A New Systems Engineering Model Based on the Principles of Axiomatic Design

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Abstract—The existing approach of SE to design of Socio-Economic Systems is an algorithmic method completed only through several iterative processes. Such an approach which depends on skill, knowledge, attitude, and experience (SKAE) of members of the design team is considered heuristic and does not give a formal theoretical framework to systems designers. This study has utilized principles of Axiomatic Design (AD) to resolve shortcomings of the existing models of SE; it serves to present a science-based model of SE to help design systems in a well-defined approach. In this regard, both “Cost” and “Complexity” which arise from coupling among “System Requirements (FRs)” are eliminated. With the help of suitable examples, we show this approach to be superior to the existing ones in the field of SE. For the case-study, we use the existing design of demand-supply subsystem of U.S. electric power sector, based on data provided by the U.S. Energy Information Administration (EIA). The result for 2012 shows the symptoms of a poor design and ineffectiveness due to coupling among the FRs of this subsystem.

Index Terms—systems engineering (SE) process, design of engineering systems, axiomatic design (AD), system requirements coupling, cost, complexity

I. INTRODUCTION

Literally, the term “system” originates from the Greek term systema, which means to “place together” [1]. In general, a system may be defined as “an integrated set of interoperable elements, each with explicitly specified and bounded capabilities, working synergistically to perform value-added processing to enable a user to satisfy mission-oriented operational needs in a prescribed operating environment with a specified outcome and probability of success” [1]. It is interesting to note that general public, in their everyday’s life, use a variety of “Complex Urban Systems” under the pretext of improving the quality of their lives; allowing them to become more productive and efficient, or even for merely survival [2]. Human-made systems usually consist of generic elements known as: “Hardware (H)”, “Software (S)” and “People or Live-ware (L)” together with their associated interfaces that function in an “Environment (E)” [3]. Such systems are designed, formed and operated to achieve their intended functions [4]. For this purpose, systems development process often requires contribution from many diverse technical disciplines [5]. In this regard, in order to enable the realization of successful systems, “Systems Engineering” (SE) as a strong interdisciplinary field is employed [6]. The SE approach is to integrate all disciplines and specialty groups into a functional team forming a structured development process that survives during a meaningful life-cycle. The Life-cycle starts from initial concepts and proceeds to other phases of production, operation and transition or disposal. Any specific system during its life-cycle is intended to successfully meet both business as well as the technical needs of all customers (stakeholders) [6], [7].

Figure 1. The V-Model as a SE process

With regard to the engineering systems development, the “SE process”-- offers a logical, systematic and comprehensive approach. However, the iterative nature of the problem solving set of processes which are selectively used to accomplish SE tasks; poses a problem in most cases. As a solution, particularly for the case of “Physical or Mechanical Systems”, the “V-model” is a used; which
is a classical approach of representing the SE process (Fig. 1) [8].

The V-model is actually a graphical representation of the systems development lifecycle. It represents how the sequence of steps in a system development should be structured. Moreover, it categorically, describes the activities to be performed and outcomes to be produced during system development. As it is well-known, “V”, has two left and right branches; for which the left one consists of “Decomposition of system requirements, and creation of system specifications”. The right side, on the other hand, is mainly devoted to the “Integration of subsystems and their validation” [9]-[12].

According to the V-model, “design of an engineering system” starts by understanding the needs of the System Users (Stakeholders) [6], [13].

