Utilizing Layer of Protection Analysis (LOPA) in Verification of Safety Integrity Level (SIL) of Instrumented System

by

Wan Mohd Fakhirin Bin Mohamed Hassan

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Universiti Teknologi PETRONAS
Bandar Seri Iskandar
31750 Tronoh
Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

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Approved by,

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(DR. MOHANAD M.A.A EL-HARBAWI)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

July 2010

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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WAN MOHD FAKHIRIN BIN MOHAMED HASSAN

ABSTRACT

The project is aimed to utilize layer of protection analysis (LOPA) to verify safety integrity level (SIL) of safety instrumented system. Safety instrumented system (SIS) is the last resort in case of emergency happened in plant. Determining the specific safety requirement of safety systems is a vital part to ensure accidents are prevented. Previous study is carried out till classification of Safety Integrity Levels (SIL) for hazardous installation by using the risk assessment techniques. In this study, the focus will be on SIL classification and verification in safety instrumented system (SIS).

The program is developed using Microsoft Excel based on established methodology found in the literatures. Thorough literature surveys are expected in order to gather appropriate SIL verification information which will further integrate in existing spreadsheet. The program is tested using two case studies related to process plant industries. The results obtained show the sufficiency of the protection system and provide risk control strategy including number of SIL required in case of the protection is insufficient. If the protection system is sufficient, it will ensure the design is the optimum. Reliability and accurateness of the result are vital due to main function of the program is to assess and validate the SIS.

The application is used either in designing the SIS or in auditing the effectiveness of the installed SIS. The verification of assigned SIL to a particular Safety Instrumented Function (SIF) is still new compared to SIL classification. Based on industrial perspective, there is no established method on verification of an installed SIS. Most scenarios can be catered by enhancing the existing design rather than adding safety protection layer.

Future study shall be continued to improve the relevancy and reliability of the tool by integrating more parameters in assessing a case.

ACKNOWLEDGEMENT

First of all, I would like to take this opportunity to praise to God, the Most Merciful and Most Grateful for His Permission so that I am able to finish my dissertation. Millions of thanks to my kind supervisor, Dr. Mohanad M.A.A El-Harbawi for his help and advice upon accomplishment of my final year project. I would like to thank to those who help me in contributing the idea and useful feedbacks either directly or indirectly to improve my thesis.

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CHAPTER 1

INTRODUCTION

1.1 Project's Background

Accidents at any plant either offshore or onshore may result in casualties and economic loss. Safety instrumented system (SIS) is the last automatic protection system in case of emergency happened in plant. Determining the specific safety requirement of safety systems is vital part in ensuring that accidents are prevented. In the 1990s the standards IEC 61508 and IEC 61511 emerged and the need for documenting compliance with these in a consistent manner led to the introduction of the layer of protection analysis (LOPA) (Lassen, 2008).

LOPA method is being used to determine if there are sufficient layers of protection against an accident scenario. A scenario may require one or many protection layer depending on complexity and potential severity of the process. For a given scenario, only one layer must work successfully for the consequence to be prevented. (CCPS, 2001). Due to no layer is perfectly effective, sufficient protection layer must be provided to minimize the risk of accident tolerable.

In this project, the framework of LOPA method is combined with framework of safety integrity level (SIL) to assess the effectiveness of SIS. The SIL is the key design parameter specifying the amount of risk reduction that the safety equipment is required to achieve for a particular function in question. It is based on *probability of failure on demand* (PFD) for a specific safety instrumentation function (SIF) in safety instrumented system. The suitable SIL assigned is inline with the concept of *as low as reasonably practicable* (ALARP) which it reduce the risk to a tolerable level.

1.2 Problem statement

Various methods in selecting safety integrity levels (SILs) have been proposed and adopted by industry. The result of using poor methods to select SILs is typically either an overdesigned or an under designed safety instrumented system (SIS). In today practice, evaluation and verification of SIL on SIS is rarely being applied. SIL classification is only performed during design phase. This situation has lead to decrement of independent protection layer (IPL)'s audit-ability which violating the IPL's rule. Other problem is lack of a comprehensive discussion of SIL verification compared to SIL classification. Therefore, this study will focus on classification and verification of SIL on SIS which it is hoped that it will be the initiating step for further development of proper SIL verification method. However, the subject is still new since the literature of the subject is small in amount and moreover is scattered among various periodicals and symposia. Hence, a rigorous literature reviews and discussion with expert from industries are expected throughout the study.

1.3 Objective

The objectives of this study are listed as follows:

- To utilize Layer of Protection Analysis (LOPA) method in the verification of Safety Integrity Level (SIL) of instrumentation system.
- To develop framework of LOPA and SIL including a common terminology and worksheet.
- To implement LOPA and SIL procedures in a practical case study.

1.4 Scope of the Project

The scope of study will involve the utilization LOPA method in the determining the safety integrity level (SIL) of instrumented system. The project will focus on combining the framework of SIL and LOPA and implement both procedures in a practical case study. Apart from that, the study also will focus on classification and verification of SIL on Safety Instrumented System (SIS). In this project, the case study related to one of the oil and gas industries will be discussed.

1.4.1 Relevancy of the Project

The purpose of this project is to combine the framework of LOPA and SIL and implement both of the procedure in industry case study. The subject is still new since the literature of the subject is small in amount and moreover is scattered among various periodicals and symposia. Hence, a comprehensive discussion of the process of selecting SILs is a need and the application of the combination between LOPA and SIL method will be shown in the study.

1.4.2 Feasibility of the Project within the Scope and Time Frame

This project will start by collecting the reading material such as the books, journals, related website, thorough discussion with supervisor and collaboration from industrial practitioners. At the end of Final Year Project (FYP) 1, it is expected that the literature survey on LOPA approaches have been carried out and understand all the basic concept of the LOPA approach. Meanwhile, for Final Year Project (FYP) 2, the study will focus on implementing the approach by collecting the information and case study from industry.

