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Total failure of a system due to time-dependent complexity- an identification framework

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Abstract

Axiomatic Design theory claims for using universal principles that allow classifying a design and choose the best one. Moreover, it helps to anticipate problems in the performance of a system. This design theory develops the design in four design domains and has two axioms: the independence axiom, and the information axiom. The probability of fulfilling the set of functional requirements allows determining the information content of the design, a measure of the complexity of a system. Complexity may change over time, called time-dependent complexity. Time-dependent complexity can be reduced using functional periodicity, a way to periodically reset the system ensuring the functionality of the system at the former design levels. System maintenance provides periodical functionality allowing to reduce the complexity of the system. However, interferences between parts or systems are often not taken into account in the design, making possible the complexity to increase until a total failure of the system. The authors propose to use the Design Structure Matrix, to help to define the changes in the physical domain over time. Thus, computing the distributions of the functional requirements in a fuzzy environment allows calculating the probability of success of a system along the time. It was found possible to compute the time-dependent complexity using ranges of lifetime of compounds and to identify the probable failure of a system by the pick increase of information at a certain time.

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Keywords: Axiomatic design; time-dependent complexity; DSM; FMEA.

1. Introduction

Axiomatic Design (AD), published by Nam P. Suh on 1990, is a theory that aims to help to do good designs, [1]. AD synthesises data into a design, by mapping from the customer domain to the functional domain, and from the functional domain into the physical domain. Design is the mapping between the Functional Requirements (FRs) of the functional domain and the Design Parameters (DPs) of the physical domain. Starting on the FRs of higher level, the design team choose the DPs that fulfil the FRs at the same level, in a process called zig. Thus, using the chosen DPs the process evolutes to the next level, by defining children FRs that fulfil at the same time the father DP as well as the father FR, making a zag. This zigzag process makes the decomposition from the high level requirements to the DPs at the lower level, which are artefacts easy to acquire.

The zig is the final representation of many trial and errors at a certainly level of decomposition, involving synthesis and backward analytic processes.

The design equation (DE) formulates the ultimate relationships between the FRs and the DPs, expressed by the following equation, [A] being the design matrix (DM).

$$\{FR\} = [A] \cdot \{DP\} \tag{1}$$

According to the shape of [A] the design is classified as uncoupled, decoupled or coupled design. An uncoupled design is the best design, as each DP affects just a FR, and therefore

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the DM is a diagonal. The DM of a decoupled design is a triangular matrix making the FRs to be adjusted in a certain order to ensure independency. If the DM has non-zeros on both sides of the diagonal and cannot be reduced to a triangular matrix, then the design is a coupled design.

AD defines complexity as the measure of the probability of achieving the FRs, therefore computed on the functional domain [2]. Figure 1 expresses the probability of fulfilling a FR, calculated using the intersection area (*IA*) between the system probability density function (pdf) and the design range.

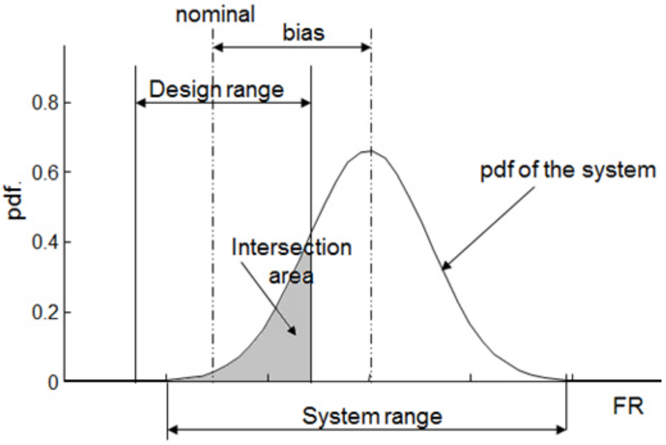


Fig. 1 – System pdf and the design range

The information content in bits of a FR with the probability of success *p* is defined by Equation 2 so that, if the probability is equal to unity, then the information content is nil.

$$I = \log_2\left(\frac{1}{IA}\right) = -\log_2(p) \tag{2}$$

If the design is an uncoupled design, the probability of achieving each FR is independent from the other FRs, and the probability of success is the product of all probabilities of achieving each FR. If the design is a decoupled design, the tuning of the FRs needs to follow a certain sequence. The DM of a decoupled design is triangular what makes the design to define first the DP that affects more FRs. Suppose the DM is a lower triangular matrix according to the following equation:

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{Bmatrix} = \begin{bmatrix} X & & \\ X & X & \\ X & & X \end{bmatrix} \cdot \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{Bmatrix} \tag{3}$$

Setting DP_1 fulfils FR_1 and affects all FRs. The choice of DP_2 needs to fulfil FR_2 subjected to the condition that DP_1 already influences FR_1. Therefore the probability of fulfilling FR_2 and FR_3 is a Bayesian probability, and the probability of success of the design is calculated according to Equation 4:

$$P = P(FR_1) \cdot P(FR_2 | DP_1) \cdot P(FR_3 | DP_1) \tag{4}$$

AD defines complexity as real and imaginary. If a design team is unable to identify the design as a decoupled design, may start to tune the DPs on a wrong sequence, repeating the tunning unnecessarily. This type of complexity is the so-called imaginary complexity. If the range of tolerances of the DPs creates a fdp of the FRs that are out of the range of acceptance, then the system has real complexity, and there is a probability that the system works out of the design range of the FRs. Both complexities, real and imaginary, can decrease the productivity in an industry [3].

Moreover, the tolerances of the DPs may change over time causing a shift on the fdp of the FRs out of the design range. It reduces the probability of success of the system or, in other words, the information increase along the time. For this reason, systems might be re-initialized. In industry, it is necessary to understand the complexity of the system to choose the correct moment to re-initialize it [4]. This paper aims to present a way to compute the time-dependent complexity (TDC).

TDC can arise if the range of acceptance of the FRs change, but we will focus our attention on the shift of the pdf of a system over time. The system fails when the information reaches a certain level.

Failure in this context may not necessarily mean a rupture, but a working mode out of the defined ranges. A beam fails if the deflection on the centre exceeds a visual safety values; a bearing ball fails when it produces vibration at certain frequencies; an air-conditioning system fails when it is unable to provide the necessary heat or cool to maintain the indoor conditions on a certain temperature range.

Many compounds have known pdf, and it is possible to define the probability of failure of a system knowing the pdf of each compound. However, this approach may lack the interferences that the DPs may cause between each other, and may not be suitable for new designs.

The Design Structure Matrix (DSM) [5] is a design instrument that defines the flow of influences between DPs. The flow from a DP to another DP can be data, relationship at the interfaces, or process flow between DPs. DSM is very helpful to define groups of DPs that has coupling relations and integrate them as set. However, to apply DSM, there is a need to understand the working modes of the system deeply.

From the DM of the AD, it is possible to deduce the matrix of a DSM in what regards to the flow of information between parts [6].

The identification of failure modes allows to define the reliability of a system. It also helps to analyse a proposed design solution, therefore being an instrument of analysis on a zig. This idea is in accordance to the need of specify-ideate-validate a design [7]. If the result is unsuitable, the designer needs to seek for other DPs at the same level of decomposition to perform the FRs.

Failure Method and Evaluation Analysis (FMEA) [8] is the common industrial method to study the failure of a system. Design FMEA aims to eliminate the risk of a design, a process or a service. However, once more, the design team needs to have a strong understanding of the design. FMEA identifies the function concerning the failure of a part, which according to the AD is only possible on uncoupled designs.

AD and FMEA has already been used to improve reliability [9], but it lacks a structured way to provide the correct questions and evaluate the information content of the design.

This paper aims to present a framework able to identify failure modes using DSM and AD and to quantify the probability of success of a time-dependent system. This approach has a dual contribution: to structure the reliability of a system making use of the DM; and to analysis a proposed design in a zig to declare the design acceptable or non-acceptable upon the second theorem of AD.

Next section describes the motivation of this paper and some past examples of systems that failed. Thus, section three defines the structure of the proposed framework, section four an example and section five the discussion and conclusions.

2. Motivation

Now-a-days many systems fail despite the development of theories of design, use of methodologies for the design of some types of systems, and use of failure evaluations. In many cases, the contact between nearby parts are the cause of failure. Following paragraphs show some examples.

On 1994 US flight 427 Boing 737 crashed with no survivals, due to a mechanical problem in the rudder. Further, on 1996, a similar Boeing flight 517 was able to survive because it was flying at a higher speed. Further investigation allowed to identify that the servo system of the rudder locked when the hot fluid entered in contact with the cold metal of the servo.

A coastguard ship stopped suddenly on the sea due to a motor failure. The crew was unable to put the motor running. After a long inspection, they found that the tube that supplies fuel to the Diesel motor was galvanic eroded by the metal of the sewage tank. Gray water entered the motor and turned the ship ungoverned.

