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A Module Identification Approach to the Electrical Design of Electronic Products by Clustering Analysis of the Design Matrix

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Abstract: This paper aims at implementing modular electrical design of electronic products at the system design level. An approach is proposed to identify modules by analyzing the design matrix, which represents the mapping relationships between design objectives (Functional Requirements) and physical solutions (Design Parameters). Algorithms derived from similar problems in group technology and cellular manufacturing are applied to the clustering analysis of the design matrix. A real case study in power supply design is conducted to illustrate the proposed approach.
Keywords: Product Design; Clustering Analysis; Design Matrix; Axiomatic Design.

1. INTRODUCTION

Generally, there are two stages in the design of electronic products, viz, electrical design and physical design. The former mainly commits the circuitry design with delivery of the schematic. The latter one subsequently manifests the schematic with routing design, PCB (Printed Circuit Board) lay out, and mounting design. Electrical design has been considered as the early conceptual stage of the overall product development process, which absorbs almost 40 percent effort of product development, and has high impact on downstream manufacturing and assembly with low cost [Gjone, 1994].

Modular design has been long touted as one of the most effective approaches to streamline product realization and reduce development cost and lead time. However, it is very difficult to practice the idea in electronic product development, especially in the electrical design stage [Ahronowitz, 1994]. The main hindrance lies in the determination of modules resulting from the particular characteristics of electrical design, which are quite different from mechanical design. For example, the reverse engineering approach to determining modules from physical design is disabled by the mesh of components. In addition, the generalized rules have not been explicitly explored in practice, nor has research delved into the issue well. It is very demanding to develope a structured approach to help designers to determine modules objectively in the early stage of electrical design.

Towards this end, this paper discuss an approach through clustering analysis of a design matrix based on axiomatic design theory [Suh, 1990]. In the following section, the related works are reviewed. As the theoretical basis of the proposed approach, Section 3 briefs the axiomatic design theory in the context of modular design. In section 4, the approach of clustering analysis on design matrix is introduced as well as its technical basis derived from group technology and cellular manufacturing. A case study on power supply design is reported in section 5. Finally, discussion and conclusions are drawn in section 6.

2. MODULAR PRODUCT DESIGN

Modular product design has been long and widely touted as a good design practice with credit to streamline product realization and reduce development cost and lead time [Pahl and Beitz, 1988; Ulrich and Tung, 1991; Karmarkar and Kubat, 1987]. The approach of Pahl and Beitz [1988] stresses the importance of function structures in modular product development. From a study of seven companies, Erlandsson et al. [1992] have shown that increased modularity of a product gives positive effects in the total flow of information and material in the company, from development and purchasing to storage and delivery.

Issues associated with modular design include (1) module creation/identification, (2) interface analysis/evaluation, and (3) module selection/configuration, viz, synthesis. Erlandsson et al. [1992] developed a method with three major steps that helps to identify product modules. In their method, the right product specification is attained by adopting QFD (Quality Function Deployment) [Clausing, 1994]. Module creation, interface analysis and module selection are conducted through creating different modular structures according to the QFD matrix, i.e., the House of Quality. By using Pugh's concept-selection matrix [1991], the best modular structure is chosen. Finally, DFA (Deisgn For Assembly) analysis is conducted for each module. In a later work, Erixon and Ostgren [1993] developed this method further by naming the QFD matrix for modular analysis the MFD matrix (Modular Function Deployment), and by outlining a new evaluation tool. Further, Erixon et al. [1996] systematized the procedures for modular product design mainly concerning the above MFD matrix and DFMA analysis with focus on the evaluation of module integration. Kohlhas and Birkhofer [1996] developed a program system for the computer-aided development of structures for modular systems with focus on the synthesis aspect. Hillstrom [1994] proposed a method that helps the designer clarify how interfaces between modules influence module functions and select the best interface location. His method is based on axiomatic design theory and contributes to the mechanical part design.

All in all, most approaches focus on, and are only suitable for, mechanical design. In addition, current practice mostly assumes that modules are referred to as physical parts or components in the context of manufacturing and assembly, which lie in the process domain. That is, rarely have the efforts put on the functional and physical domain of design, especially the early conceptual stage. Moreover, similar works are seldom well-explored in the electronic product design [Brown, 94]. Furthermore, it is difficult, if not impossible, to find a coherent modular approach across the entire electronic product design process. That is there exist diverse understandings on, and thus approaches to, the modules and modular contexts among electrical designers, mechanical designers, industrial engineers, and process engineers.

