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ARTICLE

Genetic Algorithm Optimization Model for Determining the Probability of Failure on Demand of the Safety Instrumented System

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ABSTRACT

A more accurate determination for the Probability of Failure on Demand (PFD) of the Safety Instrumented System (SIS) contributes to more SIS realiability, thereby ensuring more safety and lower cost. IEC 61508 and ISA TR.84.02 provide the PFD detemination formulas. However, these formulas suffer from an uncertaity issue due to the inclusion of uncertainty sources, which, including high redundant systems architectures, cannot be assessed, have perfect proof test assumption, and are neglegted in partial stroke testing (PST) of impact on the system PFD. On the other hand, determining the values of PFD variables to achieve the target risk reduction involves daunting efforts and consumes time. This paper proposes a new approach for system PFD determination and PFD variables optimization that contributes to reduce the uncertainty problem. A higher redundant system can be assessed by generalizing the PFD formula into KooN architecture without neglecting the diagnostic coverage factor (DC) and common cause failures (CCF). In order to simulate the proof test effectiveness, the Proof Test Coverage (PTC) factor has been incorporated into the formula. Additionally, the system PFD value has been improved by incorporating PST for the final control element into the formula. The new developed formula is modelled using the Genetic Algorithm (GA) artificial technique. The GA model saves time and effort to examine system PFD and estimate near optimal values for PFD variables. The proposed model has been applicated on SIS design for crude oil test separator using MATLAB. The comparison between the proposed model and PFD formulas provided by IEC 61508 and ISA TR.84.02 showed that the proposed GA model can assess any system structure and simulate industrial reality. Furthermore, the cost and associated implementation testing activities are reduced.

1. Introduction

Standards and regulations began being issued following catastrophic industrial accidents that occurred during the second half of the last century. The target of these standards and regulations has been to obtain safeguarding methods for the prevention and mitigation of risks associated with the industrial process. In 1974, 28 people died and 36 were injured in Flixborough, UK.

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[1]. In 1976, 17000 people were affected by dioxin release, 200 were poisoned, and 600 were evacuated [2]. In 1987, 167 people died in Piper Alpha, UK [3]. Consequently, the standards IEC 61508 [4], IEC 615011 [5], and ISA-TR.84.00.02 [6] were issued, which are considered the most recent and widely accepted standards. Moreover, SIS is defined as a protection layer in the mentioned standards, which contributes to reduce the risk posed by industries including potential hazards such as those in the oil and gas industry.

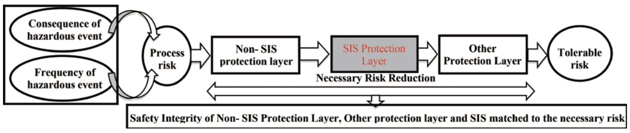

Figure 1. Flow chart shows SIS contribution to risk reduction

The function of SIS is to continuously monitor the process parameters, and in case any abnormal deviation occurs, it performs a predetermined action to return the process to its safe state. As shown in Figure 1, the SIS layer is considered as one of the most critical protection layers due to its ability to reduce the overall risk. Moreover, SIS consists of several safety-instrumented functions (SIFs). Each SIF consists of various subsystems (Sensor, Final Control Element, and Logic solver). Each SIF protects against an identified hazard and contributes to reduce the overall risk by a risk reduction Factor (RRF) or its inverse probability of failure on demand (PFD). Further, RRF identifies SIF associated safety integrity level (SIL).

The standards [4,5] provide a framework for establishing the overall requirements and technical activities related to the safety life cycle of SIS. As shown in Figure 2, the safety life cycle consists of three phases (analysis, realization, and operation), each of which consists of several steps. This paper is concerned with the PFD formula used for the SIS verification step included in the realization phase.

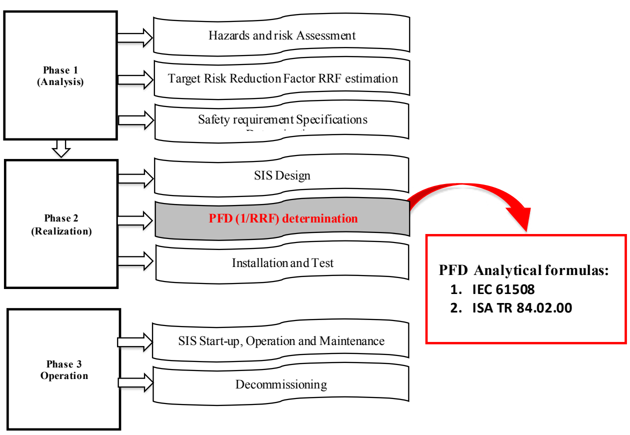

Figure 2. Phases of safety Life Cycle

The conventional PFD determination formulas provided by IEC 61508 and ISA-TR.84.00.02 suffer from the uncertainty problem as demonstrated in [7]. This problem is due to assumptions, approximation and limitation contaminations. As an example of the formula limitations, only 1oo1, 1oo2, 2oo2, 2oo3, and 2oo4 architectures can be examined. Therefore, there is no capability for a higher redundant system structure examination [8]. Additionally, the failure rates (λ) are assumed as being constant. Another impractical assumption is the perfectness of the proof test as it is assumed to reveal all undetected dangerous failures neglecting the effectiveness of the test procedures [9]. Further, the CCF data estimation methodology is based on the checklist questions, which involve operational, environmental, and human factors that may be difficult to be accurately answered [7]. However, parameters such as PST and online channel output comparison can reasonably improve the PFD value, which are not included in the formulas [10]. Finally, high efforts and significant time are consumed to examine the PFD and determine the values of design parameters (such as proof test interval, main repair time, and main time to restore, etc.). As a result, research contributed to identify, describe the uncertainty sources in conventional PFD formulas, and develop new formulas capable of minimizing the problem. As discussed in [7,11], the uncertainty sources in SIS PFD examination are completeness, model, and parameter sources. The authors identified and described the uncertainty sources and ranked the highest importance for completeness uncertainty followed by parameter and model uncertainty. They stressed the uncertainty assessment importance during any SIS reliability examination and demonstrated that analysis results should include the performed uncertainty assessment.

In [12], authors reduced one source of uncertainty by developing a new PFD formula considering non-constant failure rate through incorporating the degradation effect within different subsequent proof testing intervals, but the formula is limited to FCE, where PFD examination formulas for LS and SE are not included.

In [10,13], authors reduced another source of uncertainty by deriving the PFD formula while incorporating PST. As they presented the impact of PST incorporation on PFD value, the derived formula in [10] can examine 1oo1 architecture only and does not include other important variables influencing the PFD such as the β factors.

A Koon generalized formula for PFD presented is in [14], where the PFD formula for different system architectures has been derived based on IEC 61508.

Also, Authors in [15] proposed a generalized KooN formula for PFD determination based on ISA TR84.00.02. Both formulas have the capability of examining the re-

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liability of SIS with high redundancy architecture. But the formula derived in [15] includes the contributions from DU failure, DD failures, DD and DU failures combination, and CCF for DU failure and DD failures with binary functions representing the independent failure coefficient or CCFs. The two proposed formulas assumed the perfect tests where the PTC factor was not included.

Another Generalized KooN formula presented in [16] considered whether or not the DD failures are repaired. The proposed equation counts for CCF for DU failure and DD failures, along with the perfect proof tests being assumed.

In [17], the classification of the non-perfect test and its effect on four IEC61508 formulas was discussed. Accordingly, two models from scientific papers and the PDS method in addition to the PTC impact were examined using the PTC factor, but the human error effect has not been deeply discussed.

