An Axiomatic Model for Development of the Allocated Architecture in Systems Engineering Process

A. Sharahi, R. Tehrani, A. Mollajan

Abstract**—**The final step to complete the “Analytical Systems Engineering Process” is the “Allocated Architecture” in which all Functional Requirements (FRs) of an engineering system must be allocated into their corresponding Physical Components (PCs). At this step, any design for developing the system’s allocated architecture in which no clear pattern of assigning the exclusive “responsibility” of each PC for fulfilling the allocated FR(s) can be found is considered a poor design that may cause difficulties in determining the specific PC(s) which has (have) failed to satisfy a given FR successfully. The present study utilizes the Axiomatic Design method principles to mathematically address this problem and establishes an “Axiomatic Model” as a solution for reaching good alternatives for developing the allocated architecture. This study proposes a “loss Function”, as a quantitative criterion to monetarily compare non-ideal designs for developing the allocated architecture and choose the one which imposes relatively lower cost to the system’s stakeholders. For the case-study, we use the existing design of U. S. electricity marketing subsystem, 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.

Keywords**—**Allocated Architecture, Analytical Systems Engineering Process, Functional Requirements (FRs), Physical Components (PCs), Responsibility of a Physical Component, System’s Stakeholders.

I. INTRODUCTION

AT a time when the world is more interconnected, more interdependent, and more rapidly changing than ever before, the more ways of seeing, the better [1]. Concentrating on major problems of our time indicates that these problems cannot be understood well enough in isolation [2]. These problems are, in fact, systemic ones which are tightly interconnected [3]. Understanding of these interdependencies requires a new way of thinking; it requires systems thinking [4].

Today, the “systems thinking” is widely accepted as a critical approach to addressing many of environmental, industrial, economic, and social challenges that we are facing in the real world [1]. According to the logic incorporated in the “systems thinking”, any large - scale system must always be put in the context of the larger environment of which it is a part and, then, the actual role the system plays can be studied [5].

Focusing on what happen in systems thinking process reveals that the major reason why the systems thinking emphasizes the interconnections and interdependencies among different entities of a given problem is, in fact, rooted in an essential concept which is referred to as “system”. Literally, the term “system” originates from the Greek term systema, which means “to place together” [5]. 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 operational environment with a specified outcome and probability of success” [6], [7].

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)” [8]. Such systems are designed, formed and operated to achieve their intended functions [9]. For this purpose, systems development process often requires contribution from many diverse technical disciplines [10]. In this regard, in order to enable the realization of successful systems, “Systems Engineering” (SE) as a strong interdisciplinary field is employed [11]. 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 System’s 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 [5], [6], [11].

Following logic of the system thinking in analyzing behaviors of systems, significance of interactions and relationships between any system and other elements included in the operational environment of the system can be understood more deeply [12]. According to the literature on SE, these included elements are identified as “stakeholders” of the system [5], [6]. By definition, The system’s stakeholders are, in fact, those neighboring systems which have a vested friendly/competitive/ adversarial interest in the outcome produced by the system of interest (SOI) in performing its assigned mission” [5] [7]. In this regard, it is important to note that those stakeholders actively involved with the SOI may influence the system outcomes and can be also influenced by the system’s outcomes as well [5], [6], [13], [14].

From principles of SE, the fact is that, any close and deep involvement with main stakeholders of a SOI may pave the way for achieving success of the SOI [6], [13]. To be more

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specific, the real success of any system can be achieved only through "identifying, understanding, and fulfilling every need of all major stakeholders that are associated with the system in a sustainable way [13]. Therefore, the better designers of the SOI understand the needs of the associated stakeholders, the higher the probability of successfully satisfying the stakeholders will become [15].

With respect to attempting for fulfilling requirements of the stakeholders in a successful way, "Functional Requirements" (FRs) for a SOI are defined to completely address the needs and objectives of the stakeholders [16]. Generally, The SOI's FRs may be defined as a minimum set of independent requirements which completely characterizes the final design of the SOI. Such a set is, in fact, an acceptable engineering solution to the major problem of the SOI [17]-[21].

In order to address the process of establishing the FRs of the SOI, "Analytical Systems Engineering Process", as a logical, systematic and comprehensive approach, is commonly used for developing the SOI. According to this approach, the path of developing any kind of human-made system can be described as a process which begins with the system's operational concept and includes development of three separate architectures (functional, physical, and allocated) as parts of this decomposition (Fig. 1) [22].

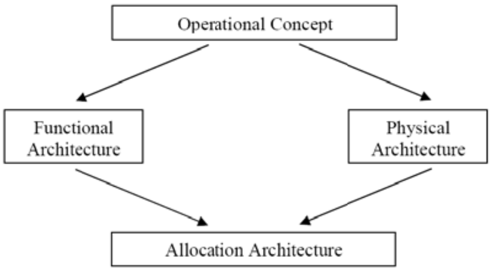

Fig. 1 Analytical Systems Engineering Process

In Fig. 1, the "operational concept", in general terms, is a vision for what the SOI is, or a statement of mission requirements and/or a description of how the system will be utilized. Moreover, a set of scenarios may also describe how the system will be used by defining the interactions of the SOI with other entities included in the operational environment associated with the system [6]. In this regard, for instance, the operational concept for an Aircraft is "Flight" or for an Economic System of a country, as a large and complex system, is production and distribution of all required goods and services and allocation of available resources in that society.