In electronic product design, module synthesis is handled by the functional architecture diagram, viz, the topology of the overall circuitry. The interface between modules is manifested by the linkage of the circuitry. However, there is no discrete physical boundary between modules as there always is in mechanical design. Module identification is difficult due to the particular characteristics of electrical design and the mostly experience-dependent propensity in electronic product design. For example, both PCB routing and schematic, as well as mechanical mounting, have to be taken into account in module identification. With focus on the electrical design stage, this paper is motivated towards tackling how to identify modules in electronic product design with a structured approach. The technical basis is the axiomatic design theory briefly described in the following section.

3. AXIOMATIC DESIGN

A) $\begin{bmatrix} X & X \\ X & X \end{bmatrix}$ B) $\begin{bmatrix} X & O \\ X & X \end{bmatrix}$ C) $\begin{bmatrix} X & O \\ O & X \end{bmatrix}$

Fig.1 Design matrices: A) coupled, B) decoupled, C) uncoupled

In axiomatic design, a hierarchy of functional requirements (FR), at various levels of abstraction, describes what should be accomplished. A hierarchy of design parameters (DP), at various levels of abstraction, describes how the FRs are met, i.e., the physical solution. Matrix equations describe the relations between FRs in the functional domain and DPs in the physical domain as {FRs}=[DM]{DPs}. There are three types of design according to the elements of design matrix [DM], as shown in Fig.1.

The independence axiom states that in an acceptable design, the mapping between FRs and DPs is such that FR can be satisfied without affecting any other FRs. To satisfy the independence axiom, a design matrix is required to be either diagonal or triangular. Based on the process of decomposition and the development of uncoupled or decoupled designs, axiomatic design inherently assures good modularity [Kim et al., 1991], because modules are generated to make the associated FRs uncoupled or decoupled, which contains less information than coupled designs. Modules can thus be represented with proper sets of DPs corresponding to the independent sets of FRs. In addition, axiomatic design enables the module determination early at the conceptual stage of design [Suh, 1990].

However, the underlying assumption of axiomatic design lies in that designers are always creative enough to generate ample plausible design solutions to satisfy the independence axiom. In addition, zigzagging decomposition follows the subjective arrangement or selection of FRs and DPs, without explicit exploration of underpinning objective structure existing in DPs with respect to FRs. As the ideal guideline for a good design, axiomatic design has difficulties in practice to achieve the independence axiom right at from the start. The fact is that in real case, especially for complex products and manufacturing systems, subjectively selecting DPs to make FRs uncoupled or decoupled is often difficult, if not impossible, due to unavoidable coupling among FRs and DPs, plus compulsory constraints on cost, technology, resources and lead time.

Suh [1996] pointed out the importance of identifying the subset boundaries among FRs to satisfy the independence axiom for large systems, which is characterized by a large number of FRs at the highest level of specification or at the problem definition stage. Harutunian et al. [1996] emphasized the necessity to provide computable support for analyzing the design matrix such as reordering the FRs and DPs in order to conform to the independence axiom. In this regard, the following section discusses an approach to analyzing the design matrix to implement a strategy that clusters the elements of a coupled design matrix into modules so as to be transformed to the uncoupled or decoupled matrix which conforms to the independence axiom, thus enabling modular design in light of axiomatic design for complex coupling scenarios.

4. MODULE IDENTIFICATION BY CLUSTERING ANALYSIS OF DESIGN MATRIX

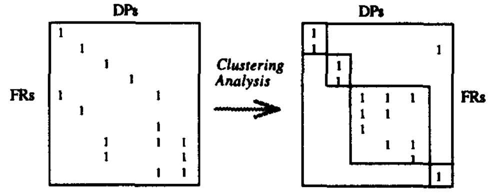


Fig.2 Clustering analysis of design matrix

Facing the fact that, in practice, design matrices are often coupled, axiomatic design can not be directly applied to determine modules. However, given a design matrix with 0-1 elements denoting the corresponding FR-DP relationships, clustering analysis can be conducted to induce element cells, each of which indicates the what-how relations between a set of FRs and a set of DPs, while different cells have looser coupling. Infra-cell elements comprise a cluster of FRs and the corresponding DPs with distinct boundary from other cells. As a result, FR-DP cells or clusters in fact indicate the boundaries among different design modules. Inter-cell elements indicate the interfacing relationships between different clusters (modules), which often form the trade-off bottleneck for design decision making. Furthermore, this module analysis can be performed at any level of abstraction when needed in the early stage of design, which proves to be overwhelmingly significant. Fig.2 illustrates the idea.