The practicality of perfect test assumption has been discussed in [18], which involved investigating the reasons of non-perfectness. The investigation resulted in five reasons known as the 'five Ms' (Method, Machine, Manpower, Milieu, and Material).

Further, in [19,20], the authors discussed the non-perfectness of the proof test, PTC determination, and the factors that may affect it; they demonstrated that perfect PTC assumption is not practical. In addition, different practical considerations can influence PTC. In [9], The authors proposed procedures tables for PTC determination; that based on the test procedures.

The above-discussed researches have some merits and provided contributions. However, some drawbacks will be explained in more detail in Section 2.

This paper introduces the optimization model for PFD determination using the GA artificial technique. The GA is a stochastic search technique that guides a population of solutions towards optimum values using the principles of evolution and natural genetics after searching a small portion of the search space [21]. Further, the GA model can accurately determine the PFD value and identify the best values for PFD variables in order to achieve the target RRF. Another credit for using GA is time and effort saving. In order to add the capability of higher redundant system examination, a generalized formula has been developed. Moreover, CCF and DD failures have been considered. The PTC factor has been incorporated into the formula to simulate the proof test effectiveness and the PFD value has been improved by incorporating PST for the final control element into the formula. The proposed model has been implemented on the SIS design for crude oil test separator using MATLAB. The model results were compared with conventional method results for interpretation.

The rest of this paper has been organized as follows:

Section 2 shows the problem areas of conventional PFD determination formulas through the formulas uncertainty assessment.

Section 3 shows the development for the proposed model and implementation procedures.

Section 4 explains the results for the practical case study where the proposed model is implemented.

Finally, the conclusion is given in Section 5.

2. Traditional PFD Determination Formulas and Main Contribution of the Paper

Conventional PFD determination formulas provided in IEC 61508 [4], ISA-TR.84.00.02 [6] and proposed alternatives still need improvements as they suffer from limitations and drawbacks, such as uncertainty contamination, that can affect SIS design. Further, uncertainty can be defined as something 'not definitely ascertainable or fixed' [11], which is caused by assumptions, approximations, limitations, lack of understanding, and time and effort consumptions [7]. Moreover, PFD cannot be perfectly described since the knowledge of its phenomena is not complete, so uncertainty can be reduced when knowledge about the system increases or when new technology such as Artificial Intelligence can be used.

In this section, the thoroughness of PFD conventional determination methods will be assessed through the uncertainty assessment. Thus, the general sources for uncertainty should be primarily be defined, followed by PFD formula uncertainity assessment being applied.

The general uncertainty sources are as follows:

(1) Model Uncertainty

(2) Parameter Uncertainty

(3) Completemness Uncertainty

Model Uncertainty: is due to simplification, assumption or approximation included in the model, which simulate the system or have different results for the same system when assessed using different models. Another concern is that reducing one uncertainty source may influence another source.

Parameter Uncertainty: is usually, due to the probabilistic and non-probabilistic distributions for available data described the parameter values.

Completeness Uncertainty: is usually due to the inclusion of assumptions, simplifications, and approximation; it can be known or unknown since each type has different causes. The cause of known completeness uncertainty is the non or improper inclusion for known factors that have influenced the model due to difficulty of estimation, insufficient data availability or lack of understanding of the model. Therefore, it can be reduced by specific and conceptual incorporation for known factors that contribute to the model output; the cause of unknown completeness uncertainty are identified factors with marked contribution for their reduction through the expansion of the searching space, including the indirect factors that may impact the model or by incorporating new intelligent methods or algorithms into the model.

Table 1 illustrates the uncertainty sources for conventional PFD formulas.

Table1. Uncertainty assessment in the conventional PFD formula

1. Model Uncertainty	1.1 Formula Implementation Procedures. 1.2 Perfect Proof test assumption. 1.3 Different results obtained for the same system.
2. Parameter Uncertainty	2.1 Constant λ_D assumption. 2.2 Relative Unavailability of Failure rate data. 2.3 CCF estimation methodology.
3.Complete-nessUncer-tainty	3.1 Lack of system architectures inclusion. 3.2 Lack of testing and maintenance strategies' effect on mission time inclusion. 3.3 Non-inclusion of human error variable. 3.4 Non-inclusion of the PST effect on the formula. 3.5 Channel output comparison limited to the 1oo2 structure (1oo2D).

From Table 1:

(1.1) Implementation procedures can increase the model complexity. Further, the complexity increases with completeness uncertainty reduction through incorporating new parameters, and parameter uncertainty may increase by the procedures of estimating the value of input parameters.

(1.2) Perfect proof test assumption does not simulate industrial reality, and the non-perfect proof test must be considered due to the effect of the implementation quality of the test procedures, errors committed by the maintenance crew during the test, test equipment quality, and some inherent conditions for the tests.

(1.3) Different results can be obtained for the same system using different formulas, especially with high DC or long MRT.

(2.1) λ_D is a determination methodology usually determined from general data bases; such data bases are built based on the data from components that were installed several years before the data collection, and at different operational and environmental conditions. The collected failure rate data are based on recorded maintenance strategies, which may not be accurately applied.

(2.2) Failure rate data for new technology devices are often not available.

(2.3) CCF estimation is based on checklist questions that involve operational, environmental, and human factors that may be difficult to be accurately answered.

(3.1) The formulas are limited to 1oo1, 1oo2, 2oo2, 2oo3, and 2oo4 (only the ISA formula) system architectures where higher redundant architectures such as 3oo5 cannot be examined.

(3.2) Conventional formulas do not include the effect of testing and maintenance strategies on mission time of the subsystems.

(3.3) Conventional formulas do not include any variable that simulates human error although human error is a well-known variable that may increase the probability of failure.

(3.4) PST is not included in the formula, although it can reasonably improve the PFD value.

(3.5) Channel output comparison is limited to the 1oo2 structure named 1oo2D, while applying the online comparison between output channels can reasonably improve the DC factor as it can be applied for any system architecture with redundancy.

Main contributions of this paper

This research contributes to reducing the uncertainty associated with the PFD detrmination citerion as described below:

Reference to point (1.1) in order to overcome the model complexity, GA will be used to model the formula in addition to widely decreasing the time and efforts required to determine the PFD value and the values of PFD variables. Moroever, it solves the problem of obtaining different results for same system: point (1.3).

Reference to point (1.2) the proof test PTC factor (PTC) will be incorporated into the formula to simulate the effectiveness of the proof tests.

Refrence to point (3.1) The newly developed formula will be genalized into the KooN system that can examine high redundant system architectures.

Reference to point (3.4) The PST variable for the final cotrol element will be incorporated into the formula to simulate the effect of PST on system PFD value.

Points (2.1), (2.2), (2.3), (3.3) and 3.5 are out of this research scope and will be considered in the future work.

3. Procedures of the Developed GA-based Optimization Model for the Probability of Failure on Demand

In order to overcome the drawbacks associated with conventional PFD determination methods and to reduce the uncertainty sources in the PFD formula discussed in Section 2, we must develop a new formula that can assess any KooN structure, incorporate all variables that can influence PFD, and finally model the formula using GA to find the optimal solutions for PFD variables as shown in Figure 3.