The "Functional Architecture" of the system is next important step in developing the SOI. By definition, the functional architecture of the SOI is, in fact, a logical architecture that defines what the SOI must do. That is, a decomposition of the SOI's top - level function(s) [6]. At this step, both definition and development of all required FRs are the most critical tasks should be accomplished by designers [22].

Following the FRs architecture of the SOI, the "Physical Architecture" of the SOI is another basic step at which all physical components (PCs), which are required to satisfy all FRs and have been developed at the previous step, are established [6], [22].

In other words, the "Physical Architecture" of the SOI is to provide required physical resources, such as programs, offices, activities, etc., for satisfying every FR established in the functional architecture of the SOI [16].

Finally, after development of the functional and physical architectures, the design team has to assign the FRs developed in the functional domain of the SOI into PCs defined in the physical domain. Mapping of FRs to PCs of the SOI is the so called "Allocated Architecture" of the SOI [5], [22].

II. RELEVANT WORKS

With respect to the existing models describing allocation of FRs of a system to corresponding PCs, Fitts (1951) was the first to try to systematize the allocated architecture issue by introducing the MABA-MABA (Men Are Better At & Machines Are Better At) method. The main idea of this method is to compare the relative ability of human and machine, as physical components of a system, to accomplish a set of tasks as the system functions. In this method, a list of the advantages of man and machine in successfully performing the functions of engineering systems was developed [23]. However, this list, which is the so called MABA-MABA list, does not have significant impact on engineering design practices because such criteria are, in fact, overly general and non-quantitative [24]. Regarding development of allocated architecture of any system, Jordan (1963) pointed out that "as the process of establishing an engineering system continues, new and more creative ways of thinking will appear" [25]. Price (1985) argued that, in process of fulfillment of system tasks(functions), in most of cases, there might be some tasks that no physical components (neither human nor machine) can do well, while, on the other hand, there might be other tasks that more than one physical component (both human and machine) can do [26]. Based on such a discussion, he proposed the "Decision Matrix Method" which represents a decision space in which the x-axis is the judgment variable of performance of some of physical components of the system (for example, humans), scaled from unacceptable to excellent, and the y-axis is the corresponding variable of performance of other physical components of the system (for example, machines) [26]. The performance of any functions can be represented by a point in the decision space. The Price Decision Matrix is constituted from six zones that are qualitatively different in their implication for allocation of functions [26]. However, this method cannot explain how to judge the relative performance of the defined physical components of the system explicitly. In addition, the description of the allocation scheme of the six areas is also ambiguous. Therefore, this matrix can hardly be used in the engineering design practices. Saaty (1970s) proposed the AHP (The analytic hierarchy process) as a quantitative solution to the problem of allocation and planning in engineering systems

[27]. The AHP method consists of three steps: (1) building a hierarchy model, which is constituted from an overall goal, a group of alternatives and a group of criteria; (2) asking experts to analyze the model via a series of pair-wise comparisons of the criteria against the goal for importance and pair-wise comparisons of the alternatives against each of the criteria for preference; and (3) calculating the pair-wise comparison matrixes in a mathematical way and deriving the weights and priorities for each node of the hierarchy model [27]. Moreover, AHP provides a useful mechanism for checking the consistency of the evaluation measures and alternatives suggested by the experts and, also, reducing bias in decision making process [28]-[30]. However, application of the AHP method are mainly suitable for industrial automation systems, so the criteria used in their hierarchy models may not be useful for the function allocation in the all types of systems. Hancock (1992) argued that it is only once both human and machine can do the same function; the question of function allocation becomes an issue [31]. In addition, in line with Jordan, this research agreed that the function allocation should be considered a complementary between man and machine, as two main physical components of systems, rather than dividing functions just to one resource [31]-[34]. Suitable allocation of the system functions has to be made between physical components (human operators and machines) and techniques and must also be able to be dynamically changeable over time. However, it is common that systems designers automate all subsystems that lead to an economic benefit for those subsystems but leave the operator to manage the rest [35]. Parasuraman et al. (2000) stated that automation system design is not an exact science; however, neither does it belong in the realm of the creative arts, with successful design dependent on the vision and brilliance of individual creative designers [36].

III. DIFFICULTY IN DETERMINING A SPECIFIC PHYSICAL COMPONENT RESPONSIBLE FOR FULFILLING A GIVEN FR DUE TO THE EXISTENCE OF A POOR DESIGN FOR THE SYSTEM'S ALLOCATED ARCHITECTURE

Structure of a system is a common term which is often used to determine how "Functions", "Power", and "Responsibilities of the system" are assigned, controlled, and coordinated [37]. In general, the structure of a system consists of activities such as "task allocation", "coordination", and "supervision", which are all directed towards achievement of the system's aims [5].

Basically, the main purpose of the structure of any system is to exhaustively define all required FRs of the system to meet the needs and objectives of the stakeholders as well as clearly specify the responsibility assigned to each of physical components (PCs) needed to satisfy the associated FR(s) [6], [7]. Therefore, study of the structure of a system is mainly concentrated on differentiating and patterning all relationships which should be defined between functional and physical elements of the system [6], [16].

With respect to design of any engineering system structure, finding a way in which the pattern of assigning "responsibility" of every PC for satisfying the allocated FR(s) can be clearly specified is considered to be one of the most significant challenges the system designers has to face.