CHAPTER 2

LITERATURE REVIEW

2.1. Layer of Protection Analysis

Layer of protection analysis is a semi-quantitative risk analysis technique that is applied following qualitative hazard identification tool such as HAZOP. LOPA is described as semi-qualitative due to the technique does use numbers and generate a numerical risk estimate. The primary purpose of LOPA is to determine if there are sufficient layers of protections against an accident scenario (CCPS, 2001).

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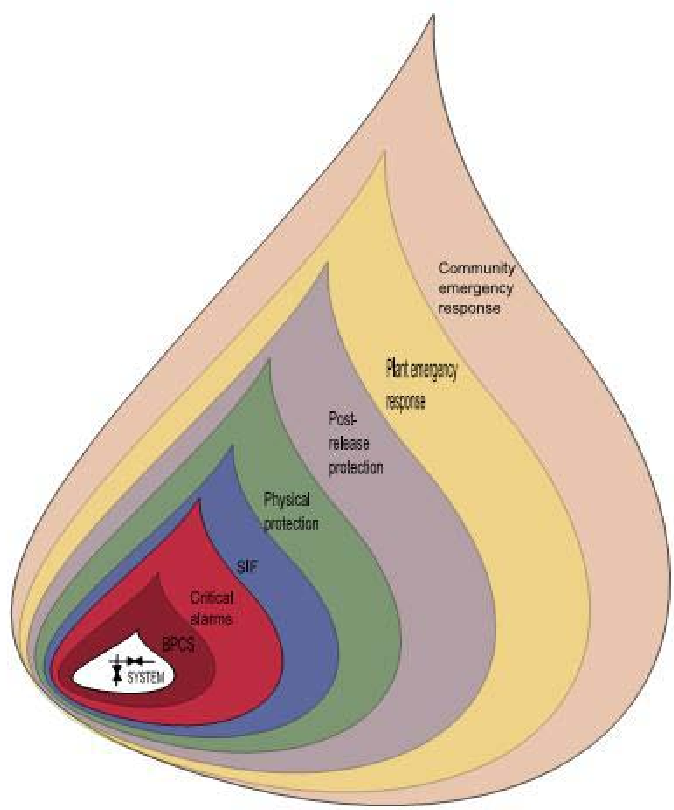


Figure 1: Layer of defense against possible accidents (Lassen, 2008).

Based on Figure 1, many type of protection layer are possible. A scenario may require one or many protection layers depending on the process complexity and potential severity of a consequence (CCPS, 2001). Theoretically, only one layer is enough to prevent the consequence. However in reality, no layer is perfectly effective. Therefore, sufficient protection layer must be provided to minimize the risk of accident.

For LOPA, the term Independent protection layer (IPL) is used rigorously to describe the protection layer. An IPL must be effective in reducing risk and must be auditable (Wei et al., 2008). Each layer should be analyzed to determine its basic independence from the initiating event and from the other protection layers. A probability of failure on demand (PFD) is assigned to an IPL to account for its reliability to respond to system demand.

LOPA is limited to evaluating a single cause-consequence pair as a scenario. In this context, a LOPA scenario represents one path. Normally the path to the worst consequence is selected via an event tree. Figure 2 shows an event tree for a given initiating event. The limitation of LOPA method will be further discussed in next section.

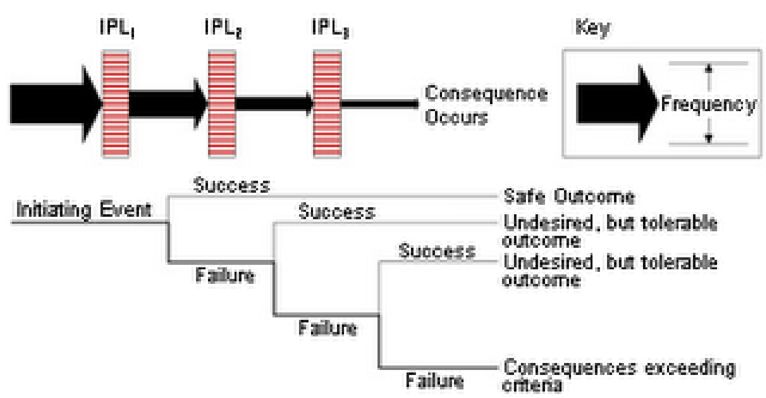


Figure 2: Comparison of LOPA and event tree analysis (CCPS, 2001).

According to Marszal and Scharpf, (2002), LOPA can be viewed as a special type of event tree analysis (ETA) as illustrated in Figure 2, which has the purpose of determining the frequency of unwanted consequence that can be prevented by a set of protection layers. As mentioned before, the approach evaluates a worst-case scenario where all the protection layers must fail in order for the consequence to occur. Assuming the layers are determined to be independent, the final mitigated event frequency, f_i^C, is calculated by multiplying the initial cause frequency, f_i^1, by the PFDs of the individual IPLs, PFD_{ij} , as shown in Equation 1 (CCPS, 2001).

$$f_i^C = f_i^C \times \prod_{j=i}^{j} PFD_{ij} \tag{1}$$

2.2. Limitation of LOPA method

It is important to fully understand the limitation of the selected approach to ensure the LOPA works best and delivers accurate and reliable result. LOPA is limited to evaluating a single-cause consequence pair as a scenario. A method such as fault tree or event tree analysis is more suitable in case of more detailed and complex issues. Besides that, LOPA may be inappropriate for a very high consequence event according to Figure 3. Based on ANSI /ISA S84.01, if the consequence estimation is too severe or the likelihood too aggressive, the final selected Safety Integrity Level may be too high which result in an over designed and over costly Safety Instrument System (SIS). The topic will be further explained in next chapter.