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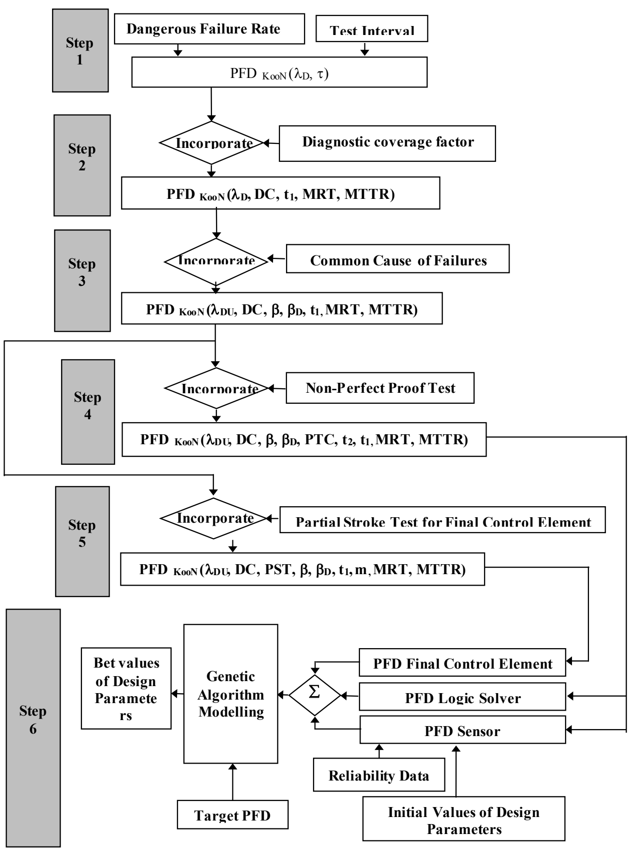

Figure 3. Procedures of the developed GA optimization model for PFD

Step 1: Generalized the formula for KooN structure

KooN expresses the system structure, where N is the number of channels/equipment sets, and K is the number needed to initiate the trip as it describes the connection between subsystem channels/equipment.

The KooN system has minimal cut sets of order (n - k + 1); the average PFD of the kooN system is expressed as:

$$PFD_{avg} \approx \int_0^{\tau} \binom{n}{n-k+1} . (\lambda_D\, \tau)^{n-k+1} \quad [22,23]$$
$$= \binom{n}{n-k+1} \frac{(\lambda_D\, t)^{n-K+1}}{n-K+2}$$
$$= \frac{N!}{(k-1)! \times (N-K+1)!} \times \frac{(\lambda_D\,(\lambda_D\, \tau))^{n-K+1}}{n-K+2}$$
$$= \frac{N(N-1)(N-2)\ldots(K+2)(K+1)K}{(N-K+2)!} \times (\lambda_D\,(\lambda_D\, \tau))^{n-K+1}$$
$$= \prod_{i=K}^{N} \left[\frac{(i\,\lambda_D\,(\lambda_D\, \tau))^{n-K+1}}{N-i+2}\right]$$

$$\boldsymbol{PFD_{KooN} = \prod_{i=1}^{N-K+1} \left[\frac{(N-i+1)\lambda_D\, \tau}{i+1}\right]} \quad (1)$$

The system structure is identified as per the fault tolerance requirement based on the following factors:

(1) The determined safety fractional factor

$$(SFF) = \frac{\sum \lambda_S + \sum \lambda_{DD}}{\sum \lambda_S + \sum \lambda_{DD} + \sum \lambda_{DU}} \text{[4]}$$

(2) Device type (A or B)

(3) Determined target SIL

Step 2: Incorporating the DC factor into the formula.

Many dangerous failures of modern safety devices may be revealed by diagnostic self-testing of the portion of failures detected by a diagnostic called Detected Dangerous (DD) failures with a dangerous detected failure rate λ_{DD}; the diagnostic testing is assumed to be carried out frequently enough for the failures to be revealed immediately. In subsystems with redundant elements, a failure may sometimes be repaired while the subsystem is online and can perform its safety function. In other cases, the subsystem must taken off-line to repair the failure; the mean downtime of the subsystem to repair the failure of an item in the subsystem that has been revealed by diagnostic self-testing is known as mean time to restoration (MTTR). The remaining portion of dangerous failure rate is considered as undetected dangerous (UD) failure rate , λ_{DU} which is supposed to be revealed by a periodic manual proof test with test interval t_1. When a failure is detected by manual proof test, the subsystem has to be taken offline to be repaired with the mean repair time *MRT*.

Thus, the dangerous failure rate λ_D is the sum of the undetected failure rate λ_{DU} revealed by a periodic manual test with test interval t_1 and mean repair time *MRT* in addition to detected failure rate λ_{DD} revealed by diagnostic self-testing with mean time to restoration *MTTR*,

$$\lambda_D = \lambda_{DD} + \lambda_{DU} \text{[4]} \quad (2)$$

DC is the measure of the effectiveness of the self-diagnostic test expressed by the fraction of dangerous failures detected by self-dangerous to total dangerous failures,

$$DC = \frac{\sum \lambda_{DD}}{\sum \lambda_D} \text{[4, 6]}$$

$$\lambda_{DD} = DC\lambda_D \quad (3)$$

$$\lambda_{DU} = (1-DC)\lambda_D \quad (4)$$

From Eqs. 2, 3 and 4 in Eq.1;

$$PFD_{KooN} = \prod_{i=1}^{N-K+1} \left[(N-i+1)\left((1-DC)\,\lambda_D \left(\frac{t_1}{i+1} + MRT\right) + DC\,\lambda_D(MTTR)\right)\right] \quad (5)$$

Step 3: Incorporating CCF into the formula

An additional PFD arises where more failures may occur due to a common cause (CC). Thus, the total dangerous failure rate equals the sum of independent dangerous failure rate in addition to the common cause failure rate;

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$$\lambda_D = \lambda_{Ind,D} + \lambda_{CC} \text{ [24,25,26]}. \tag{6}$$

Where:

$\lambda_{Ind,D}$ is the independent dangerous failure rate, and

λ_{CC} is the common cause failure rate.

The fractional of CCF rate is defined by the beta factor (β),

$$\beta = \lambda_{CC} / \lambda_D \tag{7}$$

The β factor provides the fraction of undetected dangerous failures with a CC while the β_D provides the fraction of detected dangerous failures that have a CC; thus:

$$PFDKooN\text{-}total = (1-\beta)\, PFDKooN + \beta\, PFD1oo1 \text{ [22]} \tag{8}$$

From eqs. 6, 7 and 8 in Eq. 5;

$$\boldsymbol{PFD_{KooN}} = \prod_{i=1}^{N-K+1}\left[(N-i+1)\left((1-\beta)\,(1-DC)\,\lambda_D\,\left(\frac{t_1}{i+1}+MRT\right)+(1-\beta_D)\,(DC)\lambda_D(MTTR)\right)\right]+\beta(1-DC)\,\lambda_D\left(\frac{t}{2}+MRT\right)+\beta_D(DC)\lambda_D(MTTR) \tag{9}$$

Step 4: Incorporating the PTC factor into the formula.

