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비용 요소에 근거한 신뢰도 최적화 및 On-Line SIS 지원 도구 연구

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Advanced Optimization of Reliability Based on Cost Factor and Deploying On-Line Safety Instrumented System Supporting Tool

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요 약

SIS는 공정안전시스템 분야에서 폭넓게 활용될 수 있는 계장안전시스템이다. SIS는 유해화학물질 누출 사고로부터 인간, 물질적 자산 그리고 환경에 미치는 피해를 줄이기 위해 필수적이다. 현재 전기, 전자 그리고 프로그래밍 가능한 전자 (E / E/ PE) 장치가 기계, 공압 및 유압 시스템과 상호 작용하는 통합 안전 시스템은 IEC 61508과 같은 국제 안전 표준을 따르도록 되어있다. IEC 61508은 안전 수명주기의 모든 사항을 규정한다. SIS 지원 도구 없이 안전 수명주기에 따라 IEC 61508의 요구 사항을 충족시키는 것은 복잡한 일이다. 본 연구에서는, 사용자가 보다 쉽게 안전 수명주기의 설계 단계를 구현할 수 있도록 도움을 줄 수 있는 On-Line SIS 지원 도구를 제시하였다. On-Line SIS 지원 도구는 데이터 읽기 및 수정 시스템과 통합될 수 있는 안드로이드 응용 프로그램의 형태로 되어있다. 이 도구는 안전 수명주기의 설계 단계에서 소요되는 계산 시간을 줄이고 계산 과정에서 발생할 수 있는 오류를 줄인다. 또한 On-Line SIS 지원 도구는 비용 요소에 근거한 최적화 접근법을 제시할 수 있으며, multi-objective GA를 사용하여 최적의 솔루션 조합을 찾을 수 있도록 하였다.

Abstract - Safety Instrumented Systems (SIS) have wide application area. They are of vital importance at process plants to detect the onset of hazardous events, for instance, a release of some hazardous material, and for mitigating their consequences to humans, material assets, and the environment. The integrated safety systems, where electrical, electronic, and/or programmable electronic (E/E/PE) devices interact with mechanical, pneumatic, and hydraulic systems are governed by international safety standards like IEC 61508. IEC 61508 organises its requirements according to a Safety Life Cycle (SLC). Fulfilling these requirements following the SLC can be complex without the aid of SIS supporting tools. This paper presents simple SIS support tool which can greatly help the user to implement the design phase of the safety lifecycle. This tool is modelled in the form of Android application which can be integrated with a Web-based data reading and modifying system. This tool can reduce the computation time spent on the design phase of the SLC and reduce the possible errors which can arise in the process. In addition, this paper presents an optimization approach to SISs based on cost measures. The multi-objective genetic algorithm has been used for the optimization to search for the best combinations of solutions without enumeration of all the solution space.

Key words : Safety Life Cycle, Safety Instrumented Systems, Intelligent Support System, Multi-Objective Genetic Algorithm, Optimization

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I. Introduction

Safety Instrumented System (SIS) as defined by ANSI/ISA-91.00.01-2001 is 'Instrumentation and controls installed for the purpose of taking the process, or specific equipment in the process, to a safe state. This does not include instrumentation and controls installed for non-emergency shutdowns or routine operations' [4]. To implement SIS design, deep knowledge of life cycle of SIS is mandatory. Designing SIS following the life cycle makes it complete and reliable. This design usually takes a lot of time to complete and since different phases of the life cycle of SIS require different experts, it is a huge burden on the life cycle cost. To reduce the time and cost burden, SIS design has been aided with support tools. Most of the support tools are designed for specific phases of the life cycle. Carefully selected tools are appropriate for ensuring life cycle support of SIS.

The benefits that can be achieved from appropriate SIS supporting tools include:

- Significant reduction in the time taken for Safety Integrity Level (SIL) determination
- Greater visibility of recorded data for audit and regulation purposes
- Interactive and simplified design processes
- Optimal selection of the design elements
- Greatly reduced design time
- Validation and security of design calculations
- Optimization of design against test and maintenance strategies
- High integrity data handling and recording
- Improved life cycle management of SIS [14].