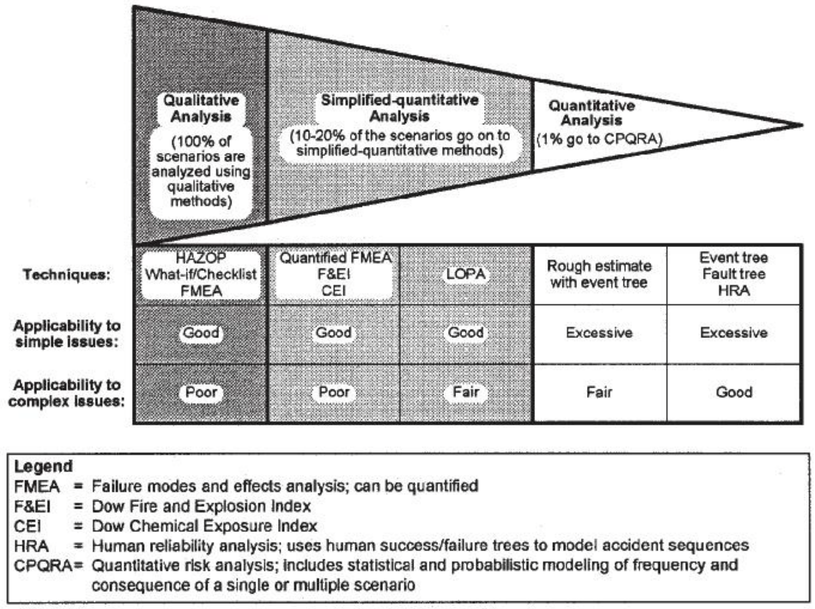


Figure 3: Spectrum of tool for risk-based decision making (CCPS, 2001).

Moreover, the LOPA breaks down with human initiated events covered by human initiated safeguard with little or no equipment intervention (equipment failure, equipment sensing, equipment activated functions) (PETRONAS Group Technology Solution, 2009). Human errors are very difficult to quantify and can be easily extend outside the capabilities of limited database driven methodology such as LOPA. It works best when the scenario being evaluated is dominated by equipment/instrument failures, sensors and logic driven field element with little or no human intervention. Another caution is to avoid incorporating an IPL failure into the initiating event frequency. As described in (CCPS, 2001) it will jeopardize the PFD for a human IPL.

2.3 Safety Integrity Level (SIL)

The concept of safety integrity levels (SILs) was introduced during the development of BS EN 61508 (BSI 2002) as a measure of the quality or dependability of a system which has a safety function- a measure of the confidence with which the system can be expected to perform that function (Gulland, 2004). In other word, SIL is a way to indicate the tolerable failure of a particular safety function. The method of SIL classification is described in next chapter.

There are several people developed LOPA application. For example Markowski and Mannan, (2009) have developed pfLOPA tool for pipeline industries. The fuzzy piping risk assessments enable a better pipelines risk assessment output compare to classical LOPA in term of incident scenario risk and appropriate selection and assessment of layer protection. Wei et al., (2009) have developed a simplified semi-quantitative risk analysis model using LOPA to evaluate a highly reactive process and furthermore it illustrates the benefits of risk assessment to follow HAZOP hazard analysis. Guo and Yang (2007) developed a simple reliability block diagram (RBD) method for safety integrity verification. The RBD analysis is carried out to compute the PFD_{avg} of voted group and it yield the result that is accordance with those in IEC 61508-6. This method can be applied to the quantitative SIL verification. Besides, it helps those take IEC 61508-6 as their guidance.

On the other hand, Kosmowski, (2006) have proposed a formal method to describe web applications by means of process algebra which can be automatically verified by a model checker. Andrews and Bartlett, (2005) introduced a branching search approach. The approach has proven to be effective for High Integrity Protection System (HIPS) safety system optimization. This method shows potential for application to a wider range of problem. According to Mannan et al., (2004), using point values in calculating the overall system safety availability or SIL may lead result in misleading evaluation of SIL of an SIS. In the paper, they proposed practical and efficient procedures to deal with data uncertainty in determining SIL for an SIS and identify the inputs that may lead to a change in the estimation of SIL. This methodology will guide SIS designers and process hazard analysts toward a more accurate SIL estimation and avoid misleading results due to data uncertainty.

Stavrianidis and Bhimavarapu, (1998) have discussed two performance safety standards (ANSI/ISA S84.01 IEC d61508). In order to comply to the standard requires a hazards and risk analysis to establish the safety requirements for safety instrumented functions in terms of SIL. The identified safety instrumented functions were then conceptually integrated into an SIS.

2.4 SIL and SIS Development

The concept of SIL was initially introduced during the development of BS EN 61508 (BSI 2002) as a measure of the quality or dependability of a system which has a safety function.

Previous study completed until determination of scenario frequencies and making risk decision (SIL selection) where SIL is determined using LOPA method which follows 6 steps shown below:

- Step 1: Estimating Consequences and Severity
- Step 2: Developing Scenarios
- Step 3: Identifying Initiating Event Frequency
- Step 4: Identifying Related IPLs
- Step 5: Determining Scenario Frequency
- Step 6: Making Risk Decision. Determine SIL

The scenarios or sequence of events are developed using event tree analysis from initiating event till results in an undesirable outcomes. Figure 4 is the example of the event tree developed from previous study by Zatil, (2009). Based on the 2 examples given below, the previous study uses spreadsheet tool to calculate the required SIL of each initiating event based on the event tree analysis. The scenario frequency is then calculated using equation 1 prior computing the LOPA ratio shown in Equation 2 (CCPS, 2001). From the LOPA ratio gained using equation 2, the SIL target can be determined using Table 4. However, it does not specifically indicate the recommendation required for each case. In other word, it studied on SIL evaluation on safety instrumented function (SIF). As mentioned before, the current study will continue the previous work by focusing SIL evaluation on SIS which will give well and more specific recommendation for each case which will be further discussed in next chapter.

$$\text{LOPA ratio, LR} = \frac{\text{Risk Tolerance}}{\text{Scenario frequency}} \qquad (2)$$

According to PETRONAS Group Technology Solution, (2009) if LR ≥ 1, there is no need to add other IPL otherwise additional IPL is required.