In Eq. 9, the proof test was considered to be perfect for revealing all undetected dangerous failures with the device being regarded new in condition at the end of the test interval. However, practically, the proof test can never be perfect as it depends on the quality of the procedure(s), errors committed by the maintenance crew during the test, test equipment quality, some inherent conditions for the tests, and the inherent features of the system itself. Moreover, device condition can be considered as a new condition only when major maintenance overhaul has been carried out or when a demand is made at demand period t_2. PTC is the percentage effectiveness of proof tests to check the existence of undetected danger failures expressed by the fraction of revealed failures during proof test to the non-revealed failures during proof test

$$PTC = \lambda_{\boldsymbol{DU}_{\boldsymbol{rv}}} / \lambda_{\boldsymbol{DU}_{\boldsymbol{nrv}}} \tag{10}$$

$$PFD_{DUKoon} = PTC\; PFD_{DUKoon}(\lambda_{\boldsymbol{DU}}, t_1, MRT) + (1-PTC)PFD_{DUKoon}(\lambda_{\boldsymbol{DU}}, t_2, MRT) \text{ [27, 28, 29, 30, 31,32]} \tag{11}$$

From eqs. 10 and 11 in Eq. 9;

$$\boldsymbol{PFD_{KooN}} = \prod_{i=1}^{N-K+1}\left[(N-i+1)\left((1-\beta)(1-DC)\lambda_D\left(PTC\left(\frac{t_1}{i+1}+MRT\right)+(1-PTC)\left(\frac{t_2}{i+1}+MRT\right)\right)+(1-\beta_D)(DC)\lambda_D(MTTR)\right)\right]+\beta\,(1-DC)\lambda_D\left(PTC\left(\frac{t_1}{2}+MRT\right)+(1-PTC)\left(\frac{t_2}{2}+MRT\right)\right)+\beta_D(DC)\lambda_D(MTTR) \tag{12}$$

Step 5: Incorporating PST for the final control element

PST for final elements has the advantage of reducing the frequency of full tests to save deferment; thus, now there are two test intervals:

(1) More frequently performed partial closure test (Partial Stroke test) at t_{PST}

Where $t_{PST} = t_1 / m$ and m is the number of partial test intervals per full test interval with lower efficiency than FPT (Low coverage factor PST).

(2) Less frequent full test period ($t_1 = t_{PST} * m$) with higher efficiency than partial test (high coverage factor PTC.

$$PFD_{DUKoon} = PST\; PFD_{DUKoon}\left(\lambda_{\boldsymbol{DU}}, \frac{t_1}{m}, MRT\right) + (1-PST)PFD_{DUKoon}(\lambda_{\boldsymbol{DU}}, t_1, MRT) \text{ [33.34.35]} \tag{13}$$

From Eq. 13 in Eq. 12:

$$\boldsymbol{PFD_{KooN}} = \prod_{i=1}^{N-K+1}\left[(N-K+1)\left((1-\beta)(1-DC)\lambda_D\left(PST\left(\frac{t_1}{m(i+1)}+MRT\right)+(1-PST)\left(\frac{t_1}{i+1}+MRT\right)\right)+(1-\beta_D)(DC)\,\lambda_{DD}(MTTR)\right)\right]+\beta(1-DC)\lambda_D\left(PST\left(\frac{t_1}{2m}+MRT\right)+(1-PST)\left(\frac{t_1}{2}+MRT\right)\right)+\beta_D(DC)\lambda_D(MTTR) \tag{14}$$

In Eq. 14, failures detected by PST are considered as dangerous undetected failures, knowing that the sum of the test interval and the time to perform the repair of a detected failure is more than the mean time to restoration (MTTR) used to determine the achieved safety integrity for that safety function. Thus, PST does not affect SFF and consequently, it does not affect the architecture constrains.

The final formula to be modelled using GA is the total system probability of failure on demand expressed by the sum of the probability of failure on demand for the three subsystems (sensor, logic solver, and final control element).

$$PFD_{sys} = PFD_s + PFD_{LS} + PFD_{FE} \text{ [4]} \tag{15}$$

Step 6: Modelling the formula using the GA technique

The target of modelling the formula using GA is to find the best value for variables of PFD developed formula achieving target PFD, satisfying design constraints, and reflecting industrial realities;

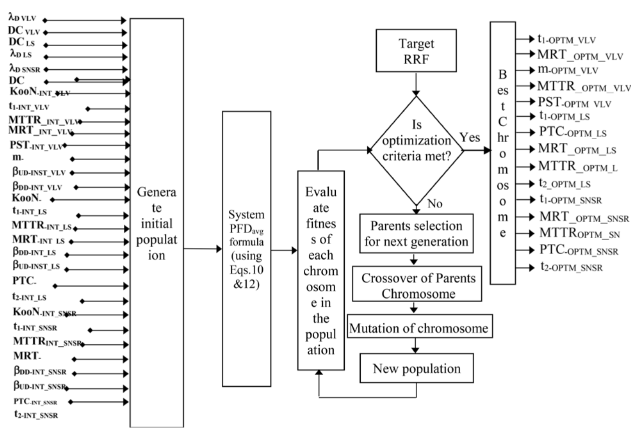

Figure 4. GA Model flowchart

GA uses populations with allowed solutions called 'individuals' that count in the group of parallel algorithms

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with constrains, implying that it is necessary to set limits at least for the values of the optimized parameters as shown in Figure 4.

Here, we use the MATLAB GA Toolbox for simulation, where the first step is to define the cost function, the next step is to encode the problem into suitable GA chromosomes, and then construct the population; some works recommend 20 to 100 chromosomes in one population since a higher number of chromosomes will give a better chance to find optimal results. However, due to execution time limitation, 80 chromosomes are used for each generation; each chromosome comprises the model parameters with varied value bounds depending on the cost functions. The population in each generation is represented by the 80 x 31 matrix, with the initial values of parameters as follows:

NL=3; KL=1; TPPTLS=1460; MLS=6; LLS=10; MTTRLS=8; CPTLS=0.8; NV=3; KV=1; TPPTV=356; MV=6; LV=10; MTTRV=8; CPTV=1; CPPTV=0.7; NS1=2; KS1=1; TPPTSNSR1=514;MSNSR1=6; LSNSR1=10; MTTRSNSR1=8; CPTSNSR1=0.8;NS2=2;KS2=1; TPPTSNSR2=730;MSNSR2=6; LSNSR2=10; MTTRSNSR2=8; CPTSNSR2=0.8.

Each row is one chromosome that comprises the parameter values, and the last column is added to accommodate fitness values (F) of corresponding chromosomes; the final values of parameters are determined by minimizing a certain cost function.

The cost function (CF1) as shown in Eq. (16) minimizes the integrated square error e(t) and improves the overall performance.

$$CF_1 = \int_0^{\infty} (e(t))^2 dt \tag{16}$$

Figures 5A and 5B show the structure of the GA tuning system for cost function. It can be noted that the input for the GA tuning system is the error signal only, which is sometimes not enough to obtain good results.

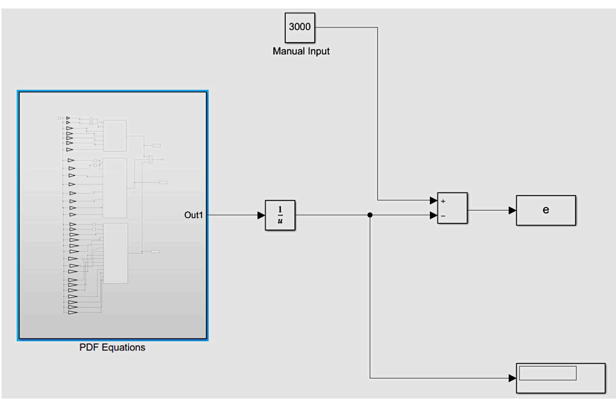

Figure 5A. GA based optimization model using MATLAB

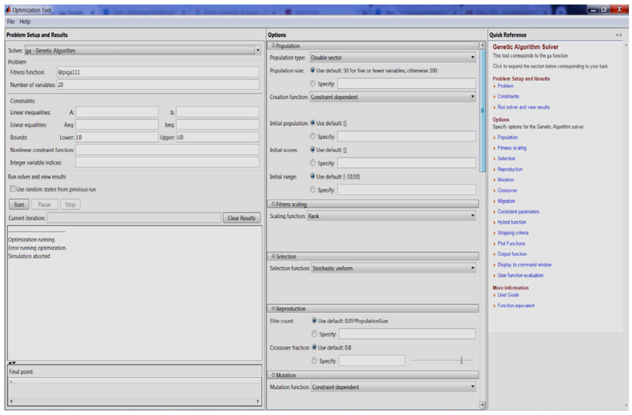

Figure 5B. GA based optimization model configuration on MATLAB

4. Model Implementation and Result Interpretation for Practical Case Study from the Oil and Gas field.

The Mansoura Petroleum company/West Khelala Gas processing plant includes the test separator (V-304) shown in Figure 6 below, where V-304 is a horizontally mounted cylindrical and 2 phase; the gravity separation and size is 300 BBL/D for liquids and 38 MMscfd for gas with a 9m3 surge volume. The produced liquid from the test separator is discharged under level control, LIC-011 using LCV-011 [36].