From the analytical systems engineering process, we can find that any failure in development of an appropriate "allocated architecture" for an engineering system may pose a problem for achieving a capability for accurately specifying exclusive "responsibility" of each PC for meeting the associated FR(s) successfully. To be more specific, presenting any poor design for an engineering system's allocated architecture in which no clear pattern of assigning the exclusive "responsibility" of each PC for satisfying the allocated FR(s) can be found, we will therefore have difficulties in determining the specific PC(s) which actually has (have) failed to successfully fulfill a certain FR on which a failure report has been given. Furthermore, these kinds of designs for developing the allocated architecture of a system are, in fact, poor ones which cannot help the system owners modify the system in order to ultimately meet the needs and objectives of the system's stakeholders.

In order to accurately address the problems that may arise from presenting a poor design for the allocated architecture of an engineering system, the present study is to develop "a mathematical model for analysis of allocated architecture in systems engineering process and is to more precisely describe real patterns in which the identified FRs of the system are mapped to their corresponding PCs. In this line of thought, this study shows how fundamentals of the so called "Axiomatic Design (AD)", which was originally introduced by Suh (1990-2001) in order to design effective physical and mechanical systems [16], could play its role. Hence, the contribution of this work is outlined as followings;

- Developing an axiomatic model for allocated architecture in systems engineering process to accurately describe mapping process between FRs and PCs defined for an engineering system.
- Establishing a "Loss Function", as a quantitative measure, to fairly compare two non-ideal designs of allocated architecture of a given engineering system and choose the one with relatively lower loss.
- Proposing a mathematical design method for developing a good allocated architecture which can effectively help engineers detect specific PC(s) actually has (have) failed to fulfill a given FR and, hence, may pave the way for the system engineers to modify the current system in order to ultimately meet the needs of the system's stakeholders more successfully.

IV. METHODOLOGY

To describe the relative importance of the current work, we need to start with proper evaluation of the existing levels of engineering practices. Such evaluation reveals the both strengths and weaknesses of the approaches available to design of allocated architecture of engineering systems. We then use "Linear Algebra", especially principles of "Matrix Representation" and "Systems of Linear Equations", to mathematically express the mapping process between the functional and physical domain (architecture) of the SOI. Furthermore, we use fundamentals of "multivariate statistical analysis" to develop the so called "Taguchi's loss function" [38], [39] which may be associated with the process of fulfilling random vector **FR**, to establish criterion of "Cost Increase"; which may arise from an indistinguishable pattern of assigning the PCs' responsibilities for meeting the allocated FRs. Finally, for the purpose of resolving the ambiguity in determining specific PCs exclusively responsible for fulfilling the associated FRs, we use the interesting properties of "diagonal and triangular matrixes" to develop a new mathematical method for appropriate design of allocated architecture of engineering systems.

To illustrate strength of the new model developing an appropriate allocated architecture for any given engineering system, the existing design of U.S. Electricity Marketing Subsystem is studied. In this regard, the multiple linear regression models are actively employed to fit linear statistical models describing the ways in which PCs are mapped to their corresponding FRs to fulfill them. For this purpose, statistics and data provided by U.S. Energy Information Administration (EIA) in the year of 2012 are analyzed [40]. 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 PCs of the system are mapped to their corresponding FRs.

V. DEVELOPING AN AXIOMATIC MODEL FOR ALLOCATED ARCHITECTURE IN SYSTEMS ENGINEERING PROCESS

A. Brief Review of Axiomatic Design

The "Axiomatic Design" has been built based upon four key elements of: (1) Domains; (2) Hierarchies; (3) zigzagging processes and finally (4) Axioms [16].

- Domains

According to Suh (1990), the world of design consists of four domains as represented in Fig. 2. Each domain on the right side is, in fact, to answer how we can achieve the goals defined on its left adjacent domain, via appropriate mappings. "Customers' Attributes", CAs, are delineated in the "Customer Domain" [16]. CAs are, in fact, the STHs' needs which will be, next, specified in terms of "Functional Requirements", FRs, and "Constraints" (Cs) [8], [9], and [16]. By definition, the "Functional Requirements", FRs, are a minimum set of independent requirements that are usually defined by engineering terms and are to completely characterize the functional needs of the product in the functional domain of the design [16], [21], [42].

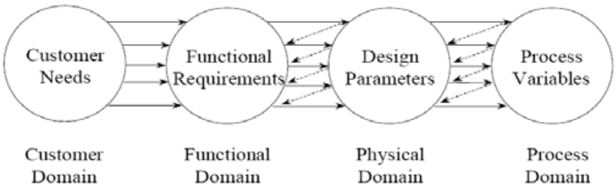

Fig. 2 Axiomatic Design Domains [16]

Next, in order to fulfill the FRs, we also have to define or select physical solutions which are referred to as "Design Parameters", DPs, in the physical domain.

Therefore, the DPs are, in fact, the critical physical variables in the physical domain that characterize the design which fulfills the specified FRs of the product under development [16]. Finally, to produce the product characterized in terms of DPs, we have to develop a process which is specified by "Process Variables" (PVs) in the process domain. To be more specific, the PVs are, in fact, the significant process variables in the process domain that characterize the process which manufacture/generate the specified DPs [16], [21].

- "Hierarchies" and "Zigzagging Processes"

As stated earlier, "Hierarchies" and "Zigzagging Processes" are two key elements of the AD method for developing engineering systems and/or products [16]. The "Hierarchical Decomposition" through "Zigzagging Processes between Domains", starts from the 'What' domain and, then, goes to the 'How' domain in order to conceptualize the product design and establish the corresponding with one previously identified in the "what" domain and it then comes back to the "what" domain to create sub-elements required at the next level of the product's levels of abstraction to collectively satisfy the highest level elements, in a top-bottom way, beginning at the system level, and continue through levels of more detail [16], [42], and [43]. Following identifying FRs and DPs at the top-level of the product (system)'s levels of abstraction, they should be decomposed till the product design reaches the final stage, the leaf level. Actually, at the leaf level, both FRs and DPs should not need either redesigning or further decomposition.