II. RELEVANT WORKS

There are quite a few numbers of models and methodologies which have been developed within the field of engineering science for mega-size systems. All the models, ultimately, aim to somehow manage decision-makings and relevant activities during the design process in order to systematically improve the system performance [14]-[19]. In this line of work, Altshuller (1946) and his colleagues introduced the TRIZ methodology as a way for creating systematic innovation and improving the designer’s thinking process [20]. In the period beginning from 1956 to 1971, thirty nine parameters together with forty principles have been introduced. This quite lengthy process has helped settle down the theoretical basis of the so called “TRIZ” as a well-established methodology [21]. TRIZ is, in fact, a very useful method for creative problem solving. However, planning and designing products that involves multiple requirements and functions with multiple contradictions is not straightforward; while TRIZ problem solving methods are effective only for simple problems. Therefore, the use of TRIZ in system design must involve proper transformation of complex problems into simple isolated ones [22]. Akao (1966) developed QFD in Japan as a systematic approach to design based upon a close awareness of stakeholders desires [23]. In this regard, Hauser & Clausing (1988) introduced the “house of quality” (HOQ) as the most important design tool within the QFD, which consists of multiple tools integrated in one matrix. This method is based upon a matrix comparing what the customers (stakeholders) want to how the designer plans to provide it [24]. The main goal of QFD is to translate the customers’ needs (voice of customers (VOC)) into technical characteristics and specifications which can be quantified and measured and which can then be used to develop a system [24], [25]. However, QFD method may be an effective tool only for re-design of an existing system, but to develop a completely new original design, the Functional Requirements (FRs) of the system must be defined in a solution neutral environment [26]. Taguchi (1986) developed the “Robust Design” method; which aimed to reduce production variance by creating a quality loss function, and optimizing the product (system) to minimize the loss function [27], [28]. Specifically, the premise of robust design is consciously considering the noise factors in the design and development process. Such noises include environmental variations in the product’s usage, manufacturing variations, component deterioration and finally the cost of failures in the field. This design method optimizes a given design concept or solution to increase the robustness [27]. However, this approach does not provide any specific process for the “System Design” and it only focuses on one requirement at a time. Obviously, problems might arise when a design has to satisfy two or more requirements simultaneously [22]. Concurrent Engineering (CE) is another systematic approach to the “Integrated Design” of systems; or which the related processes include manufacturing and support. The approach is intended to lead developers to consider all elements of the product lifecycle, from concept through disposal; including quality control, cost, scheduling and user requirements [29]. However, potential benefits of concurrent engineering have not been fully realized since there is a lack of a systematic framework for conducting group design activities, as well as principles for decision-making [30]. Design for X may be mentioned as one of the most useful design approaches to systems development. This approach is a family of approaches generally denoted as Design for X or DFX for short. The letter “X” in DFX is made up of lifecycle processes (X). The DFX techniques are part of detail design and are ideal approaches to improve lifecycle cost, quality, increased design flexibility, increased efficiency and productivity using the concurrent design concepts [31]. However, the X is one of the FRs or may be the most important FR which the final system must satisfy [32].

III. SYSTEMS ENGINEERING SHORTCOMING IN DESIGN OF ENGINEERING SYSTEMS

Considering the previously described shortcomings, the present study concentrates specifically on the current practice suggested by SE design approach and attempts to critically enhance its performance to make it more applicable to the systems, products, and services with conflicting requirements.

To be more specific, one might note that the existing approach of SE to develop systems is an algorithmic method which is completed only through several iterative processes [1]. That is, it lacks a formal theoretical framework to decrease the number of iterations involved; or even a criterion to limit the number of iterations. The fact is that, the SE approach depends strongly on the Skill, Knowledge, Attitude, and Experience (SKAE) of the design team [6]. The process is therefore, heuristic or empirical in its nature and is accompanied by some undesirable features, including “unbounded iterations”, “rework”, “time-overrun”, and “Cost-overrun”. Moreover, it would not guarantee a universal result; which is quite essential for wide variety of products with world-wide applications, such as aircrafts, automobiles, mobile phones, and computers as well as their associated services.
The fundamental aim to enhance the existing SE’s capability is expected to have a theoretical background and somehow be provable toward mathematical manipulations. In this line of thought, we show how fundamentals of the so called “Axiomatic Design (AD)” could play its role.

Originally, AD was introduced by Suh (1990-2001) in order to design effective physical and mechanical systems [33]. However, because of rational, comprehensive, and strong principles of AD approach; we attempt to apply its fundamentals to the so called “Systems Engineering process” itself. That is, the subject is not a mechanical system; rather, it is the SE process, itself. The contribution of this work is outlined as followings:

- Introducing Axiomatic Design (AD) as a tool which offers a new model of SE based upon the AD principles.
- Enhancing existing capabilities of SE process in effective design of systems/products/services in a more rigorous approach by incorporating AD principles.
- Proposing measurable criteria to compare and assess level of success among different designs that meet stakeholders’ requirements.

Following subsections describe the details.

IV. METHODOLOGY

To describe the relative importance of the current work, we need to start with proper evaluation of the existing levels of engineering practice. Such evaluation reveals the both strengths and weaknesses of the approaches available to the system engineers. We then use AD principles of “Independence” and “Information Axioms” to eliminate weaknesses and further strengthening the other strong points. Next, we use Shannon’s Entropy Theory [34], [35] to compare and evaluate of the new approach.

We further use “Linear Algebra” along with “multivariate statistical analysis” to develop the so called “Taguchi’s loss function” [36], [27] associated with fulfilling random vector FR, which includes all Functional Requirements.

To illustrate strength of the new approach, the existing design of “supply & demand subsystem of the U.S. electric power sector is studied. In this regard, the multiple linear regression models are actively employed to fit linear statistical models describing the ways in which Design Parameters (DPs) are mapped to their corresponding FRs to satisfy them. For this purpose, statistics and data provided by U.S. Energy Information Administration (EIA) in the year of 2012 are analyzed [37]. Here, we have effectively used SAS 8.2 software programming environment in order to perform all statistical analyses required to precisely estimate design equations representing the ways in which DPs of the system are mapped to their corresponding FRs.

