as the intercept of the cut-off value λ is set. We can get the results of the classification for the whole product.

3. Implementation

An internal multi-speed drive hub SG-3S40 with a total of 19 parts is used as the case study. Two kinds of sorting algorithms are implemented - fuzzy interpretive structural modeling (including fuzzy synthetic algorithm) and fuzzy clustering analysis.

3.1 Fuzzy interpretive structural modeling in multi-speed drive hub

1. Disassembly for multi-speed drive hub

After disassembly all the parts, we can get the exploded diagram, as shown in Figure 2. All the 19 parts with number is shown in Table 1. Based on the master-slave relation, we can find the initial Liaison diagram for all parts. The arrowed direction is toward to driven component. The relationship among the components can be shown in Figure 3. After the complete the initial disassembly, the connection between the parts can get the matrix relational tables, see Table 2.

2. Fuzzy synthetic evaluation for multi-speed drive hub

(1). Fuzzy synthetic matrix: Determine the synthetic evaluation of the system matrix ***U*** with various impact factors $U = [u_1, u_2, u_3, ..., u_n]$. For impact factors in internal multi-speed drive hub, this research used Chen & Tseng [8] patent as the evaluation value (Table 3).

(2). Determine the weights *W* for all impact factors: $W = [w_1, w_2, ...w_n]$

(3).Build the fuzzy evaluation scale *V*: We define the fuzzy evaluation set is *V* = [strong, medium, weak, no influence] = [0.9, 0.3, 0.1, 0] [8, 9].

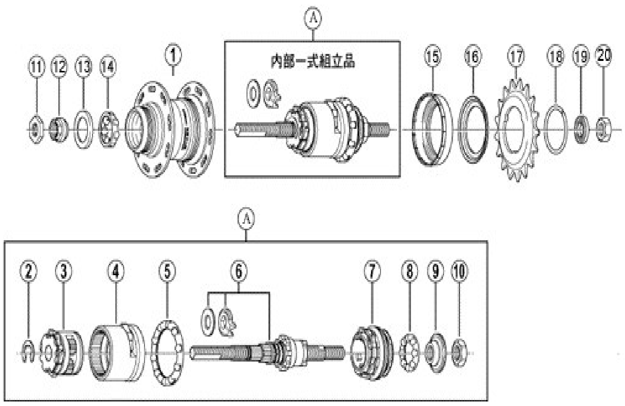

Figure 2 Exploded diagram for internal multi-speed drive hub

Table 1 Internal multi-speed drive hub parts name

No.	Parts name
1	Hub
2	Stop Ring
3	Carrier Unit
4	Ring Gear Unit
5	Ball Retainer K
6	Axle Unit
7	Driver Unit
8	Ball Retainer J
9	Right Hand Cone w/Dust Seal
10	Right Hand Lock Nut for Axle Length
11	Right Hand Lock Nut
12	Left Hand Cone
13	Left Hand Dust Cap

14	Ball Retainer A
15	Right Hand Dust Cap A
16	Right Hand Dust Cap B
17	Sprocket Wheel
18	Snap Ring C
19	Hub Nut

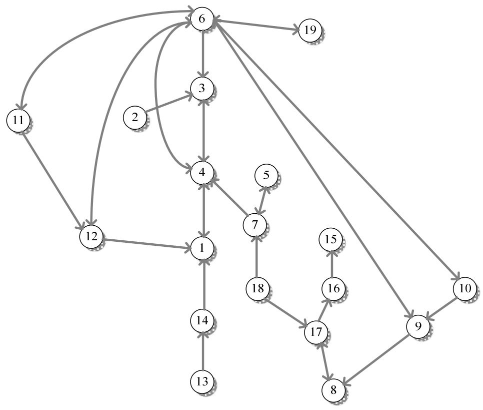

Figure 3 Initial Liaison diagram

Table 2 The matrix for internal drive hub

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1				1															
2			1																
3				1															
4	1		1			1													
5							1												
6			1	1					1	1	1	1							1
7				1	1										1				
8																	1		
9						1		1											
10						1			1										
11						1						1							
12	1					1													
13														1					
14	1																		
15	1						1												
16															1				
17								1								1			
18							1										1		
19						1													