Zatil, (2009) has developed a tool, which is capable to determine SIL. In example 1, the initiating event is pressure vessel residual failure where the failure rate is 0.000001. Table 1 shows four Independent Protection Layers (IPLs) to prevent the undesirable outcomes to occur which initiated by pressure vessel residual failure. Event Tree Analysis (ETA) method as shown in Figure 4 is used to develop the scenario of each initiating event. Scenario frequency is determined using ETA method and is the result is shown in Figure 5.

<u>Example 1: Pressure Vessel Residual Failure (0.000001)</u>

Table 1: PFD of IPLs in example 1 (Zatil, 2009)

Safety Function:	**Inherently Safe Design**	**Critical Alarms & Human Intervention**	**Safety Instrumented Function (SIF)**	**Relief Valve**
Identifier	B	C	D	E
PFD	0.01	0.1	0.01	0.01

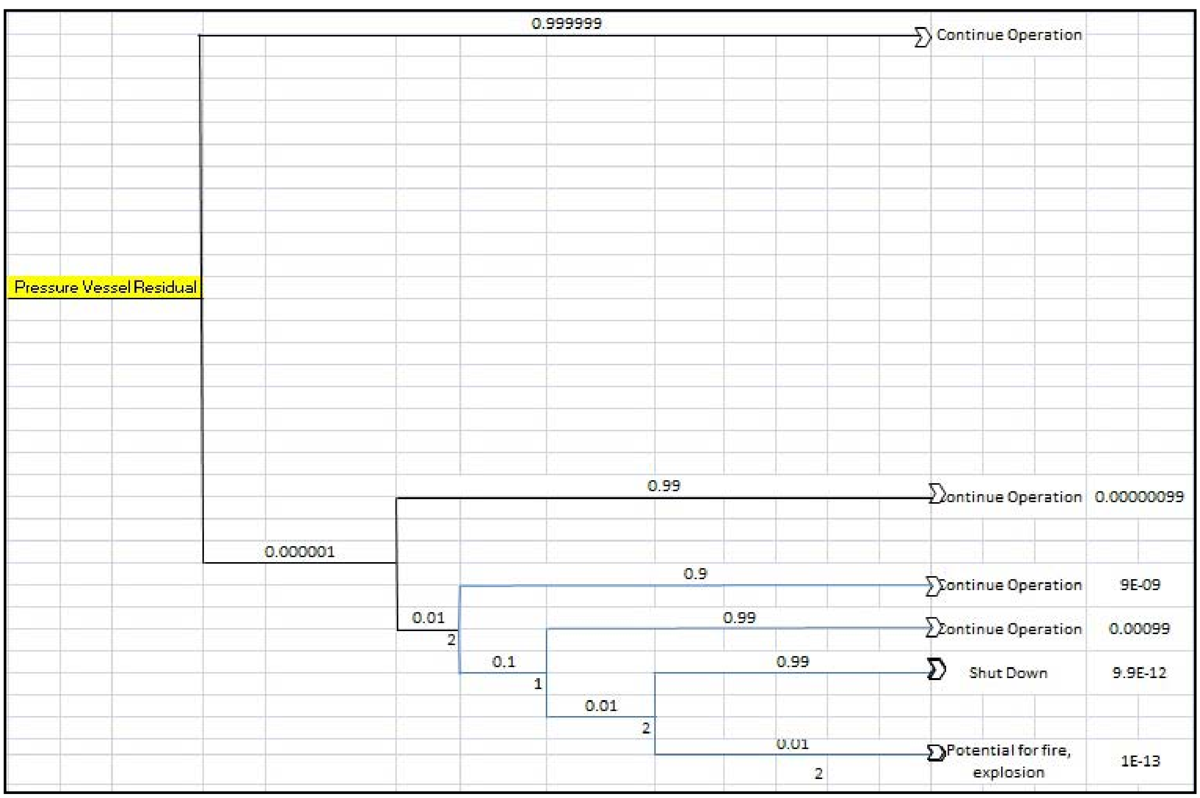


Figure 4: Event tree analysis of pressure vessel relief valve failure (Zatil, 2009)

Based on Figure 5, once the scenario frequency is gained, the LOPA ratio can be calculated. The ratio gained will determine the SIL required.

Risk Tolerance Criteria	10^{-4} - 10^{-5}	10^{-5}
	Taking 10^5, max risk tolerance	
LOPA Ratio	Tolerance/Scenario Frequency	
LOPA Ratio =	1000000	

Since LR ≥ 1, no need to add other independent protection layers (IPL). So, risk is acceptable.

Figure 5: Result from the spreadsheet (Zatil, 2009)

The methodology used in example 1 is same with example 2. The initiating event for this case is pump seal failure which its probability to occur is 0.1. The lists of available IPLs are shown in Table 2. The probability of failure of each IPLs also available which can be obtained in CCPS database.

Example 2: Pump Seal Failure (0.1)

Table 2: PFD of IPLs in example 2 (Zatil, 2009)

Safety Function:	Inherently Safe Design	Operator Response
Identifier	B	C
PFD	0.01	0.1

In order to compute the scenario frequency, again the ETA method is used and is shown in Figure 6. The calculated LOPA ratio is then shown in Figure 7.