V. AXIOMATIC DESIGN

Axiomatic Design has been built on four key elements of: (1) Domains; (2) Hierarchies; (3) zigzagging processes and finally (4) Axioms.

A. Domains

According to Suh (1990), the world of design consists of four domains represented in Fig. 2. Each domain on the right side answers how one can achieve the objectives or goals defined on its left adjacent domain, through appropriate mappings [26]. Customer (stakeholder) attributes (CAs) are delineated in the customer domain. In other words, CAs are the customer needs. CAs are then transformed into functional requirements (FRs) in the functional domain. FRs are defined by engineering words. This is equivalent to “what we want to achieve.” FRs are satisfied by defining or selecting design parameters (DPs) in the physical domain. Mostly, this procedure is referred to as the design process. Production variables (PVs) are determined from DPs in the same manner. The aspects for the next domain are determined from the relationship between the two domains, and this process is called mapping. A good design process means an efficient mapping process [26].

B. Hierarchies

As depicted in Fig. 2, the decomposition process must proceed layer by layer until the design reaches the final stage, creating a design that can be implemented [13]. It is important to keep in mind that sub FRs should be Mutually Exclusive and Collectively Exhaustive (MECE) at each layer [26], [13].

C. Zigzagging

The mapping between two domains is accompanied with top-down zigzagging decomposition organizing the design hierarchy linking a high-level conceptual design and a low level detailed design as illustrated in Fig. 3. We start at the top FR. From the top FR, we go to the physical domain to conceptualize a design and determine its corresponding DP.

Then we come back to the functional domain to create FR1 and FR2 at the next level that collectively satisfy the
D. Axioms:

Axiomatic Design pillars on two axioms proposed by Suh to govern the design process: (1) “Independence Axiom” and (2) “Information Axiom”. From these axioms, a set of theorems, corollaries and guidelines have been developed. We express the relevant ones, here.

a) Axiom 1 – The Independence Axiom suggests that SE must maintain the independence of the functional requirements. This simply means that when we perform the mapping from the functional domain into the physical one, the choice of the DPs should be completed in such a way that each FR can be satisfied without affecting other FRs. If the mapping occurs from the physical into the process domain, one should choose the process variables (PVs) that ensure the independency of the DPs [13]. The mapping between two adjacent domains can be represented by a design equation. When mapping from the functional to the physical domain, the design equation is:

\[
FR = [A].DP
\]  

(1)

where \( FR \) and \( DP \) are respectively the functional requirement vector and the design parameter vector, and [\( A \)] is the design matrix for this mapping. The design matrix displays the relationship between each \( FR_i \) and each \( DP_j \):

\[
A_{ij} = \frac{\partial FR_i}{\partial DP_j}
\]

(2)

In addition, if there are \( m \) functional requirements and \( n \) design parameters, the general format for the design matrix would be:

\[
\begin{bmatrix}
A_{11} & A_{12} & \cdots & A_{1n} \\
A_{21} & A_{22} & \cdots & A_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
A_{m1} & A_{m2} & \cdots & A_{mn}
\end{bmatrix}
\]

(3)

Ideally, a square design matrix is obtained, with an equal number of FRs and DPs \( (m = n) \), (Fig. 3). If this matrix is diagonal, the off-diagonal elements can be assumed to be zero \( (A_{ij} \equiv 0 \), where \( i \neq j \)), so an uncoupled design is obtained, and the first axiom is satisfied. If the design matrix is triangular, the independency of the FRs is assured if and only if the adjustment of the values of the DPs is made in the order indicated by the design matrix. This is the case of a decoupled design. Any other case of a square design matrix that is neither diagonal nor triangular is said to be a coupled design, in which the Independence Axiom cannot be satisfied. The values of the elements of the design matrix \( (A_{ij}) \) can assume one of three formats: binary, percentage or function. In the binary format, the values of the design matrix are “0” or “X”, where the first indicates no relationship between a certain \( FR_i-\,DP_j \) pair, and “X” indicates a relationship between them. Sometimes, it is possible to use a “1” instead of an “X”. The percentage format admits values for the design matrix elements between “0” and “1”, according to the strength of the relationship that is believed to exist for each \( FR_i-\,DP_j \) pair. The third possibility is that the design matrix elements are a quantitative expression (transfer function) of the relationship between each \( FR_i-\,DP_j \) pair. The design equation to map physical domain to the process domain is given by (4).

\[
DP = [B].PV
\]

(4)

The second axiom follows:

b) Axiom 2 – Is known as “Information Axiom” and suggests that a relatively good design would be the one that would not require less information to start with. This axiom suggests minimization of the information content of the target design.