- Axioms:

Axiom 1 – Is known as the "Independence Axiom". On the basis of this axiom, a good design of any system must maintain the independence of the FRs. This simply means that in case of mapping from the functional into the physical domain, the choice and allocation of the DPs should be made in such a way that each FR can be fulfilled without affecting other FRs. At each level of the design hierarchy, the relationships between the FRs and the DPs can be expressed as (1);

$$\boldsymbol{FR} = [A].\boldsymbol{DP} \qquad (1)$$

where; **FR** and **DP** are the functional requirement vector and the design parameter vector, respectively. In addition, [A] is the "Design Matrix" (DM) for this relationship (mapping). Each element of the design matrix [A] can be expressed as $A_{ij} = \partial FR_i / \partial DP_j$ (i = 1,…, m & j = 1,…,n). Equation (1) is known as the "Design Equation" [16], [21].

Conventionally, the relationship between a FR and a DP is represented by 'X' in a DM. It is obvious that all of the diagonal elements in a DM must be X. In addition, 'O' is also used to represent no functional dependency between a FR and a DP [16], [21].

To satisfy the independence axiom, the DM, [A], must be either diagonal or triangular. When the matrix [A] is diagonal, each of the FRs can independently be satisfied by means of one specific DP. Such a design is called an “Uncoupled Design”. When the matrix [A] is triangular, the independence of FRs can be guaranteed if and only if the DPs are determined in a proper sequence. Such a design is called a “Decoupled Design”. Any other form of the DM is called a full matrix and leads to a “Coupled Design” [16], [21] (Fig. 3).

One additional factor which affects the coupling of FRs is the number of FRs, m, relative to the number of DPs, n. If m > n, then the design is either coupled or the FRs cannot be satisfied. If m < n, then the design is redundant. Indeed, in both cases the DM, [A], is not square [16].

$$\underset{\text{Uncoupled Design}}{\begin{bmatrix} X & 0 & \cdots & 0 \\ 0 & X & \ldots & 0 \\ \vdots & . & \ddots & \vdots \\ 0 & 0 & \cdots & X \end{bmatrix}} \quad \underset{\text{Decoupled Design}}{\begin{bmatrix} X & 0 & \cdots & 0 \\ X & X & \ldots & 0 \\ \vdots & . & \ddots & \vdots \\ X & X & \cdots & X \end{bmatrix}} \quad \underset{\text{Coupled Design}}{\begin{bmatrix} X & X & \cdots & X \\ X & X & \ldots & X \\ \vdots & . & \ddots & \vdots \\ X & X & \cdots & X \end{bmatrix}}$$

Fig. 3 Axiomatic Design Matrixes [16]

Axiom 2 – Is known as “Information Axiom”. On the basis of this axiom, when multiple alternative designs satisfying the first axiom are available, the information axiom must be used to choose the one with minimum information content. This can be accomplished by comparing the information content of the existing alternative solutions in terms of their probability of fulfilling the FRs [16]. As a result, the best solution is the one that possesses the minimum information content and simultaneously satisfies Axiom 1 [16], [44]-[46]. The information content in a design which involves only one FR and one DP design is expressed as the logarithm of the inverse of the probability of the system success in satisfying the FR;

$$I = log_2 \frac{1}{P} \tag{2}$$

In the simple case of a uniform probability distribution, the information content (I) can be defined as (3), where; usually logarithms of base 2 (x = 2) are used [16], [48].

$$I = log_X \frac{(Area\ of\ the\ system\ Range)}{(Area\ of\ the\ common\ range)} \tag{3}$$

where; the area of the “System Range”, SR, can be directly computed from FR’s probability density function. The “SR” is the operating range of the designed system/product/ service. To be more specific, The “SR” of a given FR represents the actual “Performance Range”, PR, associated with that FR [16], [47], and [48]. The SR is also known as the “Voice of the Process” [49].

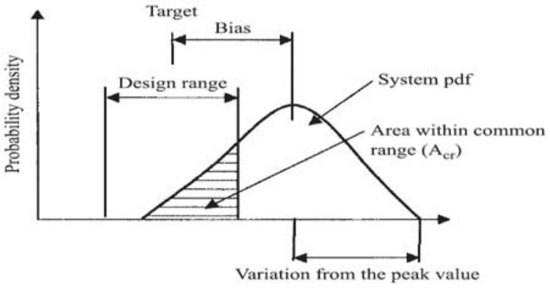

Fig. 4 Success Probability in fulfilling a single FR

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. The DR defines the acceptable range associated with the specified DP [16], [50]. Actually, the DR is recognized as translation of the so called “Voice of the Customer” into technical domain with technical terms [51], [52].

B. Axiomatic Allocated Architecture in Systems Engineering Process

With respect to developing the allocated architecture of the SOI, allocation of FRs to the defined PCs is one of the most important tasks which are expected to be perfectly accomplished by designers in development phase of the SOI’s life cycle. In order to develop a proper allocated architecture, allowing the allocation decision to be represented as a mathematical relation, and not a function, as shown in the top left of Fig. 5, is not adequate enough.