Table 3 Impact factors and weights for multi-speed drive hub

	Impact factors	weights
1	Easy assembly	0.15
2	Easy disassembly	0.05
3	Easy installation	0.10
4	Small volume	0.15
5	Light weight	0.15
6	Long life	0.40

(4). Define the synthetic evaluation set and fuzzy relational matrix: In this study, a total of 10 experts are invited to evaluate the relationship among the components after finished watch videos. The relationship between the various parts of the impact factor rating scales can be constructed the fuzzy relational matrix.

For example as Part 1, using formula (1) $A = W \circ B$, we can get the fuzzy synthetic evaluation matrix as $\begin{bmatrix} 0.2 & 0.4 & 0.15 & 0.3 \end{bmatrix}$. To put the fuzzy synthetic evaluation ***A*** into formula (2), we get the final fuzzy synthetic evaluation $N = [0.2 \quad 0.4 \quad 0.15 \quad 0.3][0.9 \quad 0.3 \quad 0.1 \quad 0]^T = 0.315$. By using the above calculation, we can get the scores for all parts in fuzzy synthetic evaluation。

3.2 FISM construction for multi-speed drive hub

The steps for multi-speed drive hub in fuzzy interpretive structural model:

Step 1: Convert Table 2 into relationship matrix and add unit matrix, we can get the adjacency matrix.

Step 2: Build the reachable matrix. Calculated by the adjacency matrix self multiplied to the power of 5, the reachable matrix can be obtained.

Step 3: Determine interpretive structural model results: Reachable matrix can be converted to FISM according to the conversion rules.

Step 4: ISM hierarchical clustering diagram: Put all scores from fuzzy synthetic evaluation and complete the FSIM hierarchy (Figure 4).

Fuzzy interpretive structural model presented as a decision model tree for easy understanding the hierarchy and importance of the components. All the evaluation scores and linked relationship is included in the diagram.

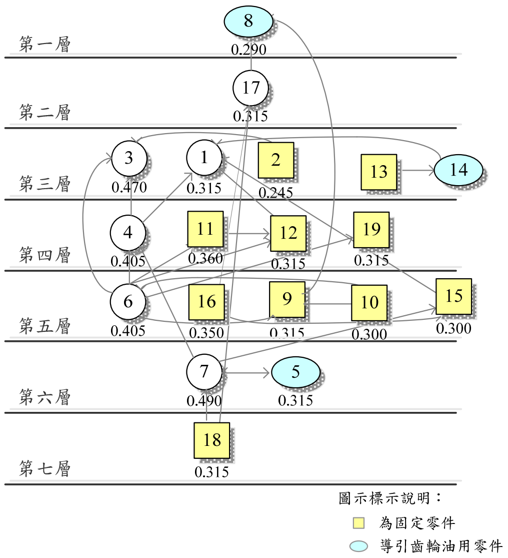

Figure 4 FISM diagram for multi-speed drive hub

For example in layer 5 in Figure 4, there are 5 components in this layer, No. 6-Axle Unit, No. 16-Right Hand Dust Cap B, No. 9-Right Hand Cone w/Dust Seal, No. 10-Right Hand Lock Nut for Axle length, No. 15-Right Hand Dust Cap A. From the fuzzy synthetic evaluation in Figure 4, No. 6 is the key component in multi-speed drive hub. No. 16, No. 9, No. 10 and No. 15 are all fixed components which attached on No. 6. After checking the scores for fuzzy synthetic evaluation, we may consider the possibility for combination of No. 9 and No. 10, or No. 15 and No. 16. We may also consider the link method between these components with No. 6. TRIZ innovative method may introduce for further study in this topic.

