

Improving Reliability of Complex Systems Using Analyses Obtained Through Design Structure Matrix and Interactive Failure Detection Procedures

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Abstract

The process of development and expansion of advanced industries reveals the need to implement more and more predictive methods and mechanisms in readiness to deal with possible failures. With complexities inherent in systems, having a proper and all-embracing model of the entirety of a system is not readily possible. Design structure matrices (DSMs) are regarded as great (a great) help in communicating, comparing, and integrating partial system models. Given that there are numerous relationships among subsystems in complex systems, it is expected that interactive failures occur giving rise to diverse problems as well as gradual or abrupt failures in the system. Correlational dependent (Correlational-dependent) failures, commonly known as interactive failures, most frequently occur in mechanical systems. In this study, we have exploited DSM for identifying interactive failures and the relationships existing among different components in complex systems. The latter matrix is generally used in industries for observing the strengths of existing relationships among interacting elements. From another perspective, by analyzing the relationships among elements and identifying coils and curls, it is possible to investigate the existing nodes in loops. Implementing this procedure leads to identifying critical components and interactive failures, eventually bringing about enhanced reliability in the system. The present paper, while considering prevailing methods adopted in previous studies for selecting critical parts and subsystems, proposes a new method for selecting critical parts so as (delete so as) to increase the reliability rates. The method set forth is derived from the Markov chain model in addition to employing mathematical methods in matrices.

Keywords: Complex systems; DSM; Interactive failure; Reliability

Introduction

The process of development and spread of advanced technologies, along with (an) immense mass of industrial products in the present era, makes it obvious that industries more than ever need to implement predictive mechanisms in confronting the occurrences of probable failures in their manufacturing systems. This necessity is more evident in the case of manufacturing industries like aviation companies whose (where) true value of their (delete their) manufactured products comprises an enormous volume of their potential assets. Modern engineering products from individual component (delete component) parts to large scale (large-scale) systems - have to be designed and produced in a way

that during the time that they accomplish their mission- they (delete they) exhibit the requisite reliability standards. In any industry, when a system breaks down or runs into problem, this can have hazardous and deleterious impacts including economic, humanistic, political ones and so on [1]. The complexities inherent in systems makes (make) it impossible for a single individual to have a proper, detailed and comprehensive mental model of the entirety of the system. Design Structural Matrix (DSM) is a great help to individuals in understanding relationships, comparisons and integrating their partial model of the system. As a matter of fact, two main advantages of a DSM lies in its capability of demonstrating a summary of quite a large number of elements and their relations as well as highlighting significant sets of elements and interactional patterns like those

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influencing modularity. DSM produces a product architecture through clustering analysis of alternative groups of existing elements in modules; improves awareness of architecture as well as facilitating innovation in architecture, which point (??) can be subject to further investigation [2]. In this context, the design structure matrix (DSM) has been widely employed in academia and various industries for improving the decomposition process of system architectures, organizational architectures, and process architectures. For system architectures, DSM is used to model system elements and their connected relationship in a compact matrix format, enabling such system-level analyses as modularization or system complexity allocation. To perform such analyses with DSM, various clustering algorithms have been developed over the years [3]. Given the latter documents and activity sheets, developing a process DSM model typically requires a manual approach in addition to extra interviews for gathering various dependencies [4]. However, a survey of prior research studies reveals that (the) majority of published DSM-based analyses and case studies have not incorporated design constraints into their algorithms' system modularization. This gap can be addressed by introducing a (delete a) new DSM-based exponentiation method constraints (constraint). By filling the research gap, DSM-based exponentiation analyses can gain more traction (traction or attraction?) in the systems engineering community as one of the key analysis features during the design stage of system architecture. In a variety of industries, the reliability optimization problem can be addressed taking into account the product as a system comprising a number of (consisting of several) subsystems. This problem is stated using system structure and limitations as well as the characteristics and arrangement of subsystems and components. In fact, (remove in fact) reliability improvement refers to the enhancement of reliability in such a way that the functions required by the system are ensured of reliable outcomes [5]. In such problems, the objective is to maximize reliability in the face of cost, weight, and volume limitations. Reliability allocation has an essential relation to the reliability design serving as an important ingredient in the process of product design and development. Hence, it is imperative to evaluate the system behaviour (behavior), function, and parameters by resorting to failure effects and data, subsystem dependencies, and the degree of reliability improvement. In fact, in order (remove in order) to determine subsystem's reliability based on target reliability, attention must be paid to upgrading opportunities and priorities based on the real potential of reliability improvement [6].