The objective, here, is to ensure the satisfaction of both “Independence Axiom” as well as “Information Axiom” for a given design. When multiple alternative designs satisfying the first axiom are available, the second axiom is used to choose the one with minimum information content. The information content is normally computed using the probability of success of the FRs [39]. Usually, there is a Probability of success in fulfilling a single FR, \( F_{FR} \), (Fig. 4); which is normally expressed through a Probability Density Function (pdf). In general, the PDF does not necessarily follow a so called “Normal Distribution” [40].

![Figure 4. Probability of success in fulfilling a single FR](image)

In the simple cases of a single FR-\( DP \) pair, the information content (I) is defined by (5), where usually logarithms of base 2 \( (x = 2) \) are used.

\[
I = \log_2 \left( \frac{\text{Area of the system Range}}{\text{Area of the common range}} \right)
\]

(5)

where the area of the “System Range”, \( SR \), can be directly computed from FR’s probability density function [39], [33], [4], [3], and [26]. The “SR” is the operating range of the designed system/product/ service [33], [4], [3], and [26]. To be more specific, The “SR” of a given FR represents the actual “Performance Range”, \( PR \), associated with that FR. The SR is also known as the “Voice of the Process” [40].

The area of the “Common Range”, \( CR \), is the fraction of the above mentioned area that is inside of the “Design Range”, \( DR \), as shown in Fig. 4 [33].The DR defines the acceptable range associated with the specified DP [41]. It is interesting to note that DR could also be recognized as the translation of the so called “Voice of the Customer” into technical domain with technical terms [41].
If an uncoupled design with m number of FRs, and each FR, has a probability of \( P_i \) \((i=1, 2, 3, ..., m)\) to be satisfied, then the total information content of the system \( (I_{\text{Total}}) \) is:

\[
I_{\text{Total}} = \sum_{i=1}^{m} I_i = \sum_{i=1}^{m} \log_2 \left( \frac{1}{P_i} \right)
\]

\( (6) \)

### VI. CRITERIA FOR RELATIVE SUPERIORITY OF THE NEW MODEL OF SE

In this section, we discuss the relative superiority of the presented model of SE over the existing one with the new two criteria of “Total Complexity” of the design approach and “Cost Increase” which arises from coupling among system’s FRs.

#### A. Total Complexity of Design Approach

With respect to design of any system/product/service, uncertainty in successfully achieving each of FRs defined in the functional domain of the system design might be given as a measure to quantitatively define the “Complexity”, \( C_{\text{Sys.}} \), of the designed system/product/service.

In order to address the uncertainty in successfully fulfilling each of FRs which belongs to a system designed based upon a given design approach, assume that \( P_i^L \) \((i=1, 2, 3, ..., n)\) represents the statistical probability of success of that system in fulfilling \( i^{th} \) customers’ (stakeholders)’s FRs at the given \( L^th \) level of the system’s levels of abstraction” [26], [13], and [33]. Further, assuming the FRs are statistically independent of each other, one might define the system’s overall probability of success, \( P_{\text{Sys.}} \), as (7):

\[
P_{\text{Sys.}} = \prod_{i=1}^{n} P_i^L
\]

\( (7) \)

In other words, \( P_{\text{Sys.}} \) might be considered a measure of the overall uncertainty of the system of interest (SOI) in all FRs.

Now, relying on the Shannon’s theory of entropy (1948), the complexity of a specific system, \( C_{\text{Sys.}} \), can be directly related to the total information content, \( I_{\text{Total}} \), of that system designed based on the given system design approach. That is:

\[
C_{\text{Sys.}} = I_{\text{Sys.}} = - \log_2 P_{\text{Sys.}}
\]

\( (8) \)

\[
= - \log_2 \left( \prod_{i=1}^{n} P_i^L \right) = - \sum_{i=1}^{n} \log_2 P_i^L
\]

\( (9) \)

To be more specific, here, \( C_{\text{Sys.}} \) represents the “system overall complexity”, in fact. In addition, in order somehow express the sensitivity of the “System Design” with respect to changes imposed upon \( P_i^L \), we could use the concept of differentiation. So, differentiating (9) with respect to \( P_i^L \) explicitly gives:

\[
\frac{\partial}{\partial P_i^L} (I_{\text{Sys.}}) = \frac{\partial}{\partial P_i^L} (C_{\text{Sys.}}) = \frac{\partial}{\partial P_i^L} (- \log_2 P_i^L - \sum_{j=1, j \neq i}^{n} \log_2 P_j^L)
\]

\( (10) \)

With,

\[
\frac{\partial}{\partial P_i^L} \left( - \log_2 P_i^L \right) = \frac{\partial}{\partial P_i^L} \left( - \frac{1}{P_i^L} \right) = \frac{1}{(P_i^L)^2} > 0
\]