The Hazard and Operability (HAZOP) Study Report [36] resulted from the HAZOP session prepared for the mentioned unit.

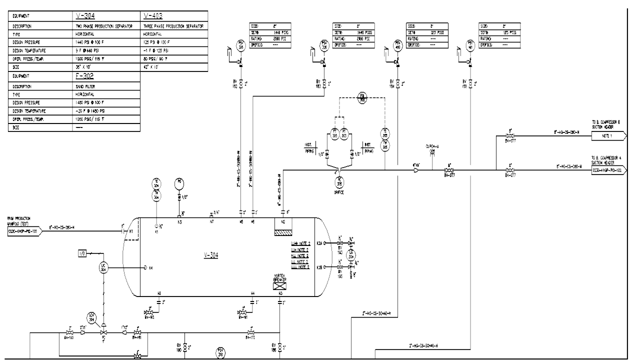

Figure 6. Test Separator P&ID (Model under study) [38]

Further, HAZOP concluded that high-level and high-pressure parable hazards exist and a safely-instrumented function is required for protection with target SIL 3 (10-4 ≤ PFDavg ≥10-3).

The initial designed SIFs is composed of three subsystems: level transmitter (LT), pressure transmitter (PT), logic solver (LS), and emergency shutdown valve (ESDV). When high pressure or level hazards are detected by the transmitter, the system should shut the supply source to the separator in order to prevent the event [37].

The structure of the system is shown in Figure 7 below. Each subsystem has a parall structure. The sensor layer is made up of two identical pressure and level transmitters structured in the 1oo2 architecture.

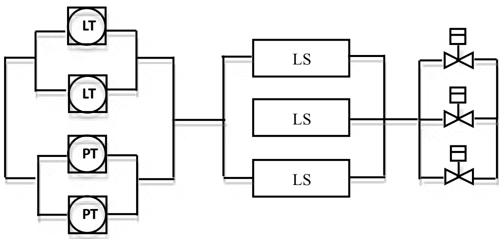

Figure 7: case study initial SIS structure

The logic solver layer (LS) is structured in the 1oo3 architecture and the shutdown valves are structured in the 1oo3 architecture.

Tables 2 and 3 illustrate the variables and corresponding PFD on demand calculations using the conventional and developed formulas.

From Table 3:

(1) The determined system PFD and all subsystem PFDs are almost the same without taking PTC and PST into account.

(2) The determined system PFD and all subsystem PFDs derived from IEC are almost equal to results derived by the developed formula, as well as the resulting PFDs with PTC being higher than the PFDs without considering the non-perfectness of the proof tests. Moreover, ISA does not have the capability of considering the PTC variable.

(3) The derived formula is the only approach that can count for the PST. Further, PST could decrease the PFD again after increasing due to the PTC consideration.

4.1 Effect of GA:

Table 4 shows the PFD variables and corresponding PFD derived by the GA based model.

From Table 4:

(1) The GA optimization model tended to increase the PST variable for the final control element from 50% to 60% with monthly interval, including what extended the FPT interval T_1 from annual to two years and what decreased the cost, process disturbance, human error, and material degradation associated with manual full FPT.

(2) Increasing the MTTR from 8 Hrs to 48 Hrs ensures enough time and permeability for practical repair activities in case of failure detection.

(3) Decreasing the PTC from 80% to 60%, consequently decreases the associated test procedures and related activities, and the associated cost facilitates the implementation.

Table 2. Design and reliability data

Subsystem	λ_D	K	N	DC	t_1	t_2	m	MRT = MTTR	B	β_D	% PTC	% PST
PT	1.90E-06	1	2	51.1	4380	43800	N/A	8	0.1	0.05	80	N/A
LT	7.60E-06	1	2	10	4380	43800	N/A	8	0.1	0.05	80	N/A
LS	3.20E-08	1	3	81.25	8760	87600	N/A	8	0.1	0.05	80	N/A
FE	3.35E-06	1	3	25	4380	N/A	6	8	0.1	0.05	80	50

Table 3. Comparison between resulted PFD using conventional formulas and developed formula

PFD using IEC formula			PFD using ISA formula			PFD using developed formula		
Without PTC	**With PTC**	**With PST**	**Without PTC**	**With PTC**	**With PST**	**Without PTC**	**With PTC**	**With PST**
2.09E-04	6.09E-04	N/A	2.09E-04	N/A	N/A	2.09E-04	6.85E-04	6.85E-04
1.87E-03	6.13E-03	N/A	1.80E-03	N/A	N/A	1.75E-03	6.12E-03	6.12E-03
2.68E-06	7.37E-06	N/A	2.66E-06	N/A	N/A	2.64E-06	7.39E-06	2.64E-06
5.53E-04	1.55E-03	N/A	5.60E-04	N/A	N/A	5.53E-04	1.55E-03	5.53E-04
5.56E-04	1.56E-03	N/A	5.63E-04	N/A	N/A	5.56E-04	1.56E-03	3.30E-04

Table 4. Variables and corresponding PFD derived by the GA model

Subsystem	λ_D	K	N	% DC	t_1	t_2	m	MRT = MTTR	B	β_D	% PTC	% PST	Target PFD	PFD
PT	1.90E-06	1	2	51.1	8760	43800	N/A	48	0.1	0.05	0.6	N/A	5.60E-04	5.50E-04
LT	7.60E-06	1	2	10	8760	43800	N/A	48	0.1	0.05	0.6	N/A		
LS	3.20E-08	1	3	81.25	17520	87600	N/A	48	0.1	0.05	0.6	N/A		
FE	3.35E-06	1	3	25	8760	N/A	12	48	0.1	0.05	N/A	60		

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(1) The credit of the GA's ability to keep the PFD below the target PFD with the above mentioned optimization is due to the incorporated PST and its contribution to improve the PFD and generalized formula for any KooN with implementation practicality credit because of the PTC incorporation.

(2) The presented generalized analytical formula for PFD determination has the capability of assessing any KooN architecture; thus, it can be used in PFD where higher redundancy architectures need to be assessed.

(3) PFD is obtained using the presented formula (excluding PST) is 5.56E-03, which is very close to the values obtained using the conventional formula 5.63E-04, as it could keep the system PFD below the target PFD despite the above improvement for PFD variables.

4.2 Effect of Generalizing the PFD Formula into KooN:

Table 5 and Figure 8 show the PFD values for the logic solver structured in 1oo1, 1oo2, 2oo2, 2oo3, 1oo3, 2oo4, 2oo5, and 3oo5 system architectures with a variety of test intervals without CC.

From Table 5 and Figure 8:

(1) For 1oo1 system architecture, when the logic solver receives the initiation signal from the sensor, it de-energizes the final control element to trip with 2.64E-06 PFD when it is being tested annually.

(2) For the same test interval, 1oo2 is used, and only one of the two logic solvers set needed to initiate the SIF with 9.43E-10 PFD. Resultantly, a great drop occurred at the PFD.