In fact, if the allocated architecture of the SOI is developed in a way which cannot be represented as a mathematical function, there may be some FRs not allocated to any PC and some FRs that are being processed by two or more PCs.

Forcing the allocation of FRs to PCs to be represented as a mathematical function, as shown in the top right of Fig. 5, ensures that every FR defined in the functional architecture of the SOI is being processed by one or more PCs established in physical architecture of the SOI[1]. Moreover, there is the possibility that some FRs will be performed by the same PC; there is nothing wrong with this because these FRs can be aggregated into a single FR.

At a given level of the SOI hierarchy, the set of FRs that define the specific needs of stakeholders constitutes random vector **FR** in the functional domain.

Similarly, the set of PCs in the physical domain that has been chosen to satisfy the FRs constitutes the **PC** Vector. The relationship between these two vectors can be written as (4).

Needless to say, in order to take the advantage of a mathematical function to ensure every FR established in the functional architecture of the SOI is being processed by one or more PCs defined in physical architecture, here we regard

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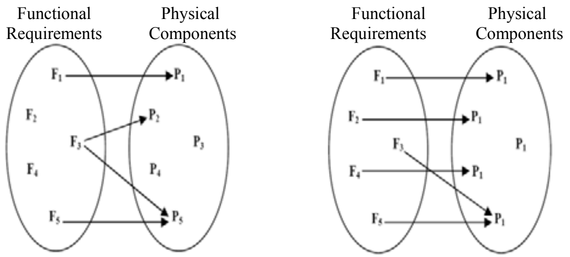
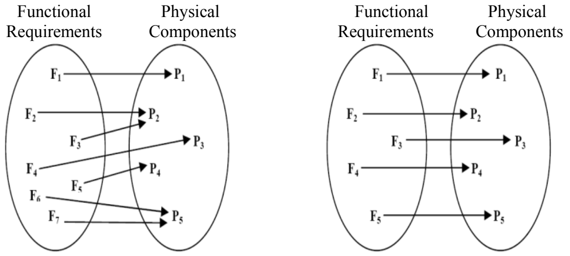
[1] However, there may be some PCs with no FRs to perform; these PCs should either be dropped from the SOI or the designers should revisit their functional architecture to ensure that the functional architecture is complete.

every following relationship between two domains (vectors) as a mathematical function.



Relation for the allocation of FRs to PCs

Function for the allocation of FRs to PCs



Onto, but not one-to-one function for the allocation of FRs to PCs

One-to-one and onto function for the allocation of FRs to PCs

Fig. 5 Mathematical Relations and Functions for the Allocation of FRs to PCs

$$\boldsymbol{FR} = [AAM].\boldsymbol{PC} \tag{4}$$

where; **[**AAM**]** is the "Allocated Architecture Design Matrix", AADM.

The AADM is to directly relate FRs to PCs and characterizes the SOI's allocated architecture design. For a system which has n FRs and n PCs, the "AAM" is of the following form:

$$[AAM] = \begin{bmatrix} AAM_{11} & AAM_{12} & \cdots & AAM_{1n} \\ AAM_{21} & AAM_{22} & \ldots & AAM_{2n} \\ \vdots & . & \ddots & \vdots \\ AAM_{m1} & AAM_{m2} & \cdots & AAM_{mn} \end{bmatrix} \tag{5}$$

When (4) is written in a differential form as (6);

$$d(\boldsymbol{FR}) = [AAM].d(\boldsymbol{PC}) \tag{6}$$

The elements of the "AADM" can be obtained by (7);

$$AAM_{ij} = \frac{\partial FR_i}{\partial PC_j} \tag{7}$$

In this regard, for example, consider a simple system with n FRs and n PCs. Obviously, (4) can be written in terms of its elements as (8);

$$FR_i = \sum_{i=1}^{n} AAM_{ij}.PC_j \;\; ; \mathrm{i} = 1,2,\ldots,\mathrm{n} \tag{8}$$

Or, in other words;

$$\begin{cases} FR_1 = AAM_{11}.PC_1 + AAM_{12}.PC_2 + \cdots + AAM_{1n}.PC_n \\ FR_2 = AAM_{21}.PC_1 + AAM_{22}.PC_2 + \cdots + AAM_{2n}.PC_n \\ \ldots \\ FR_n = AAM_{n1}.PC_1 + AAM_{n2}.PC_2 + \cdots + AAM_{nn}.PC_n \end{cases} \tag{9}$$

For a linear design, AAM_{ij} are always constants. However, for a nonlinear design, AAM_{ij} are functions of the PCs.

According to (9), during the operation phase of the SOI's life cycle, there might be a number of FRs, FR_i (i=1,2,…,n), satisfied (processed) by more than one PC defined in the physical architecture of the SOI. In other words, according to what (9) explicitly implies, there might be several PCs commonly used for satisfying more than one FR. Hence, if the allocated architecture of a SOI is mathematically expressed as (9), therefore, the processes of satisfying two or more FRs may have one or more PCs in common. As a result, under such a situation, any change in each of the common PCs to modify a specific FR may also unintentionally affect other FRs as well.

Designing the allocated architecture of a system like what (9) represents is, in fact, a fundamental shortcoming in process of developing the system. To be more specific, as long as the allocated architecture of the SOI follows a pattern which is similar to one (9) implies; we may have difficulties in determining the specific PC(s) which actually has (have) failed to successfully fulfill a certain FR on which a failure report has been given. Moreover, these types of designs for developing the allocated architecture of the system are, in fact, poor ones which cannot help us modify the system in order to ultimately fulfill the needs of the system's stakeholders.