\( (11) \)

For \( P_i^L \) approaching to 1, the asymptotical manner of the overall complexity of the designed system may be expressed as the (12):

\[
\lim_{P_i^L \rightarrow 1} (C_{\text{Sys.}}) = \lim_{P_i^L \rightarrow 1} (- \log_2 P_i^L - \sum_{j=1, j \neq i}^{n} \log_2 P_j^L) = 0
\]

\( (12) \)

That is, the more a specific system design approach is able to meet the customers’ needs, the less the complexity of the designed system will be. Also, it is clear that the minimum complexity may be achieved at \( P = 1 \). So, according to this criterion, the new model of SE which aims to find the best possible solution among all alternatives which can somehow satisfy the FRs may be preferred over any other earlier models.

#### B. Cost Increase Associated with Coupling among System’s FRs

Let’s considering (13) as a design equation which represents the mapping process between functional and physical domain of a system:

\[
\begin{bmatrix}
FR_1 \\
FR_2 \\
\vdots \\
FR_m
\end{bmatrix} =
\begin{bmatrix}
A_{11} & A_{12} & \cdots & A_{1p} \\
A_{21} & A_{22} & \cdots & A_{2p} \\
\vdots & \vdots & \ddots & \vdots \\
A_{m1} & A_{m2} & \cdots & A_{mp}
\end{bmatrix}
\begin{bmatrix}
D_{P_1} \\
D_{P_2} \\
\vdots \\
D_{P_p}
\end{bmatrix}
\]

\( (13) \)

To propose a model to estimate the amount of costs the system owners need to pay because of the any failure in satisfying the customers’ FRs, we use the so called “Taguchi’s loss function” as (14):

\[
L = K. (FR - T_{FR})^2
\]

\( (14) \)

where

- \( L \): represents the vector which its \( i^{th} \) \((i=1,2,3, ..., n)\) element shows the cost imposed on the system because of failure to meet the FR, \( i^{th} \) \((i=1,2,3, ..., n)\).
- \( K \): represents the vector which its \( i^{th} \) \((i=1,2,3, ..., n)\) element is the constant related to the FR, \( i^{th} \) \((i=1,2,3, ..., n)\).
- \( FR \): represents the vector which its \( i^{th} \) \((i=1,2,3, ..., n)\) element is the FR, \( i^{th} \) \((i=1,2,3, ..., n)\) has to be successfully fulfilled.
- \( T_{FR} \): represents the vector which its \( i^{th} \) \((i=1,2,3, ..., n)\) element is the target value of the FR, \( i^{th} \) \((i=1,2,3, ..., n)\).

Knowing FRs’ behaviors in real-world operation vary in certain limits (Not stochastic), we need to concentrate our efforts to develop suitable “mathematical expectations of the variables under consideration. That is,

\[
E(L) = E\{K. (FR - T_{FR})^2\}
\]

\( (15) \)
where

\[ \text{Var}(FR) \]: represents “the Variance-Covariance Matrix of the vector FR, VCM_{FR}. And,

\( Bias \): represents “the vector which its \( i \)-th \((i = 1, 2, 3, \ldots, n)\) element is the systematic deviation of the \( FR_i \) \((i = 1, 2, 3, \ldots, n)\) from its predefined target value, \( T_{FR_i} \).

Here, without loss of generality, it is assumed that, \( FRs \) would not be show any systematic deviation from their individual target value, \( T_{FR_i} \). In other words, each \( FR_i \) exhibits no “Bias” (the “Bias” is equal to zero). Hence:

\[ \Sigma_{FR} = \text{Var}(FR) = \text{Var}([A], DP) \]

\[ = E \left( ([A].DP).([A].DP)^T \right) \]

\[ = E([A].DP.DP^T).[A]^T \]

\[ = [A].E(DP.DP^T).[A]^T \]

\[ = [A].\text{Var}(DP).[A]^T \]

\[ = [A].\Sigma_{DP}.[A]^T \]

Thus, \( VCM_{FR} \) is:

\[ \Sigma_{FR} = [A].\Sigma_{DP}.[A]^T \] (24)

Further, again, with no loss of generality, assuming all elements of random vector \( DP \) are statistically independent of each other. Thus, the variance–covariance matrix of the \( DP, VCM_{DP} \), can be expressed as

\[ \Sigma_{DP} = \begin{bmatrix} \sigma_{11} & 0 & \cdots & 0 \\ 0 & \sigma_{22} & \cdots & 0 \\ \vdots & & \ddots & \vdots \\ 0 & 0 & \cdots & \sigma_{pp} \end{bmatrix} \] (25)

Where diagonal elements of (25) represent the variance of \( i \)-th element of the \( DP \). Therefore, the final form of the \( VCM_{FR} \) can be given as (26).