Among the above benefits, the essential features in this paper are designing SIS support tool that has a significant reduction in the time taken for SIL determination, high integrity data handling and recording, and validation and security of design calculations. Our SIS support tool gives emphasis on the significant validation and security of design calculations.

The developed SIS supporting tool is called MySIL, which is composed of three main parts, the online database, reliability analyzer (based on Probability of Failure on Demand (PFD) calculation), and optimizer. Integrating online database is vital while performing any reliability analysis since well-organized and easily accessible data plays a great role in the reliability assessment. Having effective data source by itself is not enough. We need to have effective reliability assessment based on the data input. The PFD calculator has been placed to fulfil this task. If the result achieved from reliability assessment is outweighed by cost, its practical implementation is compromised [2]. To have a reliable and at the same time, low-cost operation requires matching the exact combinations which can lower the cost and gives high reliability. This can be achieved by tedious search by enumeration, which is not practical since the solution space is huge or using optimization algorithm which can search for the desired objective, which is a better approach [15]. The third part of our tool is responsible for the optimization of safety based on cost measures.

II. Functional Safety Life Cycle

Functional Safety Life Cycle is a sequence of phases providing a logical path through to commissioning, operation, maintenance and finally decommissioning [3, 4]. Formal safety plan produces insurance that everything is in place to prepare for and manage each phase of the safety lifecycle. Technical guidance is given on appropriate measures and techniques for achieving specified levels of integrity in the systems, including the safe application of modern programmable electronics [4]. Deep understanding, appropriate skills, and knowledge for those involved in each phase of the safety lifecycle is vital [1]. MySIL tool helps the user to fulfil the parts of requirements which are stated in the functional safety lifecycle. Since MySIL is designed to work under the standard IEC 61508, it helps compliance with the standard. The user-friendly interface of MySIL with the easy accessibility of the database reduces the computation time spent on the reliability assessment.

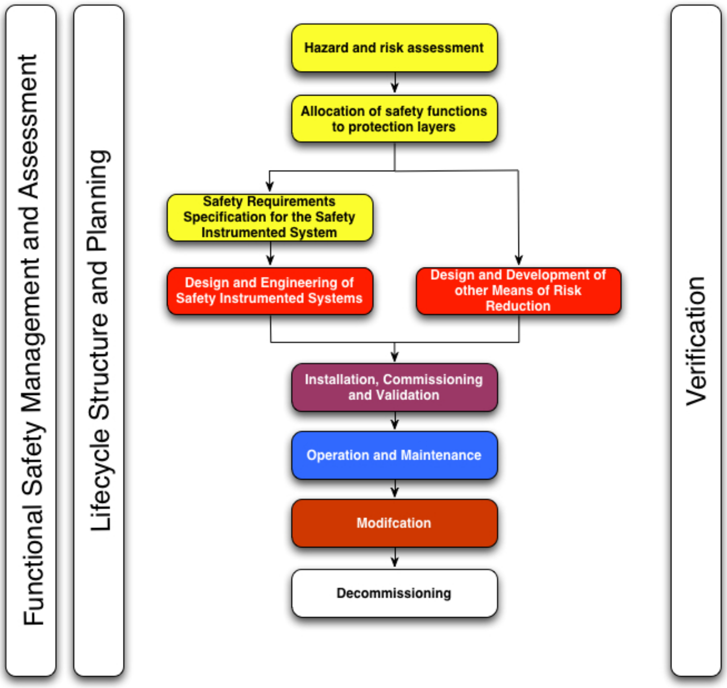

Functional Safety Management and Assessment
Lifecycle Structure and Planning
Hazard and risk assessment
Allocation of safety functions to protection layers
Safety Requirements Specification for the Safety Instrumented System
Design and Engineering of Safety Instrumented Systems
Design and Development of other Means of Risk Reduction
Installation, Commissioning and Validation
Operation and Maintenance
Modifcation
Decommissioning
Verification

Fig. 1. Flow of Safety Life Cycle [2, 3].