In a great number of models on estimating systems reliability, the assumption is that the system ingredients work "independent" of one another. However, owing to complexities in a system, the latter assumption is repudiated as component elements are interdependent in such a way that as a result of this dependency, a failure in one part of a system can affect the proper functioning of the whole system. And so, one type of failure is dependent failure. In fact (remove in fact), failures in (the) system mostly occur

concurrently. Bi-directional dependent failures (are) commonly known as interactional failures mostly cause breakdowns in mechanical systems [7]. The current paper utilizes DSM to present a novel method in system exponentiation. The proposed approach exploits a new DSM-based exponentiation method for modularizing the system architecture incorporating failures and relationship constraints while implementing DSM. Few attempts have been made in previous studies to view the problem from this angle. The authors adopt the procedure to improve (the) real life (real-life) reliability of phased array radar as a case, which can be considered a verification of the proposed method. The least effort method has also been exploited to increase reliability.

The present paper while considering common methods adopted in prior studies for selecting critical parts and subsystems, proposes a new method for selecting critical parts so as (remove so as) to increase reliability. The method set forth is derived from Markov chain model in addition to employing mathematical procedures in matrices.

Methodology

DSM is employed to identify interactional failures and relationships existing among ingredients of a complex system. Investigation of the relationships among subsystems and their significance links the failure analysis process and reliability improvement feasibility to the product design and development process [8]. In fact (remove in fact), the usual procedure adopted for computing reliability is obtained through Design Structure Matrices (DSMs) and by finding total sums of rows and columns. Although certain DSM analytic procedures have been developed, most product matrices being updated and analyzed have their focus on clustering ingredients so as (remove so as) to determine the modular architectures [9].

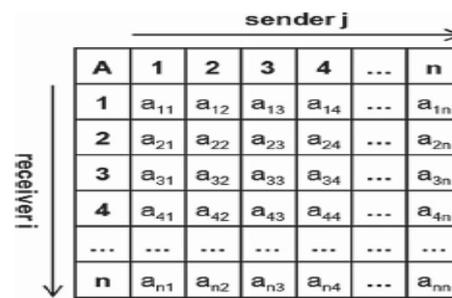


Figure 1. Design structure matrix (DSM)

$$a_{ij} \in \{1, 0\}$$

$$a_{ij} = 0 = \{a_{11} = a_{22} = \dots a_{mm}\}$$

$$a_{ij} = \begin{cases} 1 & \text{There is a relation between } i \text{ and } j \\ 0 & \text{There is a (remove a) no relation between } i \text{ and } j \end{cases}$$

In the present research- unlike the traditional approach i.e., identifying internal relationships through finding (the) total sum product of rows and columns- the course of action we have (delete we have) adopted is to utilize existing relationships in a DSM and provide (providing) an (remove an) architecture for the product. In point (delete in point) As a matter of fact, through exponentiation of the DSM and by considering the component (remove component) parts; the existing components in a complex system, length of component loops, the number and status of loops in existing elements in the matrix diameter are determined. At this point, relationships in the aforementioned components in non-diametric elements in the matrix are revealed. In this way, an improved design is obtained with the following characteristics: enhanced reliability, reduction in both repair and maintenance and production costs. Figure 1 exhibits (the) Design Structure Matrix (DSM). The matrix includes n number of rows and n number of columns. In case of the existence of a relation between ingredients of a row and a column, we place 1 and in case there is no relationship, we place 0 in the Matrix Cell (use passive voice instead of active).