\[ \Sigma_{FR} = \begin{bmatrix} \sum_{i=1}^{p} A_{1i}\sigma_{ii} & \sum_{i=1}^{p} A_{1i}A_{2i}\sigma_{ii} & \cdots & \sum_{i=1}^{p} A_{1i}A_{pi}\sigma_{ii} \\ \sum_{i=1}^{p} A_{2i}A_{1i}\sigma_{ii} & \sum_{i=1}^{p} A_{2i}A_{2i}\sigma_{ii} & \cdots & \sum_{i=1}^{p} A_{2i}A_{pi}\sigma_{ii} \\ \vdots & \vdots & \ddots & \vdots \\ \sum_{i=1}^{p} A_{pi}A_{1i}\sigma_{ii} & \sum_{i=1}^{p} A_{pi}A_{2i}\sigma_{ii} & \cdots & \sum_{i=1}^{p} A_{pi}A_{pi}\sigma_{ii} \end{bmatrix} \] (26)

Finally, as (27) and (28) show, the diagonal elements of the \( VCM_{FR} \) are summed so as to obtain the “Total Variance of the FR”.

\[ \text{Var}(Sys.) = \sigma_{sys} = \sigma_{11}^{FR} + \sigma_{22}^{FR} + \cdots + \sigma_{nn}^{FR} \]

\[ = \sum_{i=1}^{p} A_{ii}^2 \sigma_{ii} + \sum_{i=1}^{p} A_{2i}^2 \sigma_{ii} + \cdots + \sum_{i=1}^{p} A_{pi}^2 \sigma_{ii} \] (27)

Hence, in a coupled design of a system/product/service, (28) suggests that: the larger the off-diagonal elements of the design matrix are, the larger the \( \text{Var}(Sys.) \) will become.

As a result, in a coupled design under such a condition, an increase in cost would be inevitable. Such a condition is what we need to avoid throughout the system design process and here we have developed a mathematical model to show the way; or at least to relatively compare two coupled systems and choose the one with relatively lower cost.

VII. CASE STUDY: ANALYSIS OF U.S. ELECTRICITY MARKETING SUBSYSTEM

To illustrate the effectiveness of the new SE model, we study the design of existing “Marketing Subsystem” of United States electric power sector.

The U.S. electricity sector is, in fact, one of the largest Engineering Systems in the world with as many as 145,293,840 ultimate customers and net generation of 4,047,765 Thousand Megawatt hours of electricity (in 2012) [37].

Obviously, such a mega-system enjoys very large varieties of stakeholders; from Electricity Generation up to its Transmission, Distribution, and Marketing in all its major customers; namely, “Residential”, “Commercial”, “Industrial”, and “Transportation” segments [37]. However, we limit our work to its crucial sub-system, that is, marketing for ITS main customers. Therefore, this sub-system’s FRs are as follows:

\( FR_1 \): Provide electricity for residential segments
\( FR_2 \): Provide electricity for commercial segments
\( FR_3 \): Provide electricity for industrial segments
\( FR_4 \): Provide electricity for transportation segments

The U.S. electric power producers were previously divided into electric utilities and non–utilities. However, currently, it consists of the “Electric Utilities”, “Independent Power Producers (Non–Combined Heat and Power Plants/ Combined Heat and Power Plants), “Commercial”, and “Industrial” Sectors [37]. In addition, each of these four main sectors is also responsible for supplying required electricity to every U.S. electricity provider that is to meet demands of all categories of the customers involved with this system. Hence, the system’s DPs which have to be defined at the first level of abstraction to satisfy the system’s specified FRs can be stated as followings:

\( DP_1 \): Electric Utilities
\( DP_2 \): Independent Power Producers
\( DP_3 \): Commercial Sectors
\( DP_4 \): Industrial Sectors

On the basis of such descriptions of U.S. Electricity Marketing subsystem, the current “Engineering Design” of this sub-system may be modeled as we describe it in the following sub-sections.
A. Modeling the U.S. Electricity Marketing Subsystem

Viewing from the perspective of the AD principles, in order to find out relationships between every entity of two functional and physical domains of the U.S. Electricity Marketing Subsystem, here we have to explore a set of hypothetic polynomial functions as expression of (29) to statistically correlate the amount of electricity generated by each of the producers to the amount of electricity demanded by the $k^\text{th}$ $(k=1, 2, 3, \text{and} 4)$ major customer of the system over a year.

