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An ISM, DEI, and ANP based approach for product family development

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ABSTRACT

Product customization has been used for many years, and with this concept, product families can be designed that are better matched to the needs of customers through the use of market segmentation and modular architecture. This study is composed of two phases: the first phase establishes the modular architecture, and taking a bicycle as the case study, applies the Interpretive Structural Model (ISM) to modularize and cluster parts, and then models the connecting relations between the parts numerically using a Disassembly Effort Index (DEI). The second step involves the development of a product family using cluster analysis to divide the experimental samples and the employment of an Analytic Network Process (ANP) to obtain the optimal weight performance of the modules after establishing the market segmentation model. Results of the case study establish four product families and address construction performance of both the common and independent modules between the product families.

1. Introduction

Product customization is the product engineering approach of an enterprise to develop products that meet the requirements of different customers in highly competitive markets. Hsiao and Liu [1] proposed the concept of a product family to meet the need for customer-oriented design. Because product variety is frequently required in a customization environment, modularization becomes inevitable. In the process of product design, modularization is deployed to create a common module entity used for a specific purpose by combining different model designs with similar functions and properties. Modular products are more flexible, so they can be configured conveniently with limited changes according to market demands, enhancing their competitiveness and reducing risks.

In traditional industries (such as the bicycle industry), the cost of product assembly usually accounts for 25% to 50% of all costs; however, according to Eng et al., in the electronics industry product assembly costs even more, as much as 40–60% [2]. Therefore, improving assembly efficiency is critical for the enhancement of product competitiveness. In most cases, the cost and quality of a product is already determined during the process of product design and development; the influence on these factors during manufacturing is limited. Any change in the structure, appearance or other designs will, to a certain extent, lead to extra costs for manufacturers. The concept of concurrent engineering can be incorporated into the design stage to thoroughly address underlying problems; then, the above-mentioned late design changes can be reduced significantly.

This study aimed to enhance manufacturing efficiency and to minimize potential manufacturing problems by presenting the concept of concurrent engineering to help designers take into account manufacturing problems in the design stage. An Interpretive Structural Model (ISM) is deployed to deduce the relationships of parts in product assembly. Via ISM and computation, a sequenced assembly model is established to help designers identify potential manufacturing problems as soon as possible. Through arc relationships and the calculation of the correlation matrices between parts in the sequenced model, actual numerical data is offered to help designers understand arc relationships between parts. Derived from social system engineering proposed by Warfield in 1972 [3–6], ISM is a kind of structural model used to gather information. As a management policy formulation tool, it can be employed to analyze and solve complex problems at different abstract levels. From developing a deeper and conceptual understanding of a problem, to designing and planning detailed solutions, ISM enables decision-making to be more effective, smooth and efficient. The analysis in this study uses the relationship matrix between elements in a set to show the hierarchical graphics of the elements according to discrete mathematics and graph theory [7–14].

Warfield [15] discussed the application of ISM in various areas, including education, administrative science [16], sociology and psychology, among other fields. Tazki and Amagsa [17] stated that when people study complex and divisive issues or conduct problem analysis and needs assessments, they usually make judgements using their intuition and experience. Therefore, more effective methods such as ISM, Decision-Making Trial and Evaluation

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Laboratory (DEMATEL), and the kJ Method should be used for ideal planning. ISM and DEMATEL are based on graph theory, and ISM is especially effective because all the elements can be processed with a matrix. Agarwal et al. [18] applied ISM to the management of supply chains to improve their agility. Currently, countries using ISM include Mexico, Brazil, Japan, Australia and the United States. In America for example, Warfield reported that the ISM method is widely used in many regions, counties, states and in the federal government [19]. Within the concept of modules, diversified design ideas and multiple proposals can be developed according to different needs, and manufacturing costs can be reduced through sharing some modules between products. According to the module concept proposed by Hsiao and Liu [1], potential product modules, the relationships between modules, and shared parts of modules can be explored based on the sequenced model mentioned above.