(3) For 2oo2, both logic solvers must initiate the SIF when it's important to keep the plant running. Further, it was required to be sure of the event having occurred to initiate the SIF with 5.31E-05 PFD. A great change resulted in the PFD as it increased to the double again, due to which this architecture gave an advantage of keeping the plant running and ensured the occurrence of the event in order to trip. However, it increased the PFD.

(4) For 2oo3 (triple marginal redundancy), two logic solvers out of the three set must initiate the SIF with 2.83E-09 PFD. A great change resulted in the PFD as it decreased again.

(5) 2oo3 architecture had an advantage over the 2oo2 architecture for the resulting PFD to be much lower than the resulted PFD from 2oo2.

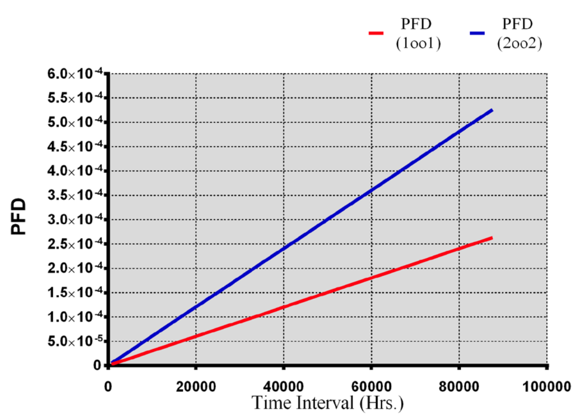
(6) However, the resulting PFD from 1oo2 architecture was lower than the resulting counterpart from 2oo3. Contrastingly, 2oo3 architecture had an advantage over the 1oo2 architecture that kept the plant running and ensured the occurrence of the event in order to trip.

(7) The higher the redundant architecture, the lower the PFD. Therefore, when we decrease the PFD by increasing the redundancy, the PFD examination is not available using the conventional PFD formulas. However, here, we could determine the PFD of 2oo4 (1.52E-13 PFD), 2oo5 (8.17E-18 PFD), and 3oo5 (3.79E-13PFD) system architectures using the developed formula.

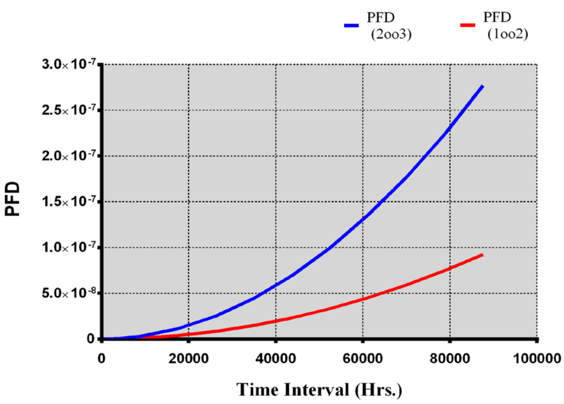
(8) On the other hand, it can be noticed from the curves that for all system architectures, the PFD increases with the increase of test interval.

Table 5. Effect of generalizing PFD formula into KooN

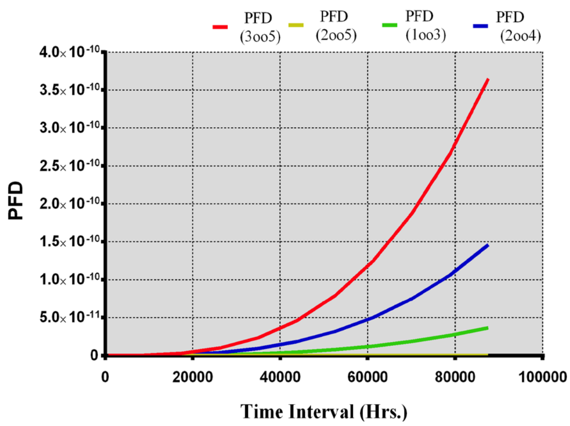
T1	PFD (1oo1)	PFD (1oo2)	PFD (2oo2)	PFD (2oo3)	PFD (1oo3)	PFD (2oo4)	PFD (2oo5)	PFD (3oo5)
Monthly	2.42E-06	8.20E-12	4.83E-06	2.46E-11	3.28E-17	1.31E-16	7.36E-22	3.28E-16
3 months	6.74E-06	6.16E-11	1.35E-05	1.85E-10	6.47E-16	2.59E-15	3.68E-20	6.47E-15
6 months	1.32E-05	2.35E-10	2.64E-05	7.05E-10	4.75E-15	1.90E-14	5.17E-19	4.75E-14
1 year	2.65E-05	9.43E-10	5.31E-05	2.83E-09	3.79E-14	1.52E-13	8.17E-18	3.79E-13
2 years	5.28E-05	3.73E-09	1.06E-04	1.12E-08	2.97E-13	1.19E-12	1.26E-16	2.97E-12
3 years	7.91E-05	8.36E-09	1.58E-04	2.51E-08	9.94E-13	3.98E-12	6.32E-16	9.94E-12
4 years	1.05E-04	1.48E-08	2.11E-04	4.45E-08	2.35E-12	9.39E-12	1.99E-15	2.35E-11
5 years	1.32E-04	2.31E-08	2.63E-04	6.94E-08	4.58E-12	1.83E-11	4.84E-15	4.58E-11
6 years	1.58E-04	3.33E-08	3.16E-04	9.99E-08	7.90E-12	3.16E-11	1.00E-14	7.90E-11
7 years	1.84E-04	4.53E-08	3.68E-04	1.36E-07	1.25E-11	5.01E-11	1.85E-14	1.25E-10
8 years	2.10E-04	5.91E-08	4.21E-04	1.77E-07	1.87E-11	7.48E-11	3.15E-14	1.87E-10
9 years	2.37E-04	7.48E-08	4.74E-04	2.24E-07	2.66E-11	1.06E-10	5.05E-14	2.66E-10
10 years	2.63E-04	9.23E-08	5.26E-04	2.77E-07	3.65E-11	1.46E-10	7.68E-14	3.65E-10



(a)



(b)



(c)

Figure 8. Effect of generalizing PFD formula into KooN on PFD.

Figure 8 (a). no fault tolerance; Figure 8 (b). one fault tolerance; Figure 8 (c). two fault tolerance

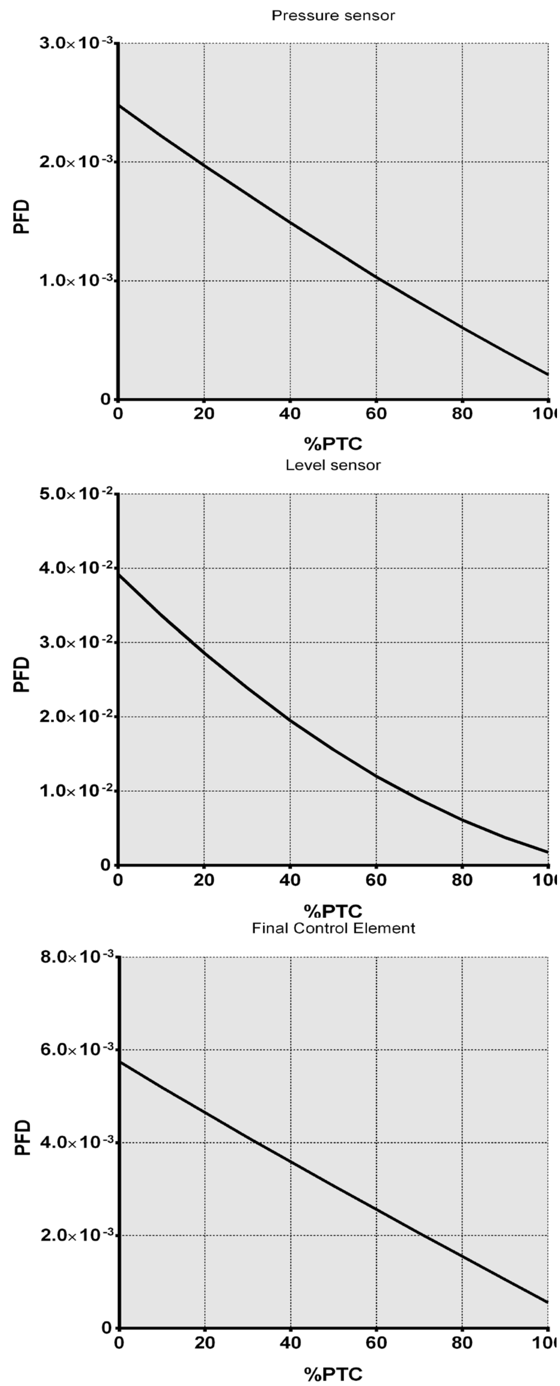
4.3 The Effect of Incorporating PTC into the Formula