$$
\begin{align*}
Y_1^k &= \beta_0^k + \beta_1^k x_{j1} + \beta_2^k x_{j2} + \beta_3^k x_{j3} + \beta_4^k x_{j4} + \epsilon_j^k \\
Y_2^k &= \beta_0^k + \beta_1^k x_{j1} + \beta_2^k x_{j2} + \beta_3^k x_{j3} + \beta_4^k x_{j4} + \epsilon_j^k \\
Y_3^k &= \beta_0^k + \beta_1^k x_{j1} + \beta_2^k x_{j2} + \beta_3^k x_{j3} + \beta_4^k x_{j4} + \epsilon_j^k \\
Y_4^k &= \beta_0^k + \beta_1^k x_{j1} + \beta_2^k x_{j2} + \beta_3^k x_{j3} + \beta_4^k x_{j4} + \epsilon_j^k
\end{align*}
$$

where

- $Y_j^k$: represents the $j^\text{th}$ $(j=1,2,3, \ldots, n)$ observation associated with amount of electricity demanded by $k^\text{th}$ $(k=1, 2, 3, \text{and} 4)$ major customer of the system over a year.
- $x_{jk}$: represents the $j^\text{th}$ $(j=1,2,3, \ldots, n)$ observation associated with amount of electricity produced by $k^\text{th}$ $(k=1, 2, 3, \text{and} 4)$ major producer sector of the system over a year.
- $\beta_k^j$: represents the $j^\text{th}$ $(j=1,2,3, \ldots, n)$ regression coefficient associated with amount of electricity produced by $k^\text{th}$ $(k=1, 2, 3, \text{and} 4)$ major producer sector of the system over a year.
- $\epsilon_j^k$: represents the $j^\text{th}$ $(j=1,2,3, \ldots, n)$ random error associated with amount of electricity demanded by $k^\text{th}$ $(k=1, 2, 3, \text{and} 4)$ major customer of the system over a year.

However, to find suitable values of every element of the “Design Matrix” which participates in mapping process between the functional and physical domains of the sub-system, the “Standardized Multiple Linear Regression (SMLR) Models which describe the ways in which DPs are employed and help satisfy their corresponding FRs are fitted using software package SAS 8.2.

Thus, (30) can be given as the “Design Equation” describing the U.S. Electricity Marketing subsystem over a year:

$$
\begin{bmatrix}
FR_1 \\
FR_2 \\
FR_3 \\
FR_4
\end{bmatrix} =
\begin{bmatrix}
0.95 & -0.09 & 0 & 0 \\
0.98 & -0.09 & 0 & 0 \\
0 & 0.602 & 0 & 0 \\
0 & 0.24 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
DP_1 \\
DP_2 \\
DP_3 \\
DP_4
\end{bmatrix}
$$

(30)

As can be seen, expression of (30) indicates that, the FRs of this sub-system are coupled at the first level of abstraction and, therefore, any perturbation in either of FRs can significantly perturb other FRs. According to the AD’s axioms, such a design is rather ineffective and may entail a lot of complexities.

B. Separation in Time and/or Space as a Possible Way To Reduce Magnitude of Coupling Among FRs

To reduce the system design coupling/complexity, we break the set of equations (29) into four separate design equations exclusively associated with four seasons of a year; which seems to be a good way to either ameliorate the problem or identify the roots of the design complexity. For this purpose,

$$
\begin{align*}
Y_{ij}^k &= \beta_0^k + \beta_1^k x_{ij1} + \beta_2^k x_{ij2} + \beta_3^k x_{ij3} + \beta_4^k x_{ij4} + \epsilon_{ij}^k \\
Y_{ij}^k &= \beta_0^k + \beta_1^k x_{ij1} + \beta_2^k x_{ij2} + \beta_3^k x_{ij3} + \beta_4^k x_{ij4} + \epsilon_{ij}^k \\
Y_{ij}^k &= \beta_0^k + \beta_1^k x_{ij1} + \beta_2^k x_{ij2} + \beta_3^k x_{ij3} + \beta_4^k x_{ij4} + \epsilon_{ij}^k \\
Y_{ij}^k &= \beta_0^k + \beta_1^k x_{ij1} + \beta_2^k x_{ij2} + \beta_3^k x_{ij3} + \beta_4^k x_{ij4} + \epsilon_{ij}^k
\end{align*}
$$

where

$Y_{ij}^k$: represents the $j^\text{th}$ $(j=1,2,3, \ldots, n)$ observation associated with amount of electricity demanded by $k^\text{th}$ $(k=1, 2, 3, \text{and} 4)$ major customer of the system in $i^\text{th}$ $(i=1, 2, 3, \text{and} 4)$ partition over a year.

$x_{ijk}$: represents the $j^\text{th}$ $(j=1,2,3, \ldots, n)$ observation associated with amount of electricity produced by $k^\text{th}$ $(k=1, 2, 3, \text{and} 4)$ major producer sector of the system in $i^\text{th}$ $(i=1, 2, 3, \text{and} 4)$ partition over a year.