A water-water chiller provides chilled water to remove the moisture from a swimming-pool in a cooling coil. The heat released from the machine helps reheating the air as well as to heat the water of the pool. With time, the fins of the cooling coil rusted, the average cooling coil temperature increased and the ability of the system to remove moist decreased. Therefore, the system stays on cooling mode more time to condense the moist, making it to release more heat in the swimming pool. The system failed because the water of the swimming-pool turned too hot to avoid the growth of microorganisms.

The readers may found many more examples from their experience that caused a failure because a part, a DP, interacts with other DPs. On coupled designs, as in the swimming-pool example, the fail of a DP may cause a total failure as many FRs depend on that DP. On other examples, a failure of a DP makes another DP to fail shifting the pdf of their FRs apart from the design range

3. Model

Equation 5 shows the model used in this paper.

$$\begin{Bmatrix} FR_1 \\ FR_2 \end{Bmatrix} = \begin{bmatrix} X & \\ x & X \end{bmatrix} \cdot \begin{Bmatrix} DP_1 \\ DP_2 \end{Bmatrix} \leftarrow \begin{array}{c} DP_1 \\ DP_2 \end{array} \begin{bmatrix} X & X \\ & X \end{bmatrix} \qquad (5)$$

The right side of the equation shows the DSM matrix in a failure situation. This matrix is not necessarily equal to the common DSM matrix. It tells that DP_2 has a strong interference on DP_1 case it fails. The left arrow shows that the failure will affect the behavior of the system, expressed by the design equation of AD. The design equation shows a decoupled design saying that DP_1 fulfills FR_1 and affects the FR_2. Therefore, DP_1 is first tuned, and then the tune of DP_2 fulfills FR_2. According to Equation 5, the failure described was not expected in the context of AD.

The cumulative distribution of failure (CDF) of a DP increases with time t. The Weibull CFD with two parameters gives a good estimation of the probability of a compound to fail at time less or equal t, after a successful start-up. Equation 6 shows the CDF of a Weibull function, α being the Weibull modulus and λ is the time constant.

$$F(t) = 1 - \exp(-\left(\frac{t}{\lambda}\right)^{\alpha}) \qquad (6)$$

In new designs, or when using new DPs in an existing design, the failure model is hard to define. However, in many situations, it is possible to estimate a range of failure for each DP. Moreover referring to Equation 5, a group of experts can define the time bounds of failure for DP_1 if DP_2 fails. With the time bounds of failure, it is possible to generate hundreds of random failure data between the bounds, and with this data define the estimators for the parameters of the Weibull CDF. Furthermore, it is meaningful to define ranges of variation for the parameters' estimators.

At this step, the model needs to evaluate the FRs. In what regards to failure, this model addresses the failure evaluation rather than the fulfilment evaluation of the FRs. Taking into consideration the DE, it is possible to evaluate failure using a simplified model of FMEA that considers on a fuzzy environment the severity of failure (SF), the detection and fixing time (DFT) and the probability of occurrence (PO), the latest given by the Weibull CDF. If L is the universe of discourse of failure with $l \in L$, then at each time t the believe on any proposition P standing for SF, DFT or PO is:

$$B_t(P) = \mu_P(l) \qquad (7)$$

In this approach the membership functions are triangles *T[a,m,c]* where a is the left value with nil membership, m is the peak center with grade one, and c is the right upper value with zero membership as well. The loss membership function LO is the product of each membership functions at the alpha cuts from 0 to 1. The information at time t is computed by Equation 8, where *Loss_ Area* is the area under the membership function LO, and an intersection area *IA* is the common area of the LO with the design range.

$$I_t = \log_2\left(\frac{Loss\ Area_t}{IA_t}\right) \qquad (8)$$

4. Example of application

During a zig between the FRs and the DPs, different DPs can apply. In this example, we discuss the choice between two types of check valves to use in a chiller: a clap check valve or a ball check valve.

A chiller is a thermodynamic equipment to cool water that works according to the reverse Rankine cycle. Therefore, it has a refrigeration circuit consisting of a compressor, a condenser, the expansion valve, and an evaporator, as main compounds. Moreover, the chiller has a security system and a control system, the latest not under address in this example. Regarding the security system, this paper will focus on the set valve of the liquid line plus check valve of the compression line. The former one shuts when the compressor stops, to avoid migration of liquid to the evaporator, and is a normally closed valve. The check valve is a mechanical device that allows the gas to go from the compressor to the condenser but shuts on the reverse direction. The common solution regarding check valves is to use a clap check valve. However, a manufacture decided to use a ball check valve due to the better retention of the refrigeration gas.