3.3 Fuzzy clustering analysis for multi-speed drive hub

During the first stage for fuzzy clustering analysis in multi-speed drive hub, Research considered the links between parts [10, 11, 12], as in Table 4. According to the link relationship, we put the strength link value for the combined components. The link or joint between components influence the steps for assembly and disassembly. Assessment values of 0-1 are introduced to different kind of combination methods. Layout interference is also considered. Layout interference is the indirect weak tie between the components with a linking strength value 0.2. After defined the linking strength of all components in multi-speed drive hub, the fuzzy numerical table of the relationship of all parts connected.

Table 4 Linking strength in components

No.	relationship	value	description
1	Permanent binding	1	Tension, bending, bonding, welding, forging, gluing
2	Using other elements	0.8	Bolt, nuts, screw, washer, rivet, key, pin
3	Geometric binding	0.6	Insert, pressing, screw in, friction
4	Layout interference	0.2	Blocked by another part
5	No relation	0	No relation between two parts

The constraints between two parts will influence the evaluation among the parts. In this research, we not only consider the scores for fuzzy synthetic evaluation, but also count the link strength for different parts. Using fuzzy synthetic evaluation and link strength value, we can fine the fuzzy similarity relation degree between any two parts. For example, in part 3 and part 4, we can find as the followings:

(1) From Fig. 4, we can get the fuzzy synthetic evaluation scores for part 3 is 0.470, and part 4 is 0.405.

(2) The relationship between part 3 and part 4 is geometric binding by insertion which has a link strength value 0.6 between these two parts.

(3) Fuzzy similarity relation degree between part 3 and part 4, $R_{3,4} = (0.47 \times 0.6) + (0.405 \times 0.6) = 0.525$.

All the subsequent parts connected relationship can be calculated by using fuzzy similarity relation degree. We can find the fuzzy equivalent matrix (Table 5) for multi-speed drive hub. Fuzzy equivalent matrix must be a symmetric matrix. It only expressed in upper triangular matrix. The related maximum tree can be drawn after the fuzzy clustering analysis is finished, as shown in Figure 5. If we choose the intercept cut-off value $\lambda = 0.483$, all the weights over the cut-off value is reserved. We can get the final cluster in Figure 6. From the cluster result, the critical core part is No. 7 and 6.

4. Results and Discussion

This research aimed at configuration decomposition for multi-speed drive hub design. Components sharing modularity consideration is the main issue for this study. By using product family concept in various components, we can achieve and share most same essential components in different modular design.

Table 5 Fuzzy equivalent matrix for multi-speed drive hub

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	1			0.432	0.378						0.135	0.126	★	★	0.369				0.126
2		1	0.429	0.130		0.390							★	★					
3			1	0.525		0.525	0.576				0.166	0.157	★	★					
4				1	0.432		0.537				0.153	0.144	★	★					
5					1		0.483						★	★	0.369				
6						1	0.537		0.576	0.564	0.612	0.576	★	★					0.576
7							1	0.468	0.161	0.158			★	★	0.474	0.504	0.483	0.483	0.161
8								1	0.363	0.118			★	★					0.121
9									1	0.369			★	★					0.126
10										1			★	★					
11											1	0.405	★	★					
12												1	★	★					
13													1	★					
14														1					
15															1	0.390	0.123		0.123
16																1	0.399	0.133	0.133
17																	1	0.378	0.126
18																		1	
19																			1