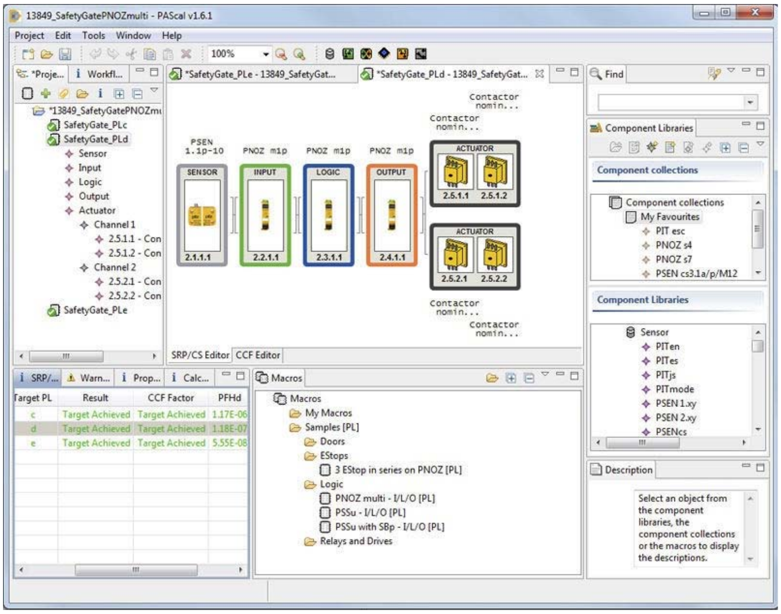
Ⅲ. Modelling SIS Supporting Tool

The purpose of modelling SIS supporting tool is not only for obtaining a point value of reliability, for example for the average PFD, but rather to help designers understand the functionality of the safety integrated system and how the whole system related to safety can be improved [9]. Along with this improvement, how single and multiple parameters like voting logic and common-cause failures (CCF) affects the final reliability of the system. As a major objective of reliability analysis, MySIL provides a decision basis which is possible to comprehend by design engineers who may not be trained in reliability engineering. As stated in IEC 61508, SIL must be determined for each safety instrumented function. Even though there are different methods for SIL determination, this kind of automation which has been deployed in MySIL is vital. As well on SIS conceptual design, this application can take a huge share on pointing out the required redundant sensors, safety PLC (Programmable Logic Controller), and Final element voting.

SIS supporting tools do exist in the current market. Yokogawa's General Reliability Configurator (GRC), exSILentia and Pilz safety calculator can be mentioned. The motive to develop the App MySIL is an improvement over available SIS supporting tools. To mention some of the improvements that should be deployed on the already existing SIS supporting tools, for instance, GRC is only in-house tool intended for Yokogawa engineers only. In GRC all the database for the PFD calculation is stored in the tool which makes it difficult to share and modify the data. In the case of Pilz safety calculator, it's a commercial software which is relatively complicated and expensive to purchase. As well, the time it takes to compute reliability analysis is long.

3.1 SIS Supporting Tool as Android Application

In the complex Safety Instrumented Function (SIF), calculating the probability of failure on demand (PFD) and optimizing an appropriate test



Target PL	Result	CCF Factor	PFHd
c	Target Achieved	Target Achieved	1.17E-06
d	Target Achieved	Target Achieved	1.18E-07
e	Target Achieved	Target Achieved	5.55E-08

Select an object from the component libraries, the component collections or the macros to display the descriptions.

Fig. 2. Pilz Safety Calculator.

and maintenance strategy can be very difficult. Thereby we have developed Android Application for simple SIF consisting sensor, logic solver, and final element incorporating with MooN (M out of N) voting architecture. The simple SIF will constitute about 90-95% of the functions that have to be designed on an average process plant [14].