	A	B	C	D	F
A	0	1	0	1	1
B	1	0	1	1	1
C	1	0	0	1	0
D	1	0	0	0	1
F	1	1	1	1	0

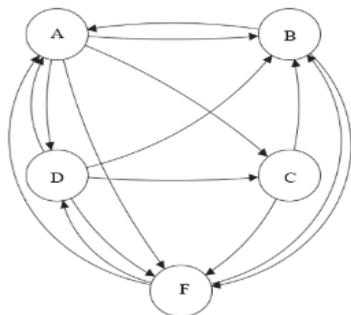


Figure 2. Sample design structure matrix (DSM)

Through exponentiation of the matrix based on the formula $N - 1$ (number of direct relationships of each element with other elements) displayed in Figure 3, the relationship of each element is investigable. As given below, element C in the matrix diameter is present at 6 loops, and the path length of each loop is 4; as well, element B to D indicates the number 11, which can be construed as the relationship degree of the latter two

elements. That is, B to D can be related through 11 paths. It is worthy of note that in each stage of exponentiation, given the degree and magnitude of the relationship number of each element in the matrix, critical elements can be recognized, which in turn, lead to the identification of influential ingredients in interactional failure and the eventual outcome of augmented reliability. Figure 2 furnishes a simple example of relationships in a hypothetical system. The relationships in this system are indicated in graphs and matrices. The hypothetical system is exhibited to substantiate the assumptions and the matrix methods and the Markov chain stochastic model employed.

	A	B	C	D	E	
A	0	1	0	1	1	$\begin{bmatrix} 22 & 13 & 11 & 21 & 20 \\ 25 & 16 & 13 & 25 & 21 \\ 13 & 7 & 6 & 13 & 11 \\ 15 & 11 & 7 & 16 & 13 \\ 25 & 15 & 13 & 25 & 22 \end{bmatrix}$
B	1	0	1	1	1	
C	1	0	0	1	0	
D	1	0	0	0	1	
E	1	1	1	1	0	
	N=1					N=4

Figure 3. Matrix to the Power of N-1

Case study

In today's world, phased array radars have wide ranging (wide-ranging) applications in all domains: ground, air, and space. In the present research, the object of our study is ground- based (remove the additional space) air defence (defense) radars which are capable of performing more tasks compared with those of conventional radars. An enormous number of elements are used in this type of radars. This number can vary between 700 and 40,000 elements. The temperature for the operation regions of this type of radars is among (the) significant issues discussed. This temperature, based on the military standard, mil - standard - 810, is determined between -70 and +70 degrees Celsius. This should be considered under different conditions and in view of (because of) different subsystems under load.

This article starts off (remove off) by elaborating on research ideas presented by Agrawal et al [10] and Abjadiyan et al [11]. They have used common reliability methods for enhancing the design of phased array radars. In their research, Agrawal et al have selected subsystems (transmitters and receivers) containing higher frequencies in phased array radar as critical subsystems. Then, through employing common reliability methods and system clustering, they have embarked on improving those systems. However, in the technique we have developed in the present research, first, we identify critical subsystems and then embark on improving them. By emphasizing the different nature of the reliability of

phased array radars, Abjadian et al have tried to expand on reliability methods.

Identifying critical subsystems

In this research, we have chosen (use passive voice) the relationships among some general subsystems of a phased array radar so as (remove so as) to observe the results and the application of the technique. The subsystems include antenna array, TRM and phase shifters, servo, control and process section (processor card), and power section. This is illustrated in Figure4 (where is figure 4?).