As mentioned previously, functional requirements (FRs) of any engineering system are a minimum set of independent requirements established as a solution to completely meet needs and objectives of stakeholders associated with the system. As each of established FRs is to effectively address a specific requirement of the associated stakeholder(s), keeping the key property of "independency" among the FRs is quite essential. This fact implies that if process of "developing" and "fulfilling" the system's FRs is completed in a way that each of the FRs is always kept independent of other FRs, we can ensure that any systematic and/or random change in a given FR of the system will never perturb other FRs of the system. For this purpose, applying the Axiomatic Design's principles especially the first (independence) axiom of the AD to design of the system's allocated architecture can pave the way for reaching a set of good designs for the system's allocated architectures in which every FR, established in the functional architecture of the system, can independently be satisfied and, as a result, a clear pattern of assigning the exclusive "responsibility" of each PC for fulfilling the allocated FR(s) can also be found.

In line with the idea of fulfilling every established FR independently, the AADM describing the pattern on which the FRs are mapped into the PCs has to be either a "DIAGONAL" or "TRIANGULAR" matrix. In fact, as the "TOTAL

UNIMODUULARITY"[2] property of every "Diagonal" or "Triangular" matrix, with zero - one elements, does allow us to satisfy FRs independently, we can be sure that the independency among the FRs is always maintained. Moreover, these types of AADMs are also suitable for making some changes and/or modifications in a given FR while other FRs will still remain unaffected. Moreover, the interesting property of both "diagonal" and "triangular" matrixes may be considered an effective mathematical solution to resolving the problem of inability to determine which of the PC(s) has (have) failed to fulfill a certain FR on which a failure report has been received.

VI. Developing a "Loss Function", as a Quantitative Criterion to Measure Additional Cost that May be Incurred Due to a Poor Design for The System's Allocated Architecture.

Let's consider (10) as an "Allocation Architecture Design Equation" (AADE) which represents the mapping process between functional and physical architecture (domain) of an engineering system:

$$\begin{bmatrix} FR_1 \\ FR_2 \\ . \\ FR_m \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & \cdots & A_{1p} \\ A_{21} & A_{22} & \dots & A_{2p} \\ \vdots & . & \ddots & \vdots \\ A_{m1} & A_{m2} & \cdots & A_{mp} \end{bmatrix} . \begin{bmatrix} PC_1 \\ PC_2 \\ . \\ PC_p \end{bmatrix} \qquad (10)$$

In order to predict amount of cost imposed on the system's stakeholders, specially the system's owners, as a result of presenting a poor design for the system's allocated architecture which is not capable enough to successfully satisfy each of the FRs established in the functional architecture (domain) of the system during the operational phase of the system life cycle, we use the "Taguchi's loss function" [38], [39] to monetarily express the amount of loss we may expect to suffer because of failing to effectively satisfy every FR (fulfilling each of the FRs within acceptable limits around its respective target value). For this purpose, let's consider (11);

$$\boldsymbol{L} = \boldsymbol{K}.(\boldsymbol{FR} - \boldsymbol{T_{FR}})^2 \qquad (11)$$

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 (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 (i=1,2,3, .., n).

FR: represents the vector which its i^{th} (i=1,2,3, .., n) element is the FR_i (i=1,2,3, .., n) has to be successfully fulfilled.

$\mathbf{T_{FR}}$: represents the vector which its i^{th} (i=1,2,3, .., n) element is the target value of the FR_i (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,

$$E(\boldsymbol{L}) = E\{\boldsymbol{K}.(\boldsymbol{FR} - \boldsymbol{T_{FR}})^2\} \qquad (12)$$

$$= \boldsymbol{K}.\left\{\sigma^2_{\boldsymbol{FR}} + \left(E(\boldsymbol{FR} - \boldsymbol{T_{FR}})\right)^2\right\} \qquad (13)$$

$$= \boldsymbol{K}.\{\boldsymbol{Var}\ (\boldsymbol{FR}) + (\boldsymbol{Bias})^2\} \qquad (14)$$

where;

Var (FR): represents "the Variance-Covariance Matrix of the vector **FR,** $\mathbf{VCM_{FR}}$. And,

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

Here, without loss of generality, it is assumed that, FRs would not be show any systematic deviation from their individual target value, T_{FRi} (i=1,2,3, .., n). In other words, each FR_i, exhibits no "Bias" (the "Bias" is equal to zero). Hence;

$$\Sigma_{\boldsymbol{FR}} = Var(\boldsymbol{FR}) = Var([\boldsymbol{A}].\boldsymbol{PC}) \qquad (15)$$

$$= [\boldsymbol{A}].Var(\boldsymbol{PC}).[\boldsymbol{A}]^{\boldsymbol{T}} \qquad (16)$$

$$= [\boldsymbol{A}].\Sigma_{\boldsymbol{PC}}.[\boldsymbol{A}]^{\boldsymbol{T}} \qquad (17)$$

Thus, $\mathbf{VCM_{FR}}$ is;

$$\Sigma_{\boldsymbol{FR}} = [\boldsymbol{A}].\Sigma_{\boldsymbol{PC}}.[\boldsymbol{A}]^{\boldsymbol{T}} \qquad (18)$$