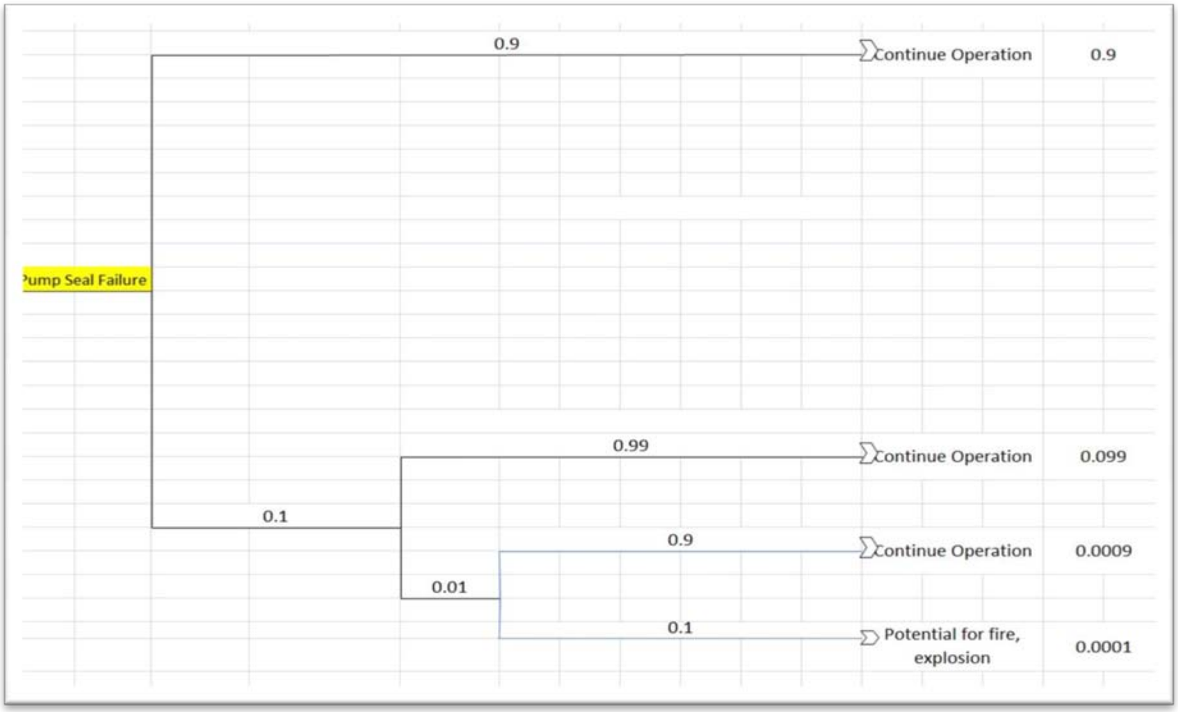
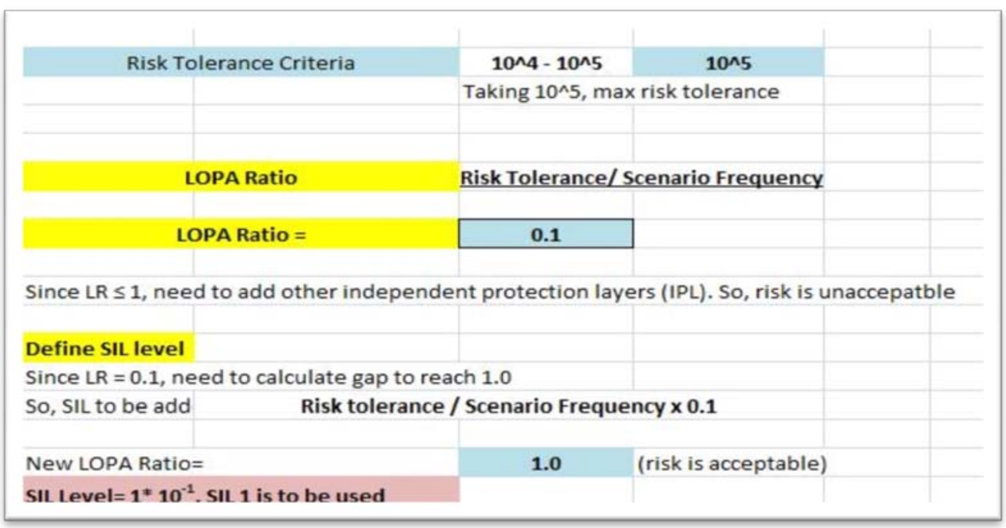


Figure 6: Event tree analysis of pump seal failure (Zatil, 2009)



Risk Tolerance Criteria	10^4 - 10^5	10^5
	Taking 10^5, max risk tolerance	
LOPA Ratio	**Risk Tolerance/ Scenario Frequency**	
LOPA Ratio =	**0.1**	

Since LR ≤ 1, need to add other independent protection layers (IPL). So, risk is unaccepatble

Define SIL level

Since LR = 0.1, need to calculate gap to reach 1.0

So, SIL to be add **Risk tolerance / Scenario Frequency x 0.1**

New LOPA Ratio=	**1.0**	(risk is acceptable)
SIL Level= 1* 10^{-1}. SIL 1 is to be used		

Figure 7: Result yields from spreadsheet (Zatil, 2009)

The results obtained using the application developed by Zatil, (2009) are tabulated in Table 3. Noted that each initiating causes have been assessed its risk tolerability. Based on Table 3, the maximum SIL assigned is 1 for the case of intolerable risk while the rest are tolerable in terms of risk. It does not specifically mention the recommendation or action plan needed to make the risk is tolerable.