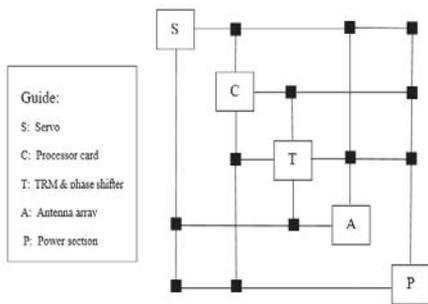


Figure 4. Subsystems of phased array radar

$\begin{bmatrix} 0 & 1 & 0 & 1 & 1 \\ 0 & 0 & 1 & 0 & 1 \\ 0 & 1 & 0 & 1 & 1 \\ 1 & 0 & 1 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 \end{bmatrix}$ <p>N=1</p>	$\begin{bmatrix} 2 & 1 & 2 & 0 & 1 \\ 1 & 2 & 0 & 1 & 1 \\ 2 & 1 & 2 & 0 & 1 \\ 0 & 2 & 0 & 2 & 2 \\ 0 & 1 & 1 & 1 & 2 \end{bmatrix}$ <p>N=2</p>
$\begin{bmatrix} 1 & 5 & 1 & 4 & 5 \\ 2 & 2 & 3 & 1 & 3 \\ 1 & 5 & 1 & 4 & 5 \\ 4 & 2 & 4 & 0 & 2 \\ 3 & 3 & 2 & 1 & 2 \end{bmatrix}$ <p>N=3</p>	$\begin{bmatrix} 9 & 7 & 9 & 2 & 7 \\ 4 & 8 & 3 & 5 & 7 \\ 9 & 7 & 9 & 2 & 7 \\ 2 & 10 & 2 & 8 & 10 \\ 3 & 7 & 4 & 5 & 8 \end{bmatrix}$ <p>N=4</p>

	Servo	Processor card	TRM & phase shifter	Antenna array	Power section
Servo	0	1	0	1	1
Processor card	0	0	1	0	1
TRM & phase shifter	0	1	0	1	1
Antenna array	1	0	1	0	0
Power section	1	1	0	0	0

Figure 5. Matrix to the power of N - 1

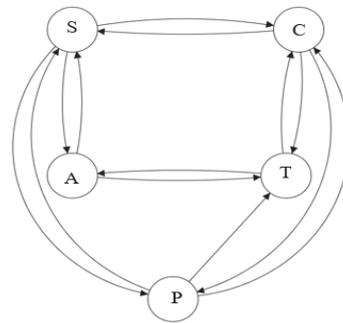


Figure 6. Graph related to relationships phased array radar subsystems

By virtue of (use under instead of by virtue of) the explained matrix and observations made of subsystems of phased array radar in DSM (design structure matrix), having plotted the product basis matrix, we raised the matrix to the

power of N-1 such that by considering the existing relationships and interactional failure, we can commence ameliorating reliability with the help of available methods (the paragraph should be revised).

Considering the graph plotted from existing relationships of phased array radar and N-1power (insert space between N-1 and power) raised matrices, it is possible to obtain the degree of relationship of each subsystem in loops with specified lengths. Of course, it should be noted that the relationship degree of each element with other elements is observable given non -diatomic numbers in the matrix. This is explained in the (remove the) Table 1 given below. By referring to Table 1, it can be seen that by way of (through) matrix exponentiation, it is possible to discern relationship degrees of a subsystem, available loops in a system, and the length of loops in each subsystem.

By the term loop, we mean (use passive voice) rounding in a graph which (that) connects a particular subsystem to itself. In fact, (remove in fact), loops are those same frequent relationships and iterations derived from the concept of rounding in matrices (matrix) rules. For instance, given the phased array radar in Figure5, it can be observed that the servo module is placed at two loops with a length of 2, at one loop with a length of 1, and at nine loops with a length of 4; and the total loops in which the latter subsystem is available is 12. Any subsystem located within (a) higher number of loops is considered (a) critical subsystem. And considering the frequency of this subsystem’s interactions, it might tamper with the product’s failure or breakdown time. Interactional failures are dependent upon the relationship degrees and the presence of subsystems in existing loops.