• **Technical Basis:** The clustering analysis of the design matrix is derived from a problem domain in group technology and cellular manufacturing where machine cells are formed by grouping a part-machine matrix while parts are classified into different machine cells. Straightforwardly, algorithms in the part-machine cell formation can be directly employed in design matrix analysis for the similar purpose. To illustrate the standpoint, we adopt the ROC (Rank Order Clustering) algorithm [King, 1980] in module determination.

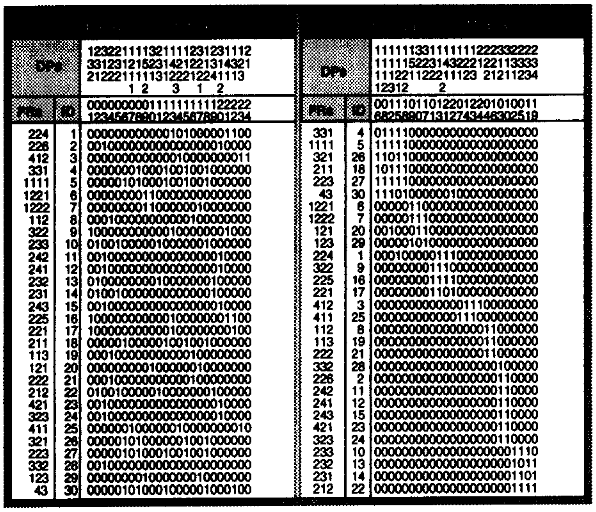
• **Methodology:** To implement the proposed approach, a systematic procedure is suggested in Table 1. Clustering analysis provides designers with feedback information on design evaluation with respect to modularity, when applying axiomatic design to achieve a good design. The approach is applicable to various levels of the FR/DP hierarchical abstraction.

Table 1 Steps to module identification based on axiomatic design

Step 1: Definition of FRs. The FRs are defined in the functional domain to satisfy a given set of customer needs. In this step, it is important that the FRs should always be stated in the functional domain, i.e., the FRs must be defined in a solution-neutral environment.
Step 2: Ideation of design solutions. Based on the understanding of domain background, a set of DPs are selected to satisfy the FRs defined in Step 1. The designer finds a set of plausible DPs corresponding to each given FR of a set of FRs.
Step 3: Construction of design matrices. The zigzagging process between FRs hierarchy and DPs hierarchy relates FRs and DPs in the design matrices at different level of abstraction. FR-DP relationships captured in the design matrices are then utilized for modular analysis.
Step 4: Modular analysis. The module identification is most straightforward when the solution consists of uncoupled designs at each level. However, the cluster analysis algorithm is introduced to determine module boundaries when the designer tries to find solutions by attempting to make a coupled design uncoupled or decoupled at individual hierarchical levels.

5. A CASE STUDY

Power supply design involves multidisciplinary exploration such as electrical, semiconductor, magnetic, mechanical domains. It is so complex that, as stated by Brown [1994], good start-to-finish practical design references are almost nonexistent. Mostly, the practice is by trial-and-error and heavily experience dependent. In power supply design, in particular electrical design, it is normally very difficult to have an explicit picture of the modular structure that is consistent with downstream design activities such as physical design, even though designers often experience modularity subjectively and intuitively. To improve power supply design, we employ the axiomatic design approach with modular considerations. Table 2 and Table 3 are FRs and DPs hierarchies for power supply design. At an abstraction level (leaf node level in Table 2 and Table 3), the design matrix is constructed as in Fig.3, which, at an initial stage, is highly coupled. By applying clustering analysis on the initial design matrix, cells are clustered so as to suggest for modular structure (Fig.3). Nine modules are identified, together with interfaces determined by cluster boundaries and inter-cell elements, as shown in Fig.4. The corresponding modular design flow is illustrated in Fig.5.



FRs	ID	DPs: 123221111321111231231112 / 331231215231421221314321 / 212221111131222122241113 / 1 2 3 1 2 — ID: 000000000111111111122222 / 123456789012345678901234
224	1	000000000000101000001100
226	2	001000000000000000010000
412	3	000000000000001000000011
331	4	000000010001001001000000
1111	5	000001010001001001000000
1221	6	000000001100000000000000
1222	7	000000001100000010000000
112	8	000100000000000100000000
322	9	100000000000010000001000
233	10	010010000001000000100000
242	11	001000000000000000010000
241	12	001000000000000000010000
232	13	010000000010000000100000
231	14	010010000000000000100000
243	15	001000000000000000010000
225	16	100000000000010000001100
221	17	100000000000010000000100
211	18	000001000001001001000000
113	19	000100000000000100000000
121	20	000000001000000010000000
222	21	000100000000000100000000
212	22	010010000010000000100000
421	23	001000000000000000010000
323	24	001000000000000000010000
411	25	000000100000001000000010
321	26	000001010000001001000000
223	27	000001010001001001000000
332	28	001000000000000000000000
123	29	000000001000000010000000
43	30	000001010001000001000100