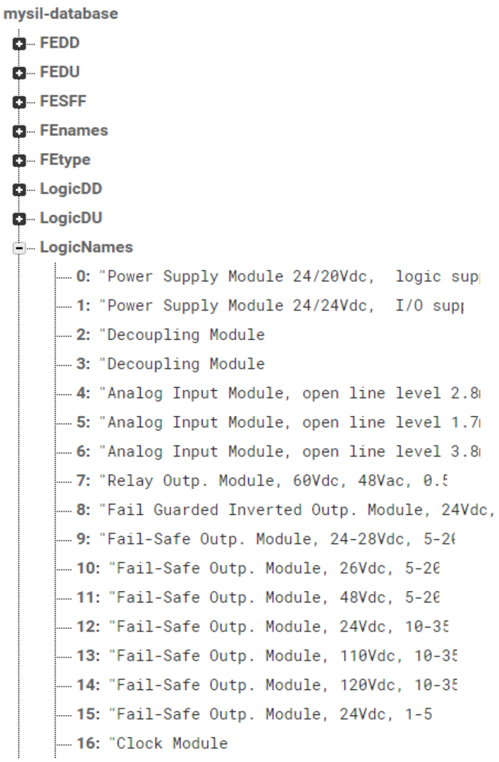
From the safety lifecycle phase, this Android application is quite useful for defining the target SIL. The user can also verify if the conceptual design meets the SIL. The advantage for developing the above functionalities in the form of Android application is for making the previously being used tools as portable as possible and to reduce the complexity of those tools by making this application user-friendly. From the survey, we have done, since most electronic devices support Android operating system, device compatibility problem is minimal.

3.2 Database Organisation

MySIL is composed of the online database system. This development was mainly designed for hardware vendors to update their data information without delay. From the three main features of MySIL, the database is separately designed to be stored on Firebase real-time database system. Since easily accessible database determines how fast and accurate the tool performs [11], a great deal has been put on the database organisation. This database can be as big as the user needs it to be and it can easily be modified, updated, or replaced. Any organisation interested using this application can update or replaces the existing database by their own data input. On the process of data modification, the organizations making the modification should take responsibility on the reliability of the data being changed. Firebase real-time database system has been used considering the key capabilities of the system. The firebase real-time database uses data synchronisation. Every time data changes, any connected device receives that update within seconds. Firebase Apps remain responsive even when offline because the Firebase real-time database SDK persists the data to disk. In addition, the user can access the database directly from a mobile device. These key capabilities are very important and applicable in SISs. For instance, access to the updates on the database will create fast interaction between different facilities of a given company. To give an example, when a certain machine is being repaired or maintained, its failure rate will be recorded automatically and will be shared instantly within departments to which this issue is concerned