Table 6 and Figure 9 show the impact of the PTC variable on the system PFD and each subsystem PFD.

In Table 6 and Figure 9, when the PTC increases, the PFD decreases while increasing the PTC improves safety by reducing PFD value. However, this consumes time, effort, and money as sticking seals during the full proof test (FPT) is relatively high since it requires flow bypasses, capital, and installation costs.

Table 6. Impact of PTC variable on system PFD and Subsystems PFDs

%PTC	Logic solver PFD	Pressure sensor PFD	Level sensor PFD	Final Control Element PFD	System PFD
100	2.64E-06	2.09E-04	1.75E-03	5.53E-04	5.56E-04
90	5.01E-06	4.04E-04	3.73E-03	1.05E-03	1.06E-03
80	7.37E-06	6.06E-04	6.11E-03	1.55E-03	1.56E-03
70	9.74E-06	8.16E-04	8.88E-03	2.05E-03	2.07E-03
60	1.21E-05	1.03E-03	1.20E-02	2.56E-03	2.58E-03
50	1.45E-05	1.26E-03	1.56E-02	3.07E-03	3.10E-03
40	1.68E-05	1.49E-03	1.95E-02	3.59E-03	3.63E-03
30	1.92E-05	1.73E-03	2.39E-02	4.11E-03	4.17E-03
20	2.16E-05	1.97E-03	2.86E-02	4.65E-03	4.73E-03
10	2.39E-05	2.22E-03	3.37E-02	5.19E-03	5.29E-03
0	2.63E-05	2.48E-03	3.92E-02	5.75E-03	5.87E-03



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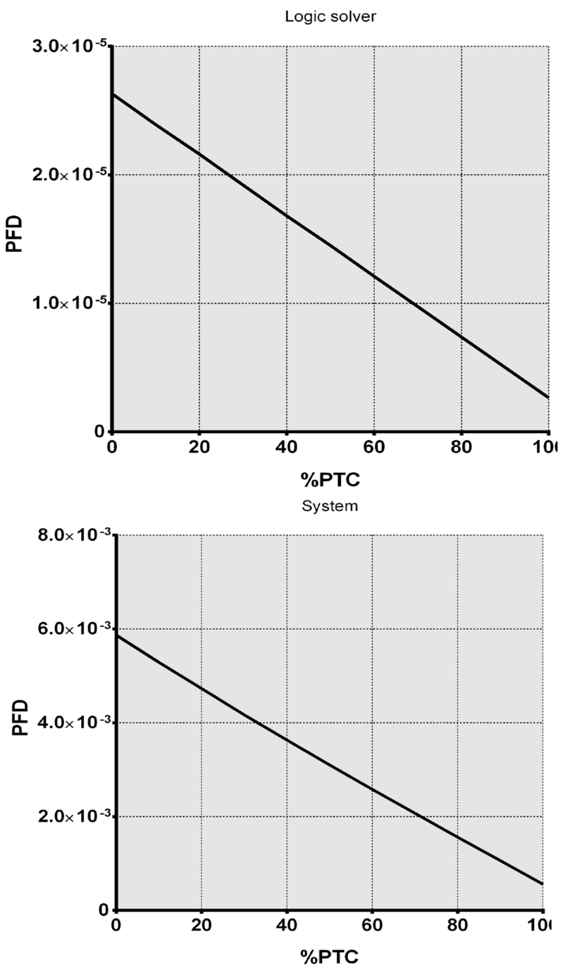

Figure 9. The impact of the PTC variable on system PFD and subsystems PFD

From Table 7 and Figure 10, the behaviour of the curves shows the system PFD with variety test intervals demonstrated through 80% PTC system PFD, which is higher than the system PFD with perfect proof test assumption. However, it reflects the industrial reality and must be considered due to the dependency on the quality of the procedure(s), errors committed by the maintenance crew during the test or repairs required, test equipment quality, some inherent conditions for the tests, and inherent features of the system itself.

Table 7. System PFD with 80% PTC to system PFD with perfect proof test assumption

T1	System PFD With Perfect proof test	System PFD with 80% PTC
6 months	5.55E-04	1.56E-03
1 Year	1.11E-03	3.15E-03
2 years	2.23E-03	6.66E-03
3 years	3.39E-03	1.09E-02
4 years	4.59E-03	1.61E-02
5 years	5.86E-03	2.29E-02
6 years	7.20E-03	3.16E-02
7 years	8.65E-03	4.27E-02
8 years	1.02E-02	5.66E-02
9 years	1.19E-02	7.39E-02
10 years	1.37E-02	9.50E-02

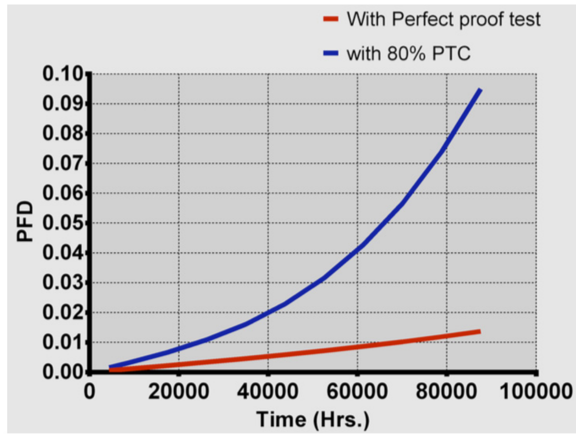

Figure 10. System PFD with 80% PTC to system PFD with perfect proof test assumption.alue

4.4 The Impact of Incorporating PST Into the Formula

Table 8 and Figure 11 show the effect of PST on the system PFD and the final control element PFD.

Further, Table 9 and Figure 12 show the effect of the number of partial stroke tests m on the system PFD and the final control element PFD.

From tables 8 and 9 as well as figures 11 and 12, when the PST increases, the PFD decreases. The incorporation of PST into the formula for the final element only reasonably decreased the PFD as well as increased the PST and/or decreased the partial test interval m, which can achieve further reduction of PFD.

