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## APPENDIX 1–A Corollaries and Theorems

Some of these theorems are derived in this book as well as in the references given. For those theorems not derived in this book, the readers may consult the original references.

### 1. COROLLARIES

*Corollary 1 (Decoupling of Coupled Designs)* Decouple or separate parts or aspects of a solution if FRs are coupled or become interdependent in the designs proposed.

*Corollary 2 (Minimization of FRs)* Minimize the number of FRs and constraints.

*Corollary 3 (Integration of Physical Parts)* Integrate design features in a single physical part if the FRs can be independently satisfied in the proposed solution.

*Corollary 4 (Use of Standardization)* Use standardized or interchangeable parts if the use of these parts is consistent with the FRs and constraints.

*Corollary 5 (Use of Symmetry)* Use symmetrical shapes and/or components if they are consistent with the FRs and constraints.

*Corollary 6 (Largest Design Ranges)* Specify the largest allowable design range in stating FRs.

*Corollary 7 (Uncoupled Design with Less Information)* Seek an uncoupled design that requires less information than coupled designs in satisfying a set of FRs.

*Corollary 8 (Effective Reangularity of a Scalar)* The effective reangularity $R$ for a scalar coupling "matrix" or element is unity. [*Note*: Reangularity is defined in Suh (1990) and in Chapter 3.]

### 2. THEOREMS OF GENERAL DESIGN

*Theorem 1 (Coupling Due to Insufficient Number of DPs) When the number of DPs is less than the number of FRs, either a coupled design results or the FRs cannot be satisfied.*

*Theorem 2 (Decoupling of Coupled Design) When a design is coupled because of a larger number of FRs than DPs (i.e.,* $m > n$*), it may be decoupled by the addition of new DPs so as to make the number of FRs and DPs equal to each other if a subset of the design matrix containing* $n \times n$ *elements constitutes a triangular matrix.*

*Theorem 3 (Redundant Design) When there are more DPs than FRs, the design is either a redundant design or a coupled design.*

*Theorem 4 (Ideal Design) In an ideal design, the number of DPs is equal to the number of FRs and the FRs are always maintained independent of each other.*

*Theorem 5 (Need for New Design) When a given set of FRs is changed by the addition of a new FR, by substitution of one of the FRs with a new one, or by selection of a completely different set of FRs, the design solution given by the original DPs cannot satisfy the new set of FRs. Consequently, a new design solution must be sought.*

*Theorem 6 (Path Independence of Uncoupled Design) The information content of an uncoupled design is independent of the sequence by which the DPs are changed to satisfy the given set of FRs.*

*Theorem 7 (Path Dependency of Coupled and Decoupled Design) The information contents of coupled and decoupled designs depend on the sequence by which the DPs are changed to satisfy the given set of FRs.*

*Theorem 8 (Independence and Design Range) A design is an uncoupled design when the designer-specified range is greater than*

$$\left( \sum_{\substack{i \neq j \\ j=1}}^{n} \frac{\partial \mathrm{FR}_i}{\partial \mathrm{DP}_j} \Delta \mathrm{DP}_j \right)$$

*in which case, the nondiagonal elements of the design matrix can be neglected from design consideration.*

*Theorem 9 (Design for Manufacturability) For a product to be manufacturable with reliability and robustness, the design matrix for the product,* [A] (which relates the FR vector for the product to the DP vector of the product), times the design matrix for the manufacturing process, [B] *(which relates the DP vector to the PV vector of the manufacturing process), must yield either a diagonal or a triangular matrix. Consequently, when either* [A] *or* [B] *represents a coupled design, the independence of FRs and robust design cannot be achieved. When they are full triangular matrices, either both of them must be upper triangular or both must be lower triangular for the manufacturing process to satisfy independence of functional requirements.*

*Theorem 10 (Modularity of Independence Measures) Suppose that a design matrix [DM] can be partitioned into square submatrices that are nonzero only along the main diagonal. Then the reangularity and semangularity for [DM] are equal to the product of their corresponding measures for each of the nonzero submatrices.* [*Note*: Chapter 3 defines reangularity and semangularity. See also Suh (1990).]

*Theorem 11 (Invariance)* *Reangularity and semangularity for a design matrix [DM] are invariant under alternative orderings of the FR and DP variables, as long as the orderings preserve the association of each FR with its corresponding DP.*

*Theorem 12 (Sum of Information)* *The sum of information for a set of events is also information, provided that proper conditional probabilities are used when the events are not statistically independent.*

*Theorem 13 (Information Content of the Total System)* *If each DP is probabilistically independent of other DPs, the information content of the total system is the sum of the information of all individual events associated with the set of FRs that must be satisfied.*

*Theorem 14 (Information Content of Coupled versus Uncoupled Designs)* *When the state of FRs is changed from one state to another in the functional domain, the information required for the change is greater for a coupled design than for an uncoupled design.*

*Theorem 15 (Design–Manufacturing Interface)* *When the manufacturing system compromises the independence of the FRs of the product, either the design of the product must be modified or a new manufacturing process must be designed and/or used to maintain the independence of the FRs of the products.*

*Theorem 16 (Equality of Information Content)* *All information contents that are relevant to the design task are equally important regardless of their physical origin, and no weighting factor should be applied to them.*

*Theorem 17 (Design in the Absence of Complete Information)* *Design can proceed even in the absence of complete information only in the case of a decoupled design if the missing information is related to the off-diagonal elements.*