Table 3: Risk tolerability of initiating event (Zatil, 2009)

No	Initiating Causes	Risk is tolerable/intolerable
1	BPCS Instrument Loop Failure	Tolerable
3	Fixed Equipment Failure	SIL 1
4	Pumps & other Rotating Equipments	SIL 1
5	Cooling Water Failure	SIL 1
6	Loss of Power	Tolerable
7	Human Error (Routine task, 1 per day opportunity)	SIL 1
8	Human Error(Routine Task, Once-per-month opportunity)	SIL 1
9	Human Error ((Non-Routine Task, Low Stress)	SIL 1
10	Human Error (Non-Routine Task, High Stress)	SIL 1
11	Pressure Vessel Residual Failure	Tolerable
12	Piping Residual Failure-100m-Ful Breach	SIL 1
13	Piping Leak (10% section)-100m	Tolerable
15	Gasket/Packing Blow-out	Tolerable
16	Turbine/Diesel Engine Over speed w/casing Breach	Tolerable
17	3^{rd} Party Intervention	Tolerable
20	Pump Seal Failure	SIL 1
21	Unloading/Loading Hose Failure	SIL 1
22	Small External Fire (aggregate causes)	Tolerable
25	Operator Failure (Routine procedure, well-trained, unstressed, not fatigued)	SIL 1

CHAPTER 3

METHODOLOGY

This project is mainly to develop an application n which will utilize layer of protection analysis (LOPA) method to verify the safety integrity level of instrumented system. The development of this application has been done using information and communication technology (ICT) and simple programming software such as Microsoft Excel 2007 to perform the study.

3.1 Method of SIL Classification

Safety integrity levels are categorized based on the probability of failure on demand (PFD) for a specific safety instrumented function (SIF). The categories PFD range has two types. According to ANSI/ISA 84.01-1996, the categories of PFD range from one to three. Meanwhile, as defined in IEC 61508 and 61511, the categories PFD range from one to four. Table 4 show the PFD ranges and associated risk reduction factor (RRF) ranges that correspond to each SIL.The degree of consequence of event will directly affect the SIL selection as discussed earlier.

Based on Table 4, the highest SIL is 4 and the corresponding PFD is 10^{-5}. Therefore, it has the limitation when the consequence of the event is too severe which further lead to very low of probability of failure on demand (PFD). In this case, the PFD that is beyond the range, will end up with too high of final SIL selection. An overdesign and high cost of SIS are expected.

Table 4: Safety Integrity Levels and corresponding PFD and RRF (CCPS, 2001)

LOPA ratio	SIL	**PFD Range**	**RRF range**
10^{-4}	4	10^{-4} – 10^{-5}	10000 – 100000
10^{-3}	3	10^{-3} – 10^{-4}	1000 – 10000
10^{-2}	2	10^{-2} – 10^{-3}	100 – 1000
10^{-1}	1	10^{-1} – 10^{-2}	10 – 100

Before going further, the fundamental question on how frequently will failures of either type of function lead to accidents need to be clarified. There are two type of function which are functions with low demand rate and functions with high demand rate or operate continuously. For functions with a low demand rate, the accident rate is a combination of two parameters:

- The frequency of demands
- The probability of function fails on demand (PFD)

The appropriate measure of performance of the function for this case is PFD or its reciprocal, Risk Reduction Factor (RRF). Based on that, the Table 9 gives the definition of SILs for low demand mode. On the other hand, for functions which have a high demand rate (operate continuously), the accident rate is the failure rate, λ, which is the suitable measure of performance. An alternative measure is mean time to failure (MTTF) of the function. Noted that the failure must be exponentially distributed and MTTF is the reciprocal of λ.

According to Gulland (2004), the parameters discussed above are related each other and can expressed as showed in Equation 3 and 4:

$$\mathrm{PFD} = \frac{\lambda \mathrm{T}}{2} \quad \text{or } \mathrm{PFD} = \frac{\mathrm{T}}{(2 \times \mathrm{MTTF})} \tag{3}$$

$$\mathrm{RRF} = \frac{2}{(\lambda \mathrm{T})} \quad \text{or} \quad \mathrm{RRF} = \frac{(2 \times \mathrm{MTTF})}{\mathrm{T}} \tag{4}$$

Where:

λ = failure rate

T = time

MTTF = reciprocal of λ

PFD = Probability failure on demand

RRF = Risk Reduction Factor, reciprocal of PFD

The function can be proof-tested at a frequency which is greater than the demand rate. The term T indicates the proof-test interval. (Note that to significantly reduce the accident rate below the failure rate of the function, the test frequency should be at least 2 and preferably $\geq$ 5 times the demand frequency.). Table 5 indicates definitions of SILs for functions which have a high demand rate or continuous mode.

Table 5: Definitions of SILs for High Demand/ Continuous Mode (CCPS, 2001)

SIL	Range of λ (failures per hour)	Ranges of MTTF (yr)[2]
4	$10^{-9} \leq \lambda < 10^{-8}$	100000 ≥ MTTF > 10000
3	$10^{-8} \leq \lambda < 10^{-7}$	10000 ≥ MTTF > 1000
2	$10^{-7} \leq \lambda < 10^{-6}$	1000 ≥ MTTF > 100
1	$10^{-6} \leq \lambda < 10^{-5}$	100 ≥ MTTF > 10

SIL is determined based on PFD on a particular SIF. Safety instrumented function is an action a safety instrumented system (SIS) takes to bring the process or the equipment under control to a safe state (Marszal and Scharpf, 2002). This function is single set of actions that protects against a sing specific hazards.A SIF's sensors, logic solver and final elements act in concert to detect a hazard and bring the process to a safe state. Meanwhile, the safety instrumented system (SIS) is comprised of safety function (see SIF above) with collection of sensors, logic solvers and actuators. The SIS is implemented to protect the same process/project acts as backup to basic process controlled system (BPCS). Figure 8 shows the relationship between SIL, SIF and SIS. Every SIS has one or more safety functions (SIFs) and each affords a measure of risk reduction indicated by its safety integrity level (SIL).