Some failures started to happen on the series of chillers that use ball check valves. The chillers lost the gas and stopped by low pressure. Thus, it was find a leak on a damage tee of the condenser collector. Damage was supposed to be due to an oil hammer stroke coming from the compressor. Finally, it was found that the steel ball of the check valve released from the valve seat and goes against the tee along with the refrigeration flow.

The question is: could it be possible to predict this result at the design phase, instead of reviewing the design after a crash?

At the first level of decomposition of the design of a chiller the function requirements are:

FR_1- Provide cooling;

FR_2- Avoid migration of refrigerant at stopping periods.

And the DPs:

DP_1- Refrigeration circuit;

DP_2- Stop valves.

The left hand side of Equation 5 shows the design equation of the chiller system. It says that the stop valves depend slightly on the arrangement of the refrigeration circuit. For DP_2 there are two possible designs: a solenoid valve plus a clap check valve (Sol.V+Clap Check V), or a solenoid valve and a ball check valve (Sol V+ Ball Check V).

Regarding the lifetime of solutions, the lower and upper bounds depend on the number of start-and-stops of the compressors and the conditions of the installation. Table 1 shows the opinion of experts about this subject.

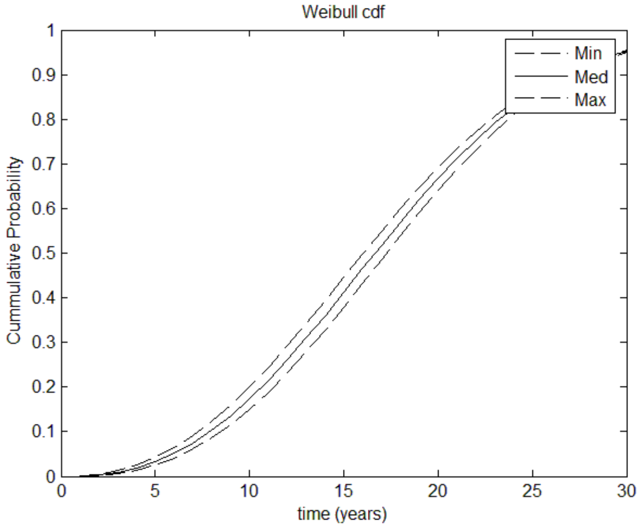
Table 1 – Lower and upper bounds of lifetime of DPs

Lifetime of DPs	Lower bound (years)	Upper bound (years)
DP_1:Ref_Circ.	4.1	30
DP_2:Sol.V+Clap Check V	2	30
DP_2:Sol V+ Ball Check V	1	5

The lower and upper bounds allow to define the Weibull CDF. Therefore, at each time t, the cumulative probability of failure is given by the limits defined by the variation of the Weibull parameters, α, and λ. According to a previous study [10], it was found suitable to use a variation of these parameters equal to the standard variation of their estimator distribution.

Figure 2 shows the CDF of failure for DP_2 the refrigeration circuit. At time t the left and right values for the triangle function of the PO are represented in dashed lines and the center value m by a solid line. Therefore, at each time t, it is possible to define the PO triangular function $PO_t[a,m,c]$ over time.

Fig. 2 – Weibull CDF for the Ref_Circ component



The SF and the DFT do not depend on time, what makes the time dependent complexity to depend only on the PO.

Table 2 shows the a, m and c values of the triangular functions for SF and for DFT, which are in accordance to the study mentioned above.

The SF uses a scale from 1 to 10, where 1 means no historical failures and 10 an almost certain failure. The estimation of DFT depends on the expected number of days to fix the problem, supposing all parts are available in stock.

Table 2 – Values for the triangular functions DF and DFT

	SF			DFT		
	a	m	c	a	m	c
DP_1:Ref_Circ.	2.9	4.2	5.1	2	3.6	4.2
DP_2:Sol.V+Clap Check V	1	2	4	0	1	2
DP_2: Sol V+ Ball Check V	6	7	8	3	5	6

The loss function LO is the fuzzy product of the SF and DFT, to the PO at each time t, as per Figure 2, multiplied by 100.

Figure 3 shows the triangular functions of loss for each compound after five years of working, as well as the design range. The design range is a fuzzy trapezoidal function represented in the figure by a solid line.