Further, again, with no loss of generality, assuming all elements of random vector **PC** are statistically independent of each other, Thus, the variance – covariance matrix of the **PC**, $\mathbf{VCM_{PC}}$, can be expressed as (19);

$$\Sigma_{\boldsymbol{PC}} = \begin{bmatrix} \sigma_{11} & 0 & \cdots & 0 \\ 0 & \sigma_{22} & \dots & 0 \\ \vdots & . & \ddots & \vdots \\ 0 & 0 & \cdots & \sigma_{pp} \end{bmatrix} \qquad (19)$$

where; diagonal elements of (19) represent the variance of i^{th} element of the **PC.** Therefore, the final form of the $\mathbf{VCM_{FR}}$ can be given as (19).

$$\Sigma_{\boldsymbol{FR}} = \begin{bmatrix} \sum_{i=1}^{P} A^2_{1i}.\sigma_{ii} & \sum_{i=1}^{P} A_{1i}.A_{2i}.\sigma_{ii} & \cdots & \sum_{i=1}^{P} A_{1i}.A_{mi}.\sigma_{ii} \\ \sum_{i=1}^{P} A_{2i}.A_{1i}.\sigma_{ii} & \sum_{i=1}^{p} {A_{2i}}^2.\sigma_{ii} & \dots & \sum_{i=1}^{P} A_{2i}.A_{mi}.\sigma_{ii} \\ \vdots & . & \ddots & \vdots \\ \sum_{i=1}^{P} A_{mi}.A_{1i}.\sigma_{ii} & \sum_{i=1}^{P} A_{mi}.A_{2i}.\sigma_{ii} & \cdots & \sum_{i=1}^{p} {A_{mi}}^2.\sigma_{ii} \end{bmatrix} \qquad (20)$$

Finally, as (21) shows, the diagonal elements of the $\mathbf{VCM_{FR}}$ are summed so as to obtain the "Total variance of the **FR"**.

$$\mathrm{Var(Sys.)} = \sigma_{\mathrm{Sys.}} = \sigma^{\mathrm{FR}}_{11} + \sigma^{\mathrm{FR}}_{22} + \ldots + \sigma^{\mathrm{FR}}_{\mathrm{mm}}$$

$$= \sum_{\mathrm{i=1}}^{\mathrm{p}} {\mathrm{A_{1i}}}^2.\sigma_{\mathrm{ii}} + \sum_{\mathrm{i=1}}^{\mathrm{p}} {\mathrm{A_{2i}}}^2.\sigma_{\mathrm{ii}} + \cdots + \sum_{\mathrm{i=1}}^{\mathrm{p}} {\mathrm{A_{mi}}}^2.\sigma_{\mathrm{ii}} = \sum_{k=1}^{m} \sum_{i=1}^{P} {A_{ki}}^2.\sigma_{ii} \qquad (21)$$

Hence, in an inappropriate design of the allocated architecture of the SOI, (21) suggests that: the larger the off-diagonal elements of the AAM are, the larger the Var (Sys.) will become. As a result, in a poor design of the allocated

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[2] A matrix A is said to be totally uni-modular if every square sub-matrix of A has determinant +1, - 1, or 0 [40].

architecture of the SOI, an increase in cost would be inevitable. Such a condition is what we need to avoid throughout the development of the allocated architecture of the SOI and here we have developed a mathematical model to show the way; or at least to fairly compare two improper designs of allocated architectures associated with the SOI and choose the one with relatively lower cost.

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

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) [41].

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 stakeholders; namely, “Residential”, “Commercial”, “Industrial”, and “Transportation” segments [41]. However, we limit our work to its crucial sub-system, that is, Marketing for ITS main stakeholders. Therefore, these 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 [41]. 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 stakeholders involved with this system. Hence, the system’s PCs which have to be defined at the first level of abstraction to satisfy the system’s specified FRs can be stated as followings;

PC_1: Electric Utilities
PC_2: Independent Power Producers
PC_3: Commercial Sectors
PC_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

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 (22) to statistically correlate the amount of electricity generated by each of the producers to the amount of electricity demanded by the kth (k=1, 2, 3, and 4) major stakeholders of the system over a year.

$$\begin{cases} Y_j^1 = \beta_0^1 + \beta_1^1 . x_{j1} + \beta_2^1 . x_{j2} + \beta_3^1 . x_{j3} + \beta_4^1 . x_{j4} + \epsilon_j^1 \\ Y_j^2 = \beta_0^2 + \beta_1^2 . x_{j1} + \beta_2^2 . x_{j2} + \beta_3^2 . x_{j3} + \beta_4^2 . x_{j4} + \epsilon_j^2 \\ Y_j^3 = \beta_0^3 + \beta_1^3 . x_{j1} + \beta_2^3 . x_{j2} + \beta_3^3 . x_{j3} + \beta_4^3 . x_{j4} + \epsilon_j^3 \\ Y_j^4 = \beta_0^4 + \beta_1^4 . x_{j1} + \beta_2^4 . x_{j2} + \beta_3^4 . x_{j3} + \beta_4^4 . x_{j4} + \epsilon_j^4 \end{cases} \quad (22)$$

where;

Y_j^K: represents the j^{th} (j=1,2,3, .., n) observation associated with amount of electricity demanded by k^{th} (k=1, 2, 3, and 4)major stakeholder of the system over a year.

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

β_K^K: represents the k^{th} (j=1,2,3, .., n) regression coefficient associated with amount of electricity produced by k^{th} (k=1, 2, 3, and 4) major producer sector of the system over a year.

ε_j^K: represents the j^{th} (j=1,2,3, .., n) random error associated with amount of electricity demanded by k^{th} (k=1, 2, 3, and 4)major stakeholder of the system over a year.