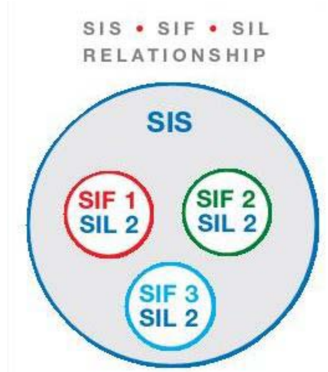


Figure 8: Relationship between SIL, SIF and SIS (Magnetrol Bulletin, 2009)

3.2 Method of SIL evaluation on SIS

3.2.1 Identify a hazardous event and assess its severity

Start this methodology with a hazard and operability (HAZOP) study, the most commonly used methodology for process plant hazard evaluation from which the highest potential risk scenario are selected. Highest potential risk scenarios are scenario with high initiating event (cause) frequency and high unmitigated consequences. These scenarios can be easily detected by looking at the amount of existing or proposed protection systems (in the safeguards and recommendation columns) where a high number of protections can be related with high risk, or by searching explosion , fire or toxic release potential mentioned in consequences which can be referred in Table 6.

Table 6 : Threshold frequency numbers for each consequence category (CCPS, 2001)

Consequence severity	Max. acceptable frequency	Threshold Frequency Index, F_t
Category 5 - Catastrophic	1/10000	3
Category 4 – Major	1/1000	4
Category 3 – Critical	1/100	5
Category 2 – Minor	1/10	6
Category 1 - Negligible	1	7

In the system, consequence severity of each category can be selected from the dropdown list as shown in Figure 9.

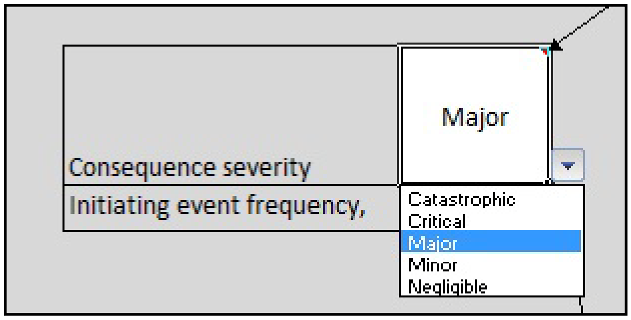


Figure 9: Consequence severity dropdown list

3.2.2 Identify the initiating event and access its frequency

The initial event for a scenario is taken from the cause column in the HAZOP study. When each scenario has been evaluated with a risk matrix, its frequency can be determined from the evaluation. This value must be compared with ranges available in literature for validation. The system developed allow user to key in the initiating event frequency as shown in Figure 10.

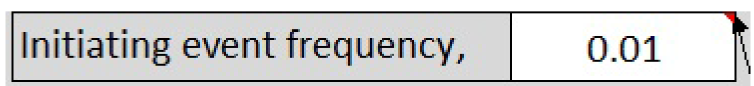
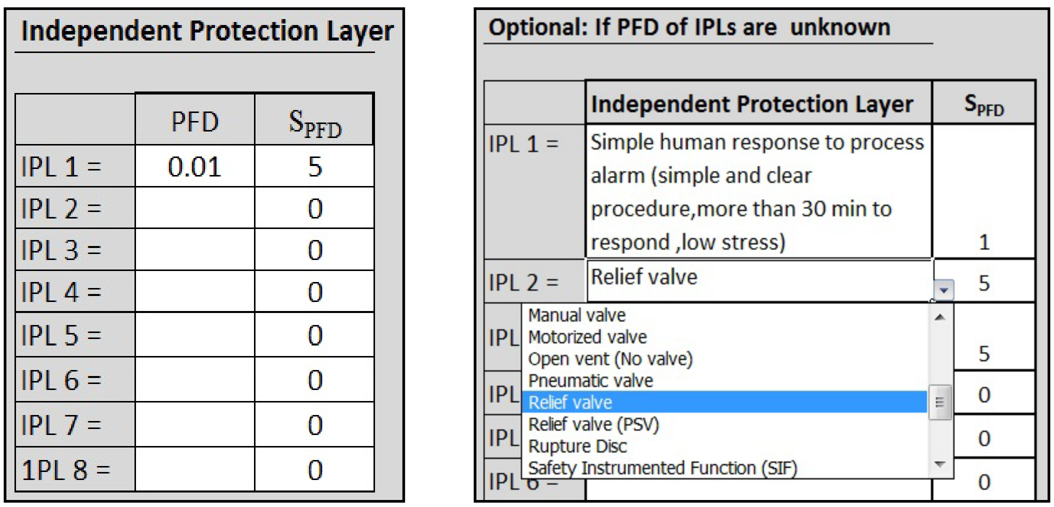


Figure 10: Initiating event frequency column that need to be filled

3.2.3 Identify the applicable independent protection layers and evaluate their effectiveness

Assumption:

For this method, the BPCS layer would not be considered because in a HAZOP, its failures are normally the initiating events. The emergency response layers are not taken into account because the objective is to end up not needing these protection layers. Thus, the following protection layers are considered in this methodology (Alarms and human response, SISs and relief systems).



(a) (b)

Figure 11: Interface of the system where list of IPLs are available to be selected.

Figure 11 (a) shows the interface of the system where users are allowed to key in the PFD for each IPLs. In case of the PFD of each IPLs are not available, Figure 11 (b) shows the other option where users can select type of IPLs from the drop down list. Notice that once either the PFD value or types of IPLs are being selected, the S_{PFD} will be displayed automatically.

3.2.3.1 Effectiveness of layers

Each layer evaluated using an index related to the order of magnitude of the PFD (S_{PFD}) according to Table 7. The S_{PFD} numbers allows us to translate the PFD in a value that is easy to manage. A low S_{PFD} numbers indicates a protection with a low effectiveness and very high probability of failure in case we need it. The effectiveness of the protection can be determined using Equation 5 (Campa and Cruz-Gomez, 2009).