FRs	ID	DPs: 111111331111112223322222 / 111115223143222122113333 / 11122112221123 21211234 / 12312 2 — ID: 001110110122012201010011 / 6825689071312743446302519
331	4	011110000000000000000000
1111	5	111110000000000000000000
321	26	110110000000000000000000
211	18	101110000000000000000000
223	27	111110000000000000000000
43	30	111010000000100000000000
1221	6	000001100000000000000000
1222	7	000001110000000000000000
121	20	001000110000000000000000
123	29	000001010000000000000000
224	1	000100000111000000000000
322	9	000000000111000000000000
225	16	000000000111100000000000
221	17	000000000110100000000000
412	3	000000000000001110000000
411	25	000000000000011100000000
112	8	000000000000000001100000
113	19	000000000000000001100000
222	21	000000000000000001100000
332	28	000000000000000000100000
226	2	000000000000000000110000
242	11	000000000000000000110000
241	12	000000000000000000110000
243	15	000000000000000000110000
421	23	000000000000000000110000
323	24	000000000000000000110000
233	10	000000000000000000001110
232	13	000000000000000000001011
231	14	000000000000000000001101
212	22	000000000000000000001111

Fig.3 Clustering analysis of design matrix for power supply

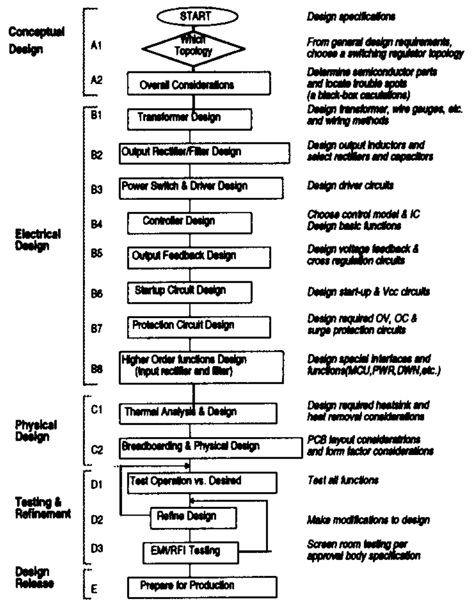


Fig.5 Modular electrical design flow of power supply

Table 2 FRs hierarchy for power supplies

FR0: Universal low power AC/DC power supplies

DESCRIPTIVE LEVEL	GENERIC LEVEL	TERMINOLOGY LEVEL	ENGINEERING LEVEL
FR1: Used in what country (Input Requirement)	FR11: Operating range	FR111: Line voltage	FR1111: Voltage range
		FR112: Input surge current	
		FR113: Line transient	
	FR12: Protection	FR121: Inrush current	
		FR122: Power-line disturbance	FR1221: Brown-out
			FR1222: Drop-out
		FR123: RFI/Surge suppression	
FR2: Used in what system (Output Requirement)	FR21: Power level	FR211: Total output power	
		FR212: No. of output/Cross regulation	
	FR22: Power quality	FR221: Regulation/Output voltage range	
		FR222: Overshoot (Turn on overshoot)	
		FR223: Output voltage	
		FR224: Ripple voltage	
		FR225: Output current	
		FP226: Holdup time	
	FR23: Loading	FR231: Dynamic loading	
		FR232: Isolated output	
		FR233: Feedback loop compensation	
	FR24: Protection	FR241: Over voltage protection (OVP)	
		FR242: Over current protection	
		FR243: Short-circuit protection	
FR3: Used in what environment	FR31: Operating condition	FR311: Operating temperature (range)	
		FR312: Operating relative humidity	
	FR32: Safety	FR321: Safety approvals	
		FR322: EMI/EMC	
		FR323: Safety ground leakage current	
	FR33: Mechanical requirement	FR331: Mechanical outline(Overall dimensions)	
		FR332: Connection/Connector/Electrical pinout	
FR4: Used for what application	FR41: Reliability	FR411: MTBF hours (Continuous operation)	
		FR412: On/Off cycles (Repetitive operation)	
	FR42: Quality	FR421: Max. failure rate (percent)	
	FR43: Efficiency		