Table 8. The impact of PST variable on system PFD and The final control element PFD

%PST	Final Control Element PFD	System PFD
0	5.53E-04	5.64E-04
10	5.07E-04	5.18E-04
20	4.66E-04	4.77E-04
30	4.15E-04	4.26E-04
40	3.69E-04	3.80E-04
50	3.23E-04	3.34E-04
60	2.77E-04	2.89E-04
70	2.36E-04	2.47E-04
80	1.97E-04	2.09E-04

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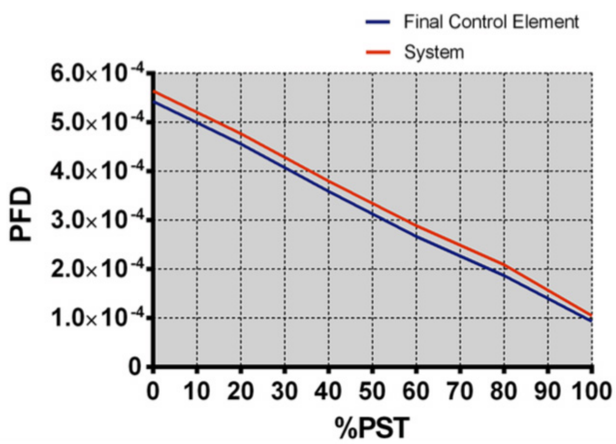

Figure 11. The impact of the PST variable on system PFD and the final control element PFD

Table 9. The impact of partial stroke tests number on system PFD and on Final control element PFD

M	Final Control Element PFD	System PFD
10	1.56E-04	1.67E-04
9	1.61E-04	1.72E-04
8	1.67E-04	1.78E-04
7	1.75E-04	1.86E-04
6	1.86E-04	1.97E-04
5	2.00E-04	2.12E-04
4	2.22E-04	2.34E-04
3	2.59E-04	2.70E-04
2	3.33E-04	3.44E-04
1	5.53E-04	5.64E-04

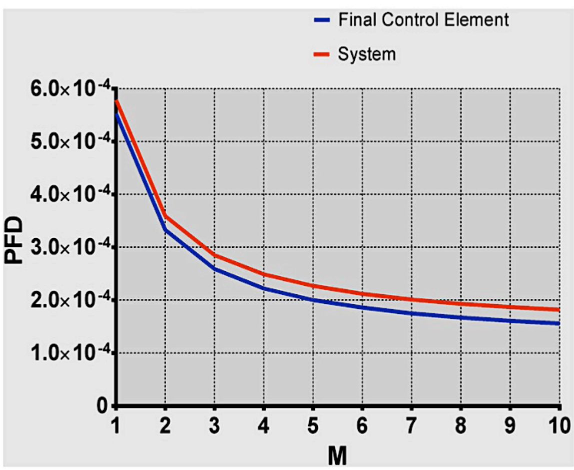

Figure 12. The impact of the m variable on system PFD and the final control element PFD.alue

Table 10 and Figure 13 show the system PFD curve without partial stroke testing and PFD curve for the system when 80% effective partial stroke tests were applied 6 times per full test interval.

Table 10. System PFD with 80% PST and 6 M to system versus PFD without partial stroke testing

T1	System PFD without PST	System PFD with 80% PST & 6M
6 months	1.56E-03	1.97E-04
1 year	3.15E-03	3.80E-04
2 years	6.66E-03	7.48E-04
3 years	1.09E-02	1.12E-03
4 years	1.61E-02	1.49E-03
5 years	2.29E-02	1.86E-03
6 years	3.16E-02	2.23E-03
7 years	4.27E-02	2.61E-03
8 years	5.66E-02	2.99E-03
9 years	7.39E-02	3.37E-03
10 years	9.50E-02	1.97E-04

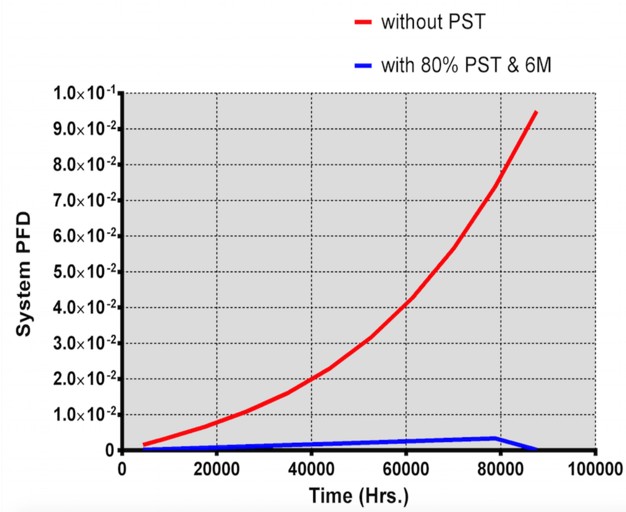

Figure 13. system PFD with 80% PST and 6 M to system PFD without partial stroke testing

From Table 10 and Figure 13, the system PFD was reasonably reduced when partial stroke tests were applied for the final control element with 80% PST 6 times per full test interval. Thus, the system safety increased and cost reduced as well due to the extension of the full proof test interval.

5. Conclusion

The proposed model in this paper can assess any KooN architecture, which is not limited to (1oo1, 1oo2, 2oo2, 2oo3, 1oo3, and 2oo4) architectures contributing to reduce the model uncertainty. Moreover, all known terms that influence the PFD values have been included, investigated, and explained; the presented formula has the capability

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of determining PFD for SIS operating in the low demand mode such that it is used in the oil and gas industry but not capable of the same task at a high complexity time, which is dependent on safety systems. Moreover, the presented PFD formula provides a wider interpretation of systems with non-perfect proof tests, as the results showed reasonable reduction in PFD with the increase of PTC and/or test frequency. Further, incorporating PST into the PFD formula for the final control element improves safety by reducing the PFD value since part of DU failures detected and repaired within a shorter time interval than the full test interval. In addition, increasing the PST and/or decreasing the stroke test interval can achieve further reduction in PFD. Moreover, cost is reduced by extending the full test interval; sticking seals during PST are less than those during FPT, thereby decreasing full flow bypasses and reducing engineering, capital, and installation costs. Consequently, the failures detected by PST are considered as dangerous undetected failures, knowing that practically, t_1+MRT of a detected failure cannot be eliminated to few minutes or hours may exceed MTTR used to determine the achieved safety integrity for that safety function. Therefore, PST does not affect SFF and consequently, it does not affect the architecture constrains as it also contributes to reducing the completeness uncertainty.

The presented PFD formula has been incorporated into the GA model for formulating optimal design of SIS in order to achieve the required RRF. The efficiency has been realized numerically in the practical case study. Moreover, it saved effort, time and cost and facilitated assessing systems with higher complexity that contributed to reducing the model uncertainty.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this paper.

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Abbreviations

CCF: Common Cause Failures
FCE: Final Control Element
GA: Genetic Algorithm
HAZOP: Hazard and Operability Study
IEC International Electrotechnical Commission
ISA The Instrumentation, Systems, and Automation Society
LS: Logic Solver
LT: Level Transmitter
PFD: Probability of Failure on Demand
PT: Pressure Transmitter
PST: Partial Stroke Testing
RRF: Risk Reduction Factor
SIF: Safety Instrumented Function
SIL: Safety Integrity Level
SIS: Safety Instrumented System

Symbols

λ_D: Dangerous Failure Rate (Per Hr)
λ_{DD}: Detected Dangerous Failure Rate (Per Hr)
λ_{DU}: Undetected Dangerous Failure Rate (Per Hr)
λ_{CC}: Common Cause Failure Rate (Per Hr)
β : Undetected Failures Common Cause Factor
β_D : Detected Failures Common Cause Factor
DC: Diagnostic Coverage Factor
K: Number needed to initiate the trip
N: Number of channels/equipment sets
m: Number of Partial Stroke Tests Per Full Proof Test Internal
MRT: Mean Repair Time (Hrs)
MTTR: Mean Time to Restoration (Hrs)
$t_{1:}$ Proof Test Interval (Hrs)
$t_{2:}$ Intervals Between Demands (Hrs)
PTS: Partial Stroke Test Coverage Factor
PTC: Proof Test Coverage

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