By consulting Table1 (insert space between table and 1), it is evident that except for antenna array, other subsystems- considering their relationship degrees- are placed in critical conditions which need improvement. In this technique, by means of (using) matrix exponentiation of the Design Structure and taking into account interactional failures, critical modules are easily identified.

Looking at Table 1, it is observed that except for the antenna array, other subsystems considering their relationship degrees are situated in critical conditions; and so these subsystems are in need of (require) improvement. In this technique, through power-raising the DSM and taking interactional failures into account, the critical modules are recognized.

Table 1. Analysis of available numbers in the matrix main diameter

Subsystem	N=1	N=2	N=3	N=4	Total
Servo	0	2	2	9	12
Processor card	0	2	2	8	12
TRM & phase shifter	0	2	2	9	12
Antenna array	0	2	2	8	10
Power section	0	2	2	9	12

Reliability allocation and improving critical subsystems

Here, given the existing information for allocating reliability and improving each of the subsystems, the least effort algorithm is exploited. Albert (reference), the innovator of the least effort method, solved the problem of series systems with the help of an effort function such that for all ingredients, the computation works the same. The least effort method is utilized when the reliability values for each of the ingredients are given, and also at a time when having the reliability of each ingredient, the target reliability is not obtainable. Hence, there is a need to upgrade the ingredients' reliability. The least effort method states that in order (remove in order) to raise the system's reliability to a desired (the desired) level, first, we should increase the reliability of those ingredients having lower reliability rates. Two reasons have been proposed for the rationale behind the method. The first reason concerns the fact that improving the reliability to a specified degree ΔR for lower values is far simpler than effecting improvement, at the same dimension, for higher values. The second reason offered pertains to the series nature of the system and since the reliability of these systems is in fact (remove in fact) obtained by multiplying each of the ingredients, the improvement effects of ingredients with lower amount reliabilities ΔR are much higher than those ingredients having higher amounts of reliabilities with the same mansion [12]. In this paper according to (the) least effort algorithm manner, first, the estimated reliabilities are to be ranked in ascending order and the critical the least amount reliabilities in weak ingredients to an R value (revision required).

$$R_i^* = \left(\frac{R^*}{\prod_{j=k+1}^{n+1} R_j} \right)^{\frac{1}{k}}$$

Where R_i^* stands (insert space) for the target reliability of each ingredient, R^* shows the target reliability, R_i denotes the reliability of each ingredient, and k representing

(represents) the number of ingredients whose reliabilities should be increased.

Results and discussions

Given the available information and according to reliability methods employed based on military standard mil_std_810, and a duration of 5000 hours of useful work by phased array radar and calculating the failure rates for each of its critical ingredients, the reliabilities related to each critical subsystem of the product are obtained. These are exhibited in Table 2 below. In this technique, the only objective is to improve the critical ingredients. The system's critical ingredients comprise the servo, processor card, power section, and the TRM and phase shifter.

Table 2. Reliabilities of critical subsystems for a duration of 5000 hours of work

Critical Subsystem	Reliability
Servo	0.94
Processor card	0.95
TRM & phase shifter	0.97
Power section	0.95

The phased array radar reliability is less than the target reliability. In fact(insert comma here) the possibility of collapse prior to (before) the determined time span is not rejected. Using Relation, the reliabilities of each of the critical ingredients have to be increased to the determined level in a way that there is no disruption in the functioning of the product in question. As a first step, for a subsystem having (the) lowest amount of reliability, a new reliability level is defined. In case the new reliability is higher than the initial reliability, the reliability for the next subsystem is calculated. In order (remove in order) to reach the target reliability, the procedure continues until the calculated reliability becomes less than the initial reliability R_j . In such a case, there is no need to increase the reliability. It is possible, however, to raise the target reliability r_j^* to $\frac{1}{k}$ power and arrive at the intended target.