*Theorem 18 (Existence of an Uncoupled or Decoupled Design)* *There always exists an uncoupled or decoupled design that has less information than a coupled design.*

*Theorem 19 (Robustness of Design)* *An uncoupled design and a decoupled design are more robust than a coupled design in the sense that it is easier to reduce the information content of designs that satisfy the Independence Axiom.*

*Theorem 20 (Design Range and Coupling)* *If the design ranges of uncoupled or decoupled designs are tightened, they may become coupled designs. Conversely, if the design ranges of some coupled designs are relaxed, the designs may become either uncoupled or decoupled.*

*Theorem 21 (Robust Design When the System Has a Nonuniform pdf)* *If the probability distribution function (pdf) of the FR in the design range is nonuniform, the probability of success is equal to one when the system range is inside the design range.*

*Theorem 22 (Comparative Robustness of a Decoupled Design)* *Given the maximum design ranges for a given set of FRs, decoupled designs cannot be as robust as* *uncoupled designs in that the allowable tolerances for DPs of a decoupled design are less than those of an uncoupled design.*

*Theorem 23 (Decreasing Robustness of a Decoupled Design) The allowable tolerance and thus the robustness of a decoupled design with a full triangular matrix diminish with an increase in the number of functional requirements.*

*Theorem 24 (Optimum Scheduling) Before a schedule for robot motion or factory scheduling can be optimized, the design of the tasks must be made to satisfy the Independence Axiom by adding decouplers to eliminate coupling. The decouplers may be in the form of a queue or of separate hardware or buffer.*

*Theorem 25 ("Push" System vs. "Pull" System) When identical parts are processed through a system, a "push" system can be designed with the use of decouplers to maximize productivity, whereas when irregular parts requiring different operations are processed, a "pull" system is the most effective system.*

*Theorem 26 (Conversion of a System with Infinite Time-Dependent Combinatorial Complexity to a System with Periodic Complexity) Uncertainty associated with a design (or a system) can be reduced significantly by changing the design from one of serial combinatorial complexity to one of periodic complexity.*

## 3. THEOREMS RELATED TO DESIGN AND DECOMPOSITION OF LARGE SYSTEMS

*Theorem S1 (Decomposition and System Performance) The decomposition process does not affect the overall performance of the design if the highest level FRs and Cs are satisfied and if the information content is zero, irrespective of the specific decomposition process.*

*Theorem S2 (Cost of Equivalent Systems) Two "equivalent" designs can have substantially different cost structures, although they perform the same set of functions and they may even have the same information content.*

*Theorem S3 (Importance of High-Level Decisions) The quality of design depends on the selection of FRs and the mapping from domain to domain. Wrong selection of FRs made at the highest levels of design hierarchy cannot be rectified through the lower level design decisions.*

*Theorem S4 (The Best Design for Large Systems) The best design for a large flexible system that satisfies* m *FRs can be chosen among the proposed designs that satisfy the Independence Axiom if the complete set of the subsets of FRs that the large flexible system must satisfy over its life is known a priori.*

*Theorem S5 (The Need for a Better Design) When the complete set of the subsets of FRs that a given large flexible system must satisfy over its life is not known a priori, there is no guarantee that a specific design will always have the minimum information content for all possible subsets and thus there is no guarantee that the same design is the best at all times.*

*Theorem S6 (Improving the Probability of Success)* *The probability of choosing the best design for a large flexible system increases as the known subsets of FRs that the system must satisfy approach the complete set that the system is likely to encounter during its life.*

*Theorem S7 (Infinite Adaptability versus Completeness)* *A large flexible system with infinite adaptability (or flexibility) may not represent the best design when the large system is used in a situation in which the complete set of the subsets of FRs that the system must satisfy is known a priori.*

*Theorem S8 (Complexity of a Large Flexible System)* *A large system is not necessarily complex if it has a high probability of satisfying the FRs specified for the system.*

*Theorem S9 (Quality of Design)* *The quality of design of a large flexible system is determined by the quality of the database, the proper selection of FRs, and the mapping process.*

## 4. THEOREMS FOR DESIGN AND OPERATION OF LARGE ORGANIZATIONS (SUH, 1995b)

*Theorem M1 (Efficient Business Organization)* *In designing large organizations with finite resources, the most efficient organizational design is the one that specifically allows reconfiguration by changing the organizational structure and by having flexible personnel policy when a new set of FRs must be satisfied.*

*Theorem M2 (Large System with Several Subunits)* *When a large system (e.g., organization) consists of several subunits, each unit must satisfy independent subsets of FRs so as to eliminate the possibility of creating a resource-intensive system or a coupled design for the entire system.*

*Theorem M3 (Homogeneity of Organizational Structure)* *The organizational structure at a given level of the hierarchy must be either all functional or product oriented to prevent duplication of effort and coupling.*

## 5. THEOREMS RELATED TO SOFTWARE DESIGN

*Theorem Soft 1 (Knowledge Required to Operate an Uncoupled System)* *Uncoupled software or hardware systems can be operated without precise knowledge of the design elements (i.e., modules) if the design is truly an uncoupled design and if the FR outputs can be monitored to allow closed-loop control of FRs.*

*Theorem Soft 2 (Making Correct Decisions in the Absence of Complete Knowledge for a Decoupled Design with Closed-Loop Control)* *When the software system is a decoupled design, the FRs can be satisfied by changing the DPs if the design matrix is known to the extent that knowledge about the proper sequence of change is given, even though precise knowledge about the design elements may not be known.*