★零件 13 和 14 因無法順利拆解，因此無法正確完成模糊綜合評價，故於矩陣中省略。

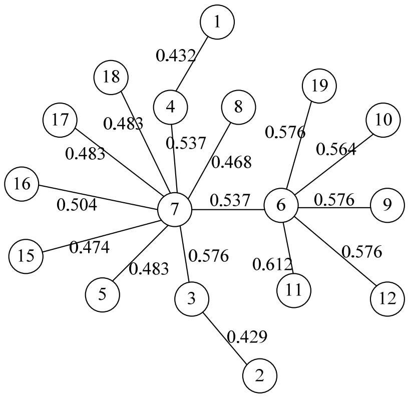

Figure 5 FCA for multi-speed drive hub

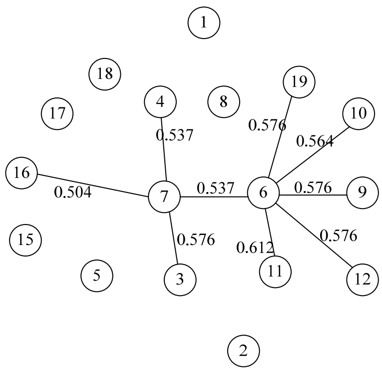

Figure 6 Diagram for weighting value more than $\lambda = 0.483$

Described by interpretive structural model and fuzzy synthetic evaluation, the components of multi-speed drive hub can be grouped and planed. Fuzzy interpretive structural model in hierarchical clustering sorting can show the importance of evaluated components. Modular design and planning can help engineers or designers doing further consideration. Part attributes and parts importance rating can provide designers insight into the important parts pick and further assessment of the important parts in the disassembly or assembly.

After the first stage in concept classification by FISM, we can get the classified components. By using fuzzy clustering analysis, it obviously observed that the key components in multi-speed drive hub are No. 6 and No. 7.

Next step issue can be used other innovative design method, such as TRIZ method to do the detailed design.

5. Conclusions

This research proposed fuzzy interpretive structural modeling and fuzzy clustering analysis in the concept of product classification. By defining the key components in product, we can achieve a solution in the classification of modular parts. The following specific objectives can be reached.

1 The success of the concept of fuzzy theory guided the product modular planning.

2 Using fuzzy synthetic evaluation scores designed and planned the modular parts. Various aspects consider the impact factors in the design process.

3 To build the relationship of strength between the linked components with fuzzy semantics approach in fuzzy clustering analysis.

6. Acknowledgement

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References

[1] Victor, B.K., (2004), *Modular product design with grouping genetic algorithm - a case study*, Computers and Industrial Engineering, 46(3), 443-460.

[2] Gu, P. and Sosale, S. (1999), *Product modularization for life cycle engineering*, Robotics and Computer-Integrated Manufacturing 15(5), 387-401.

[3] Tseng, H.E., (2008), *Modular design to support green life-cycle engineering*, Expert Systems with Applications, 34(4), 2524-2537.

[4] Kuo, Y.F., Chen, P.C., (2006), *Selection of mobile value-added services for system operators using fuzzy synthetic evaluation*, Expert Systems with Applications, 30, 612-620.

[5] Tsai, H.C. and Hsiao, S.W., (2004), *Evaluation of alternatives for product customization using fuzzy logic*, Information Sciences, 58, 233–262.

[6] Mitchell, M.T. and Jiao, J.X, (1997), *A Module identification approach to the electrical design of electronic products by clustering analysis of the design matrix*, Computers and Industrial Engineering, 33(1-2), 229-233.

[7] Warfield, J.N., (1977), *Crossing theory and hierarchy mapping*, IEEE Transactions on Systems, Man, and Cybernetics, SMC-7, 7, 505-523.

[8] Chen, J. L. and Tseng, C. H., (2000), *Design considerations for assembly in planetary gear train*, Proceedings of the International Conference on Gearing, Transmission, and Mechanical System, 157-166.

[9] Chen, S.J. and Hwang, C.L., (1992), *Fuzzy multiple attribute decision making*, New York: Springer-Verlag Press.

[10]Pahl, G. and Beitz W., (1988), *Engineering Design: A Systematic Approach*, Springer-Verlag.

[11]Gao, F., Xiao, G., and Chen, J.J., (2008), *Product Interface Reengineering Using Fuzzy Clustering*, Computer-Aided Design, 439-446.

[12]Zha, X.F., Sriram, R.D., (2006), *Platform-based product design and development: a knowledge-intensive support approach*, Knowledge Based Systems, 19, 524-543.