However, to find suitable values of every element of the “Allocated Architecture Matrix” (AAM) 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 PCs are employed and help satisfy their corresponding FRs are fitted using software package SAS 8.2.

Thus, (23) can be given as the “Allocated Architecture of Design Equation” (AADE) describing the U.S. Electricity Marketing subsystem over a year;

$$\begin{bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_4 \end{bmatrix} = \begin{bmatrix} 0.95 & -0.09 & 0 & 0 \\ 0.98 & -0.09 & 0 & 0 \\ 0 & 0.602 & 0 & 0 \\ 0 & 0.24 & 0 & 0 \end{bmatrix} . \begin{bmatrix} PC_1 \\ PC_2 \\ PC_3 \\ PC_4 \end{bmatrix} \quad (23)$$

As can be seen, (23) indicates that, the FRs of this sub-system are dependent at the first level of abstraction and, therefore, any perturbation in either of FRs can significantly perturb other FRs.

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

To reduce the system design coupling, we break the set of equations (23) 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. For this purpose,

$$\begin{cases} Y_{ij}^1 = \beta_0^1 + \beta_1^{i1} . x_{ij1} + \beta_2^{i1} . x_{ij2} + \beta_3^{i1} . x_{ij3} + \beta_4^{i1} . x_{ij4} + \epsilon_{ij}^1 \\ Y_{ij}^2 = \beta_0^{i2} + \beta_1^{i2} . x_{ij1} + \beta_2^{i2} . x_{ij2} + \beta_3^{i2} . x_{ij3} + \beta_4^{i2} . x_{ij4} + \epsilon_{ij}^2 \\ Y_j^{i3} = \beta_0^{i3} + \beta_1^{i3} . x_{ij1} + \beta_2^{i3} . x_{ij2} + \beta_3^{i3} . x_{ij3} + \beta_4^{i3} . x_{ij4} + \epsilon_{ij}^3 \\ Y_j^{i4} = \beta_0^{i4} + \beta_1^{i4} . x_{ij1} + \beta_2^{i4} . x_{ij2} + \beta_3^{i4} . x_{ij3} + \beta_4^{i4} . x_{ij4} + \epsilon_{ij}^4 \end{cases} \quad (24)$$

where;

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

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

β_K^{iK}: represents the k^{th} (j=1,2,3, .., n) regression coefficient associated with amount of electricity produced by k^{th} (k=1, 2, 3, and 4) major producer sector of the system in i^{th} (i=1, 2, 3, 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 the "AADE" describing the subsystem in spring would be:

$$\begin{bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_4 \end{bmatrix} = \begin{bmatrix} 0.95 & -0.09 & 0 & 0 \\ 0.98 & -0.09 & 0 & 0 \\ 0 & 0.602 & 0 & 0 \\ 0 & 0.24 & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} PC_1 \\ PC_2 \\ PC_3 \\ PC_4 \end{bmatrix} \tag{25}$$

and, "AADE" describing the subsystem in summer;

$$\begin{bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_4 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0.33 & 0 \\ 0.98 & 0 & 0 & 0 \\ 0 & 0.79 & 0 & 0 \\ 0 & 0.56 & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} PC_1 \\ PC_2 \\ PC_3 \\ PC_4 \end{bmatrix} \tag{26}$$

with "AADE" describing the subsystem in autumn;

$$\begin{bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_4 \end{bmatrix} = \begin{bmatrix} 0 & 0 & -0.1016 & 0 \\ 0 & 0 & -0.13 & 0 \\ 0 & 0.81 & 0 & 0 \\ 0 & 0.36 & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} PC_1 \\ PC_2 \\ PC_3 \\ PC_4 \end{bmatrix} \tag{27}$$

and finally, the "AADE" describing the subsystem in winter is:

$$\begin{bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_4 \end{bmatrix} = \begin{bmatrix} 0 & -0.50 & 0 & 0 \\ 0.90 & -0.05 & 0 & 0 \\ 0 & 0.65 & 0.23 & 0 \\ 0 & 0.12 & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} PC_1 \\ PC_2 \\ PC_3 \\ PC_4 \end{bmatrix} \tag{28}$$

As can be seen in (25)–(28), it seems that in spite of obtaining better results from seasonally partitioning (23) into four separate sub- AADEs, 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 portioning (23) 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 cost involved.

VIII. CONCLUSION & DISCUSSION

Throughout the design process, the system designers have to make many types of decisions that starting from understanding the stakeholders' 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 helps the designers to make rational decisions without too much reliance on personal believes or experiences. 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.

The approach proposed in this work, to the contrary of the existing ones, is completely mathematical which serves to accurately model exclusive responsibility of each of PCs for fulfilling the associated FR(s) and to provide systems engineers with a theoretical framework for accomplishing the allocated architecture step as one the most significant steps of the analytical systems engineering process.

Based on the mathematical model of the allocated architecture of an engineering system and analysis of different possible kinds of allocation patterns in which the FRs of the system are mapped into the corresponding PCs, any failure in keeping the key property of "Independency" among FRs is the main source of any poor design.

On the basis of the firm conclusion above, this work can also be regarded as a suitable step toward better understanding of the importance of resolving coupled FRs in the early stages of the system development process as well. 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 the current approach by showing the "Additional Cost" can indirectly help stakeholders to be more cooperative with system designers to adjust their individual FR 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 dependent requirements and are very good areas for further research.

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