Table 3 DPs hierarchy for power supply

First Level	Second Level	Third Level	Fourth Level	Fifth Level
DP0: Topology	DP1: Power section	DP11: Transformer	DP111: Core magnetic	DP1111: Core material
				DP1112: Core style
				DP1113: Core size
			DP112: Winding	DP1121: # of turns
				DP1122: Wire gauge
		DP12: Power switch	DP121: Types of semiconductors	
			DP122: Ratings of semiconductors	
			DP123: Drive circuit	
		DP13: Output rectifier	DP131: Diode technology	
			DP132: Ratings of rectifiers	
		DP14: Output filtering	DP141: Output capacitors	
			DP142: Physical layout	
		DP15: Input rectifiers	DP151: Input rectifiers	
	DP2: Control section	DP21: Controller (IC)		
		DP22: Drive circuit	DP221: Zener shunt regulator	
			DP222: Large IC bypass capacitor	
		DP23: Housekeeping circuit	DP231: Output feedback circuit scheme	
			DP232: Error amplifier	
			DP233: Optoisolator	
			DP234: Resistor divider	
	DP3: Ancillary section	DP31: Protection	DP311: Protection scheme	
			DP312: Protection circuit	
		DP32: Input filtering	DP321: Bulk input capacitor	
			DP322: Thermistor	

Table 4 Power supply design modules

Transformer Module	
FRs	FR211, FR43, FR321, FR331, FR1111, FR223
DPs	DP1113, DP1112, DP1121, DP1122
Output Rectifiers & Filters Module	
FRs	FR123, FR121, FR1221, FR1222
DPs	DP151, DP321, DP322
Startup Module	
FRs	FR43, FR221, FR224, FR225, FR322
DPs	DP131, DP132, DP141, DP142
Power Switch & Controller Module	
FRs	FR411, FR412
DPs	DP121, DP122, DP123, DP21
Protection Module	
FRs	FR243, FR242, FR241, FR421, FR323, FR226, FR332
DPs	DP311, DP312
Voltage Feedback Module	
FRs	FR112, FR113, FR222
DPs	DP222, DP221
Input Module (Rectifiers & Filtering & RFI Filter/Surge Supression	
FRs	FR212, FR231, FR232, FR233
DPs	DP233, DP231, DP232, DP234

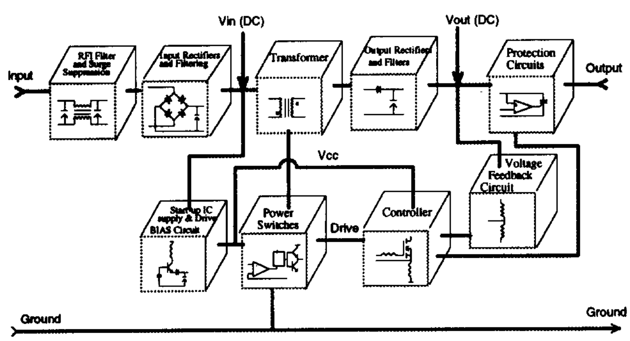


Fig.4 Module structure diagram of electrical Design

6. CONCLUDING REMARKS

The essence of the proposed approach is to represent domain design with a design matrix. Once a 0-1 FR-DP matrix is obtained, the problem is then the same as part-machine matrix clustering. The clustering analysis algorithms in group technology (GT) applications are thus applicable to the analysis of the design matrix. Only the ROC algorithm is tested in the paper in order to stimulate an open discussion on the issue. In fact, more dedicated GT algorithms can be adopted for more complex design matrix analysis. For example, the group scheduling algorithms and Petrov method with job sequence consideration [Taylor and Ham, 1981] possess the potential for handling design constraints in design matrix analysis, such as chronological order within DPs and technological feasibility. In addition, ANN (artificial neural network) classifiers [Moon and Chi, 1992] pose the capability to analyze the design matrix with a large number of parameters. In light of this, the paper aims at elevating traditional GT methods, which always lie in the process domain, early to the design domain.

Axiomatic design inherently assures good modularity based on the process of decomposition and development of uncoupled or decoupled designs. For coupled design, the proposed approach assists the module identification at different levels of abstraction in an objective way. The approach based on axiomatic design not only enables modular analysis at an early stage of design, but also provides contextual coherence across the entire product development process. In addition, design rational, captured by structural modular development, facilitates the concurrent engineering paradigm.

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