3.3 PFD Based Reliability Analyzer

The second section of MySIL is the PFD based reliability analyser. On this section, in addition on the PFD computation, the tool can perform risk analysis based on risk graph. This risk graph is qualitative and category based. The risk graph method included in the tool is consistent with those in IEC draft standard 61511. Risk graph analysis uses four parameters to select the SIL: consequence, occupancy, the probability of avoiding the hazard, and demand rate. To make it convenient for the user to go through this categorical risk assessment, the risk graph has been deployed in the form of the questioner. The tolerable level of risk is implied both in the structure of the graph and by which SIL is at the end of each path.



```
mysil-database
⊞ FEDD
⊞ FEDU
⊞ FESFF
⊞ FEnames
⊞ FEtype
⊞ LogicDD
⊞ LogicDU
⊟ LogicNames
    0: "Power Supply Module 24/20Vdc,  logic sup
    1: "Power Supply Module 24/24Vdc,  I/O sup
    2: "Decoupling Module
    3: "Decoupling Module
    4: "Analog Input Module, open line level 2.8
    5: "Analog Input Module, open line level 1.7
    6: "Analog Input Module, open line level 3.8
    7: "Relay Outp. Module, 60Vdc, 48Vac, 0.
    8: "Fail Guarded Inverted Outp. Module, 24Vdc,
    9: "Fail-Safe Outp. Module, 24-28Vdc, 5-2
    10: "Fail-Safe Outp. Module, 26Vdc, 5-2
    11: "Fail-Safe Outp. Module, 48Vdc, 5-2
    12: "Fail-Safe Outp. Module, 24Vdc, 10-3
    13: "Fail-Safe Outp. Module, 110Vdc, 10-3
    14: "Fail-Safe Outp. Module, 120Vdc, 10-3
    15: "Fail-Safe Outp. Module, 24Vdc, 1-5
    16: "Clock Module
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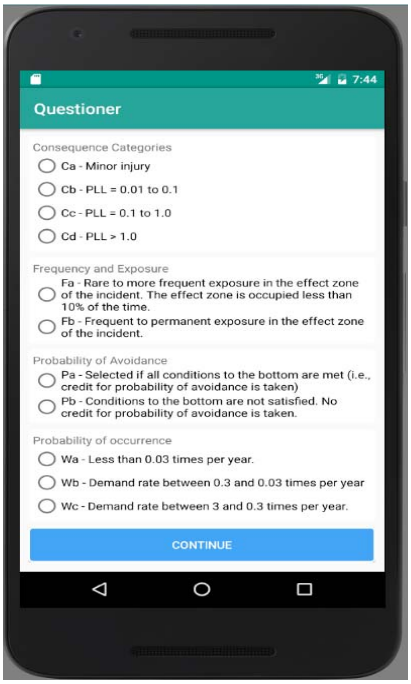
Fig. 3. Firebase Database of MySIL.

In the PFD based reliability analyser, the tool consists of four tabs. The first three tabs represent all calculations related to the sensor, the second tab represents all calculations related to the logic solver, and the third tab is representing calculations related to the final element. Unlike the first three tabs which represent individual components, the last tab represents the system PFD. The calculation that is performed by the tool is sourced formulas of ISA Technical Report TR 84.0.02 Part 2 for De-energize-To Safe state systems (DTS) [16]. The formulation is different for different voting architectures.

For 1oo1 voting architecture

$$PFD_{avg} = n * \left[\frac{1}{2} * PC * \lambda_{Du} * \frac{1}{2} * (1 - PC) * \lambda_{Du} * (T_L + 1)\right] \tag{1}$$

Where PFD_{avg} : average probability of failure on demand; n: number of components being used in the subsystem; PC : proof test coverage; λ_{Du} : dangerousundetectedfailurerate; T_L : lifetime.



Questioner

Consequence Categories

○ Ca - Minor injury

○ Cb - PLL = 0.01 to 0.1

○ Cc - PLL = 0.1 to 1.0

○ Cd - PLL > 1.0

Frequency and Exposure

○ Fa - Rare to more frequent exposure in the effect zone of the incident. The effect zone is occupied less than 10% of the time.

○ Fb - Frequent to permanent exposure in the effect zone of the incident.

Probability of Avoidance

○ Pa - Selected if all conditions to the bottom are met (i.e., credit for probability of avoidance is taken)

○ Pb - Conditions to the bottom are not satisfied. No credit for probability of avoidance is taken.

Probability of occurrence

○ Wa - Less than 0.03 times per year.

○ Wb - Demand rate between 0.3 and 0.03 times per year

○ Wc - Demand rate between 3 and 0.3 times per year.

Fig. 4. Risk Graph Questioner.

For 1oo2 voting architecture

$$PFD_{avg} = \frac{n}{2} * \left[\frac{1}{3} * (PC * (1-\beta) * \lambda_{Du} * T)^2 + \frac{1}{3} * \left((1-PC) * (1-\beta) * \lambda_{Du} * (T_L + 1)\right)^2 + \frac{1}{2} * PC * \beta * \lambda_{Du} * T + \frac{1}{2}(1-PC) * \beta * \lambda_{Du} * (T_L + 1)\right] \tag{2}$$

Where β: common cause factor; T: test interval.

For 2oo3 voting architecture