At this stage, we need to know if a failure on a DP may cause a failure on other DPs. DP_1 does not cause any damage on DP_2, and it is not probable that the DP_2:Sol.V+Clap Check V may cause a direct damage on the refrigeration circuit. The DSM matrix for this design is a diagonal, saying that the DPs do not interact case each one fails. On the contrary, DP_2:Sol V+ Ball Check V can damage the refrigeration circuit, case the ball releases. Therefore the DSM matrix is an upper triangular matrix, the same shape presented at the right side of equation 5. So, the failure of DP_2 makes DP_1 to fail and therefore affects both FRs of the design equation 5. The information content of the design turns to infinite when DP_2 fails.

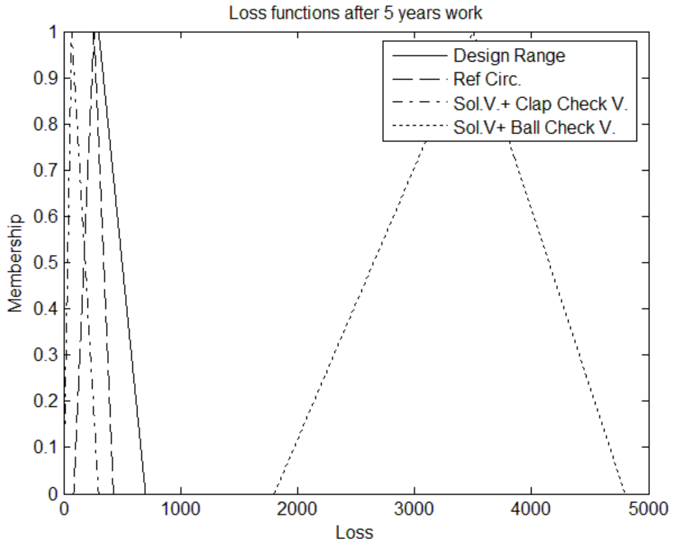


Fig. 3 – Loss functions of parts after five years of work

The information content of the design using DP_2: Sol.V+Clap Check V is the sum of the information of FR_1 and the information of FR_2, according to Equation 2 and 4.

Figure 4 depicts the results of the information content of both possible solutions. The graphic of the first design uses a solid line referenced by Ch SV; the second design uses a dashed line mentioned as Ch BCV. Infinite is plotted as 99 bits.

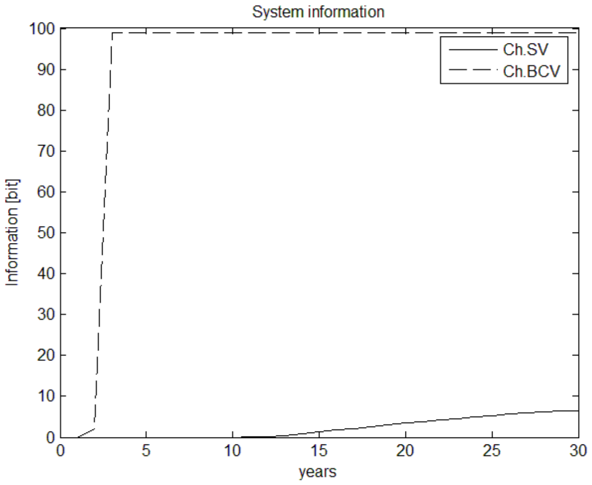


Fig. 4 – The information of the two systems

The design equations of both solutions are similar showing decoupled designs, but the information content of the second solution is higher after on the second year of working. According to the Axiomatic Design theory, the best solution after the first year is the one with solenoid valve plus clap check valve.

5. Discussion and conclusions

Table 1 shows that DP_2: Sol.V+Clap Check V is a better solution that DP_2:Sol V+ Ball Check V. Therefore, the choice would be fully expected. However, this application gives a number: it advises that the information of one of the solutions picks to infinite by the second year of working.

This case happened in the real industry. Why? Because no one asked the questions: how long the ball valve will last? What failures may it cause? As once Pablo Picasso said "Computers are useless. They just give answers", they do not provide the questions. The model used in this paper is a way to help formalizing the questions.

Moreover, this paper shows one of the first attempts to compute the time dependent-complexity.

This model may help defining the value for the information content where the system needs a restart. As well, it can provide a way to define the maintenance schedules for new designed systems.

The approach presented in this paper applies at the zig phase of AD. The choice of the best solution, among all possible ones, benefits from the evaluation of complexity over time. The main advantage of the method presented in this paper is the shortage of data needed.

To apply this method, the team of designers need to raise the DSM matrix and the AD matrix at each level of decomposition. To perform the computation, it is just necessary to know the ranges of lifetime, and the estimated consequences of a failure. It does not need a long statistic evaluation of data. Therefore, this method has an important application in the design of new systems.

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