Bañuls and Turoff [20] proposed a new step-by-step model for scenario-analysis based on a merger of Turoff's alternative approach to Cross-Impact Analysis (CIA). Lee et al. [21] proposed Quality Function Development (QFD) where the ISM technique was also adopted to construct a clear model of a hierarchical structure to establish a strategy for creating an information system design pattern with multiple components by building a hierarchical structure and analyzing the component distribution. Claesson [22] introduced and developed the concept of configurable components for supporting platform-based product development. One element of the configurable component method is using a function-means model set which includes functional requirements, constraints, and design solutions. The purpose of including a function-means model is to provide design rational for the encapsulated design solutions.

Sunnersjö et al. [23] proposed a system based on files incorporating design knowledge, executable statements, and principles for an automated workflow based on the Dependency Structure Matrix (DSM) method. Saridakis and Dentsoras [24] utilized DSM to structure design parameter hierarchies, while Tang et al. [25] applied DSM to capture and manage system-level design knowledge. Captured design knowledge through DSM can improve understanding of the design routes and design history by linking designed items to rationales, decisions, and assumptions behind them. Elgh [26] introduced principles for the modeling and management of manufacturing knowledge in design automation systems with an associated information model. The information model incorporates default links and runtime created links between manufacturing requirements, manufacturing resources, knowledge objects [27] and product items. Knowledge objects include pointers for the implementation of the knowledge (e.g. a spreadsheet file or a parametric CAD file). The principles have been applied and used when developing a prototype system for automated variant design.

Liu and Hsiao [28] further applied an Analytic Network Process (ANP) and Goal Programming (GP) to the selection of parts for diverse products to meet different market needs within limited budgets. This approach ensures that re-designed parts meet the required level of engineering quality necessary under such circumstances. Lee et al. [29] applied the Fuzzy Delphi method (FDM) to identify the most critical factors; then, ISM was employed to determine the interrelationships among the critical factors. A fuzzy Analytic Network Process (FANP) model was constructed to evaluate the technology transfer performance of equipment suppliers.

Currently, many new products are developed based on customer needs. Therefore, the correlation between diversified modular products and diverse consumer groups according to the concept of market segmentation is interwoven; in other words, there is a network relationship between them.

Previous researches on the application of ISM in product families have not considered the relationship of assembly connection (Arc) between the various parts. In addition, previous studies have not discussed the situation after the establishment of the model of the product family for various market segments and the optimizing weight distribution between the common modules and independent modules. To overcome these shortcomings this study extended the ISM theory on constructing parts module groups, calculating the association of parts' mutual bonding relationships of the strength between each module. In this study, a survey was conducted to determine each cluster's need ratio for an established product module and the distribution of segments in the market as a whole. The data is then analyzed with an ANP to set up an optimized super-matrix.

This investigation attempted to facilitate designers in creating variant designs based on current product prototypes, thus forming a product family to reduce redundant design effort and satisfy requirements of segmented markets.

The rest of this paper is organized as follows. Section 2 presents an overview of the research model development procedure. Section 3 offers a discussion of the structural approach, ISM, Disassembly Effort Index (DEI) and ANP. Section 4 presents a case study and its verification, while Section 5 considers market segmentation and module optimization in product family development. Finally, conclusions are drawn in Section 6.

2. Outline of the research model development procedure

In this study, product parts were deconstructed to identify relationships between them for the purpose of modularization. Correlation matrices and market segmentation were deployed to develop the optimal product module for a product family. Fig. 1 shows the research flowchart, including ISM, the calculation principles of the correlation matrices between parts, cluster analysis, ANP and the corresponding steps.

The implementation steps are listed as follows:

(1) Construct correlation matrix.
(2) Generate reachability matrix. The description about "reachability" is discussed in Section 3.2.
(3) Illustrate elemental hierarchical relationships.
(4) Draw element distribution graph.
(5) Generate DEI.
(6) Establish Arc weight calculation model.
(7) Group survey samples.
(8) Indentify market segmentation.
(9) Establish super-matrix group.
(10) Acquire element weight values.
(11) Develop product family.

3. Theoretical background

3.1. The module concept

Modular design is a design strategy using shared modules of parts to create product variety. Its purpose is to use independent, standard and replaceable module units to develop products with varied functions. Modular design has gradually become a systematic design strategy adopted by many companies. In addition to saving development costs due to the sharing of modules, it is also very suitable for co-development.

During the optimization of module variety, Fujita [30] suggested the classification of modules into three types according to their attributes:

(1) *Independent module:* Attributes of the corresponding modules on parallel product lines are completely different.