$$PFD_{avg} = \frac{n}{3} * [\left(PC * (1-\beta) * \lambda_{Du} * T^2 + \left((1-PC) * (1-\beta) * \lambda_{Du} * (T_L + 1)\right)^2 + 3 * \lambda_{Du} * \lambda_{Dd} * MTTR \; T + \frac{1}{2} * PC * \beta * \lambda_{Du} * T + \frac{1}{2} * (1-PC) * \beta * \lambda_{Du} * (T_L + 1)\right] \tag{3}$$

Where λ_{Dd}:dangerous detected failure rate ; MTTR : mean time to repair.

3.4 Optimization of Reliability based on Cost Measure

In this section, multi-objective optimization of SISs in compliance with the standard IEC 61508 is presented. Even though our prior objective is safety, if the risk reduction process costs more than the benefit we get from the safety integrated process, the whole concept of safety might get jeopardized. In this work safety measures, used as optimization objectives are quantified by the Probability of Failure on Demand (PFD) and Spurious Trip Rate (STR). To make sure the system is cost-effective, as a third objective function, Lifecycle Cost (LCC) is optimized. The multi-objective Genetic algorithm has been used to demonstrate the optimization approach based on the formulae, Eq. (4)-(10), borrowed from [15].

$$LCC = C_{PROC} + (C_{OP} + C_{RISK}) * PVF \tag{4}$$

Where LCC: lifecycle cost; C_{PROC}: procurement cost; : operational cost; : risk cost; PVF: present value factor, which is $\frac{1-(1+R)^{-T}}{R}$; R: discout rate; T: useful life of the system in years

$$C_{PROC} = \sum_i \left(C_i^{purchase} + C_i^{design} + C_i^{inst|comm}\right) * N_i + C_{Start-up} \tag{5}$$

Where N_i: number components of the ith subsystem; C_i^{design} : design cost; $C_i^{purchase}$: purchase cost; $C_i^{inst|comm}$: installation & commissioning cost; $C_{Start-up}$: initial plant start-up cost

$$C_{OP} = C_{cons} + C_{PM} + C_T \tag{6}$$

Where C_{cons} : consumption cost; C_{PM} : preventive maintenace cost; C_T : testing cost.

$$C_{RISK} = C_{STR} + C_{HAZARD} \tag{7}$$

Where C_{STR} : spurious trip cost; C_{HAZARD}: hazard cost.

$$C_{STR} = [(\sum_i C_i^{cm} + SD_{Loss})SD_{Time} + \sum_i C_i^{spares} N_i] * STR \tag{8}$$

Where C_i^{cm} : cost of repair per hour; SD_{Loss} : loss of production per hour; SD_{Time}: plant restoration downtime after the spurious trip.

$$STR = \sum_i (\lambda_i^{SUN} + \lambda_i^{SDN}) * N_i + (\lambda_i^{SUC} + \lambda_i^{SDC}) \tag{9}$$

Where λ_i^{SUN} : safe undetecfted normal failure rate; λ_i^{SDN} : safe detected normal failure rate; λ_i^{SUC} : safe undetected common failure rate; λ_i^{SDC} : safe detected common failure rate.

$$PFD_{avg} = \sum_i \frac{\left[[((\lambda_i^{DUN}(TI+T_r) + \lambda_i^{DDN} * T_r)^{N_i+1} - ((\lambda_i^{DUN} + \lambda_i^{DDN}) * T_r)^{N_i+1}\right]}{\lambda_i^{DUN}(N_i+1) * TI} + \lambda_i^{DUC}\left(\frac{TI}{2} + T_r\right) + \lambda_i^{DDC} * T_r] \tag{10}$$

Where DUN: dangerous undetected normal failure; DDN: dangerous detected normal failure; DUC: dangerous undetected common failure; DDC: dangerous detected common failure; TI: test interval; Tr: repair time.

3.5 Case Study

A compressor's outlet pipeline must be protected against leakages. The detection system is comprised of a pressure transmitter subsystem, a logic solver subsystem and a shut-down valve as final control element subsystem [15]. The system is required to achieve an SIL 3 and the tolerable risk frequency or risk target has been set to 1*10^{-6}

per year to protect the compressor's outlet pipeline against leakages. To achieve this, the system integrity must be enhanced by changing components, increasing redundancy, or reduction of Common Cause Factor (CCF) in the system. The maximum PFD_{avg} of the system is set to be $1.7*10^{-4}$. To optimise the system, the decision variables are:

- Redundancy
- Type options
- Common Cause Factor
- Test Interval

The objective functions are Probability of Failure on Demand, Spurious Trip Rate, and Life Cycle Cost. The Genetic algorithm optimization program was created in MATLAB.

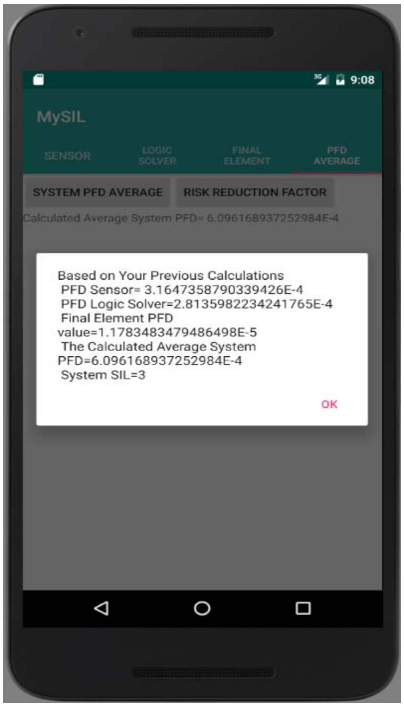
Ⅳ. Result and Discussion

4.1 MySIL Result