$\beta_{ik}^j$: represents the $k^\text{th}$ $(j=1,2,3, \ldots, n)$ regression coefficient associated with amount of electricity produced by $k^\text{th}$ $(k=1, 2, 3, \text{and} 4)$ major producer sector of the system in $i^\text{th}$ $(i=1, 2, 3, \text{and} 4)$ partition over a year.

It is noted that, here each season would not necessarily follows the well-known seasons of spring-summer-autumn and winter. Such seasons each have similar number of days. However, the four seasons, as far as, the Electric Power Supply is concerned could have quite different number of days. However, due to the lack of detailed-data, we first assume the seasons to be the same as formal seasons; each with 120 days. Then Design Equation describing the subsystem in spring would be:

$$
\begin{bmatrix}
FR_1 \\
FR_2 \\
FR_3 \\
FR_4
\end{bmatrix} =
\begin{bmatrix}
0.95 & -0.09 & 0 & 0 \\
0.98 & -0.09 & 0 & 0 \\
0 & 0.602 & 0 & 0 \\
0 & 0.24 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
DP_1 \\
DP_2 \\
DP_3 \\
DP_4
\end{bmatrix}
$$

(32)

And, design equation describing the subsystem in summer:

$$
\begin{bmatrix}
FR_1 \\
FR_2 \\
FR_3 \\
FR_4
\end{bmatrix} =
\begin{bmatrix}
0 & 0 & 0.33 & 0 \\
0.98 & 0 & 0 & 0 \\
0 & 0.79 & 0 & 0 \\
0 & 0.56 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
DP_1 \\
DP_2 \\
DP_3 \\
DP_4
\end{bmatrix}
$$

(33)

With design equation describing the subsystem in autumn:

$$
\begin{bmatrix}
FR_1 \\
FR_2 \\
FR_3 \\
FR_4
\end{bmatrix} =
\begin{bmatrix}
0 & 0 & -0.1016 & 0 \\
0 & 0 & -0.13 & 0 \\
0 & 0.81 & 0 & 0 \\
0 & 0.36 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
DP_1 \\
DP_2 \\
DP_3 \\
DP_4
\end{bmatrix}
$$

(34)

And finally, the design equation describing the subsystem in winter is:

$$
\begin{bmatrix}
FR_1 \\
FR_2 \\
FR_3 \\
FR_4
\end{bmatrix} =
\begin{bmatrix}
0 & -0.50 & 0 & 0 \\
0.90 & -0.05 & 0 & 0 \\
0 & 0.65 & 0.23 & 0 \\
0 & 0.12 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
DP_1 \\
DP_2 \\
DP_3 \\
DP_4
\end{bmatrix}
$$

(35)
As can be seen in (32)-(35), it seems that in spite of obtaining better results from seasonally partitioning the (29) into four separate sub-design equations, the coupling among the FRs of the subsystem still exists. This signifies a basic problem rooted in a poor design of the sub-system under study. In such a situation, other tools, such as partitioning the (29) in terms of different types of seasons with different number of days; or partitioning based on states and even season-state would come into mind; which is beyond of the scope of the current work. Nonetheless, the current approach in each type of partitioning can effectively help the design-team to evaluate the relative complexities involved.

VIII. CONCLUSION AND DISCUSSION

Throughout the design process, the system designers have to make many types of decisions that starting from understanding the customers’ needs and requirements. The main process, however, starts by developing a set of appropriate functional requirements to create or select the best design. A theoretical framework which unifies different approaches to a single-comprehensive technique is an effective tool that help the designers to make rational decisions without too much reliance on personal believes or experiences.

The approach proposed in this work, similar to the existing techniques, is an algorithmic method. But, to the contrary of the existing ones, is not heuristic; nor it too much depends on the design team skill, knowledge, attitude and experience.

We firmly believe that a well-founded systematic design approach should not rely on trial-error or heuristic approaches; that need to be tested and debugged before entering to the service. Such an approach is obviously would be expensive, and entails both technical and business risks; therefore, it is irrational. A new model of SE improved by Axiomatic Design principles can significantly resolve these shortcomings of the existing model of SE. The fact is that, any coupling among FRs is the source of any poor design and this work is a suitable step toward better understanding of the importance of resolving conflicting FRs in the early stages of the design process. However, we are not suggesting that conflicting FRs could be eliminated. In fact, due to the nature of the mankind, such an idea would sound impossible. However, we believe that current approach by showing the “Cost increase”, indirectly help stakeholders to be more cooperative with system designers to adjust their individual FRs and so help diminishing the effects of conflicting FRs.

To have a more comprehensive approach, further investigations is quite essential in different fields, such as proper ratio among modes of transportation (Rail, Sea, Road, Air) and Health and Care systems. Such systems exhibit very conflicting requirements and are very good areas for further research.

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