Table 3. Allocated reliabilities to critical subsystems for a duration of 5000 hours of work

Critical subsystems	Degree of improvement	Initial reliability	Target reliability
Servo	0.0549	0.94	0.9949
Processor card	0.0449	0.95	0.9949
TRM & phase shifter	0.0249	0.97	0.9949
Power section	0.0449	0.95	0.9949

As per calculations performed, there is a need to increase the reliabilities related to each critical ingredient, as a result of which, improvement is attained and the target

reliability of 0.98 is realized. The allocated reliabilities are demonstrated in Table 3. Figure 7 shows the comparisons made of the target reliability, initial reliability, and the degree of improvement.

Figure 7 shows (the) initial reliability of phased array radar computed and obtained according to mil-std-810. Based on (the) algorithm's calculations, (the) least amount of effort is needed to increase the whole system to a rate of 0.9949 so as (remove so as) to acquire a reliability enhancement defined as target reliability. The differential value of the initial reliability and the target reliability is defined as the improvement rate to be achieved through employing existing strategies and method (methods). This is indicated in orange color in Figure 7.

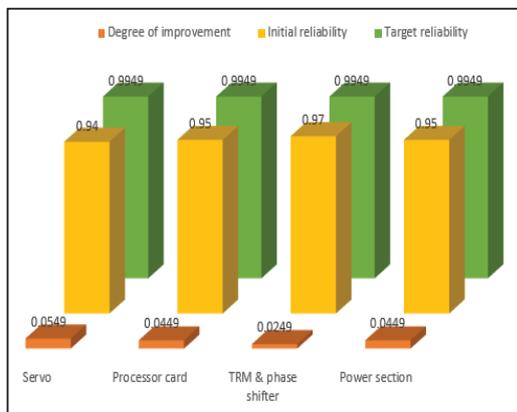


Figure 7. Comparison of allocated reliabilities to critical subsystems for a duration of 5000 hours of (of) work

Conclusion

Modern products, ranging from individual component (remove component) parts to immense systems, have to be designed and manufactured in (a) way that in time of (the) mission, they possess the requisite reliability. In any industry, when a system collapses, the problem becomes significantly hazardous and damaging from diverse points of views (view)-- economic, humanistic, social, political, etc. Reliability is regarded as one of the most important qualitative characteristics of immensely complex components, products, and systems [13]. Disregarding the dependencies that exist among ingredients is not a proper course of action to follow. Indeed, in a great number of research works conducted on reliability, the assumption is that the failures in the building block ingredients of a system are statistically independent of one another and equally distributed. The latter assumption enables direct applications of mathematical methods from classical probability theory. This supposition, however, disregards the observed phenomena from common cause failures where two or more building ingredients collapse at the same time [14]. Design structure matrices (DSMs) are exploited in complex systems for observing the strength of the relationships that exist among formative ingredients. In this research, we

investigated existing nodes in loops by analysing (analyzing) the relationships existing among elements and (the) recognition of loops. Adopting this procedure leads the way toward identifying critical parts or components alongside interactional failures, the result of which can be improvements effected (affected) in reliabilities. In the present research, in order (remove in order) to substantiate the correct functioning of our method, we explored (passive voice) the interactional relationships in a phased array radar whereupon through identifying critical ingredients and via the proposed technique, we (passive voice) embarked on improving the reliabilities of the latter ingredients by invoking the least effort method.

It should be reminded that the researchers of the present paper--based on previous studies-- have come to the conclusion (concluded) that in order to achieve a durable and long-life product, it is imperative to boost the entire system's reliability. In complex systems, considering time and cost, this objective is accomplished through improving critical subsystems. Referring to recent studies reveals that identifying critical parts is not seriously considered. In this regard, in the research works referred to above, mostly the subsystems having higher frequencies in the system -or in terms of industry, susceptible to hazards- are considered critical subsystems. This article claims that, (remove comma) with the help of a proposed method- developed based on DSM- one can identify critical subsystem (subsystems) both in simple and sophisticated systems.

As a final word, it is suggested that in case there is a need to prioritize critical subsystems and select (the) most critical part from among a set of critical parts or subsystems, the proposed method be expanded through combined mathematical techniques.

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