Figure 4 Shows the result achieved from MySIL. This result is a combined effect of all the three subsystems in the whole system. After analyzing each subsystem individually, the average PFD was achieved by integrating the results from the three individual subsystems. If the user desires to have only part of the subsystem without analyzing the system PFD, partial subsystem PFD calculation is also possible. Note that this calculation has been done using the sourced formulas of ISA Technical Report TR 84.0.02 part 2 for De-energize-To Safe state systems and Yokogawa's GRC database.

4.2 Optimization Result

The graphical representation of the optimization result as presented in figure 5 shows the relationship between PFD, STR, and LCC. To improve visualization difference of scale (linear and logarithmic) between the below graphs has been used. We can easily observe which variables are conflictive and which variables have a linear relationship. PFD_{avg} and LCC become conflictive in the Pareto optimal front in a range between 10^{-4} and 10^{-3}. Before this range, these two variables are not conflictive which implies the introduction of safety system results in a lower LCC due to the reduction of risk cost. wherein the PFDavg and STR relationship, neutral points are observed (no change in PFD as a response to a change in STR). The LCC vs, STR relation suggests they are generally not conflictive objectives implying any spurious trip (false trip) can increase the LCC by interrupting production.



Calculated Average System PFD= 6.096168937252984E-4

Based on Your Previous Calculations
PFD Sensor= 3.1647358790339426E-4
PFD Logic Solver=2.8135982234241765E-4
Final Element PFD
value=1.1783483479486498E-5
The Calculated Average System
PFD=6.096168937252984E-4
System SIL=3

Fig. 5. MySIL Result Display.

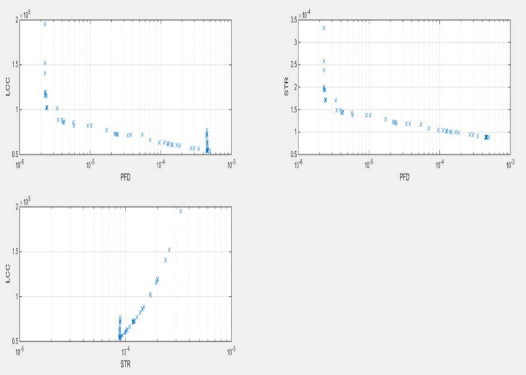


Fig. 6. Pairwise Plot of Result from GA.

V. Conclusion

This paper introduced optimization of reliability based on cost factor deploying Android application called MySIL that can easily assess the reliability of SIS. This application can aid compliance with international safety standards as well as not conflict with the company standards and procedures since it is developed to perform computations by ISA TR84.0.02 Part 2-sourced formulations. This application can provide valid information on PFD_{avg} calculation and risk reduction factor. Compared with existing tools (e.g., Yokogawa's GRC tool), it is user-friendly and the time it takes for the reliability assessment is very short (less than 20 minutes).

MySIL has integrated with online database system using Firebase real-time database. This development was mainly designed for hardware vendors to update their data information without delay. Any company who desires to use this App can just modify/replace the database by their own data and use this App for safety analysis purposes. It is executable on any Android supporting devices. Any devices connected to our Firebase real-time database can receive the change made on the data automatically. By using this data, the scope of the calculation can be defined part by part (only for the sensor, logic solver, or final element) or it can be defined over the whole system.

The genetic algorithm optimizer, which is working side-by-side with MySIL is a powerful tool developed to optimize reliability based on cost factors. It can find the optimal parameters for the SIS that can give the best combination of optimally high safety with lower lifecycle cost. The optimization result has been compared against the leading work of Torres-Echeverria (2009) and gives similar Pareto-optimal front distribution. In this version of MySIL, the optimizer is not included in the tool but working separately. There will be the final version of MySIL which will include the optimizer along with different new features to make it a complete set.

Acknowledgment

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