Table 7 : Probability of Failure on demand indexes (CCPS, 2001)

Probability of failure on demand index (S_{pfd})	**Probability range**	**Expected failure based on 1000 demand**
0	**1**	> 1000
1	**1 to 10-1**	100 to 1000
2	**10-1 to 10-2**	10 to 100
3	10-2 to 10-3	1 to 10
4	10-3 to 10-4	0.1 to 1
5	10-4 to 10-5	0.01 to 0.1

Effectiveness of the protections which demoted as ES is shown in equation 5 while the system will calculate and display the ES value once all the IPLs have been specified as shown in Figure 12.

$$ES = \sum S_{\mathrm{PFD}} \quad (5)$$

The main advantage of using indexes instead of exponent numbers is shown here, where a multiplication of probabilities is handled as adding integer numbers.

Effectiveness of protection , ES	16

Figure 12: Output of the summation of all S_{PFD}

3.2.4 Calculate the expected frequency for the hazardous event

The total protection effectiveness number is used to calculate the expected frequency for the hazardous event taking into account the IPLs. This frequency is called reduced frequency F_r. It can be found using Equation 6 (Campa and Cruz-Gomez, 2009).

$$F_r = F_i - ES \qquad (6)$$

Where:

F_r = Frequency reduction

F_i = Initiating index frequency

ES = Effectiveness of protection

The system will perform the calculation using equation 6 and display the result in the system interface.

Figure 13: Output of the subtraction of F_i and ES

3.2.5 Determine the need for additional layers of protection and the required SIL if a SIS is recommended.

Once the reduced frequency (F_r) is obtained, it is necessary to compare it with the threshold frequency (F_t) for the selected scenario in Table 9. If the protection is sufficient, there is no risk control strategy will be suggested as shown in Figure 14.

However, the system will check whether it is overdesigned or not based on parameter which can be specified by users. In the risk control strategy column, no recommendation required which is denoted as NILL as shown in Figure 14.

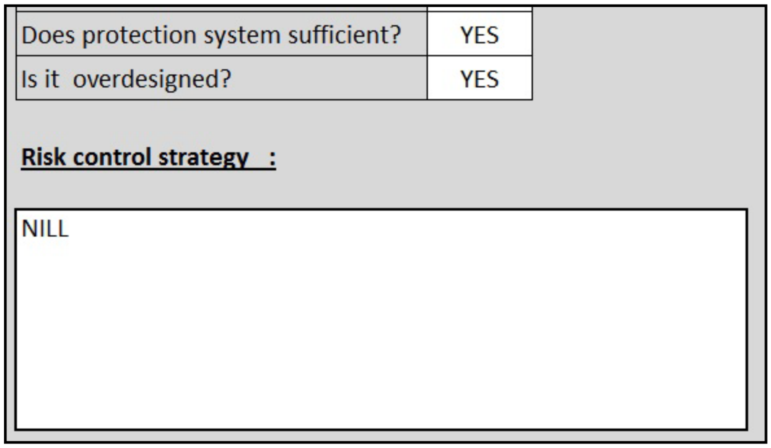


Figure 14: Risk control strategy interface

3.2.6 Determination of required SIL for an already installed SIS

To determine the required SIL of previously installed SIS, it can be done by evaluating the risk of scenario without considering the SIS protection layer. Table 8 shows the value of S_{ADD} that will give the required SIL for the SIS. Equation 7 shows how the S_{ADD} is calculated.

$$S_{ADD} = F_r - F_t \tag{7}$$

Table 8 : Determination of required SIL from S_{ADD} number (CCPS, 2001)

S_{add}	Required SIL	PFD Range
4	3	$10^{-3} - 10^{-4}$
3	2	$10^{-2} - 10^{-3}$
2	1	$10^{-1} - 10^{-2}$

Table 9: Comment and suggestion for each condition (Campa and Cruz-Gomez, 2009)

Condition	Comment
$Fr \leq Ft$	Protection are sufficient for risk scenario (if Fr << Ft, then there is an over design according the acceptability criteria
$Fr > Ft$	The protection are insufficient for the risk scenario (the combined IPLs effectiveness are not enough to reduce the initiating event frequency to the maximum acceptable frequency for the scenario Need to establish a risk control strategy based on the required effectiveness. Frequency reduction, S_{ADD} = Fr - Ft **<u>Case 1: $S_{ADD} \leq 1$</u>** If we already have IPLs , we need to recommend improving the effectiveness of these layers (more frequent and systematized maintenance program, enhance operators response to alarms by training / emergency drill If there are no IPL applicable, need to recommend installing a non-SIS PL. Only if no non-SIS layers can be applied, we could suggest using a SIS with SIL 1 **<u>Case 2: $2 \leq S_{ADD} \leq 4$</u>** Non-SIS protection layers and existing protection layer improvement must be suggested if possible and reevaluated to determine if this is enough. If no non-SIS protection layers can be suggested and existing protection have been improved, we can suggest installing a SIS. **<u>Case 3: $S_{ADD} > 4$</u>** The value of S_{ADD} is very high and a SIS protection would not be enough to mitigate the risk. Therefore reevaluation of the equipment or process searching for a high effectiveness solutions and second, implement several SIS and non-SIS protection layers until the risk is at acceptable level. If a SIS is recommended, the required SIL can be determined from the S_{ADD} value after considering the other non-SIS alternatives using Table 8.

3.3 Tool Development

The flow chart of the system is shown by Figure 15. It describes how the system works from raw data, processing it into useful information. Based on Figure 15, there are five main processes involve which are data key-in, input processing, display, calculation and output. There are three type of data required - consequence of severity, initiating event frequency and types of IPLs. Several equations mentioned in previous subchapter are used to calculate and assess the reliability of the SIS.

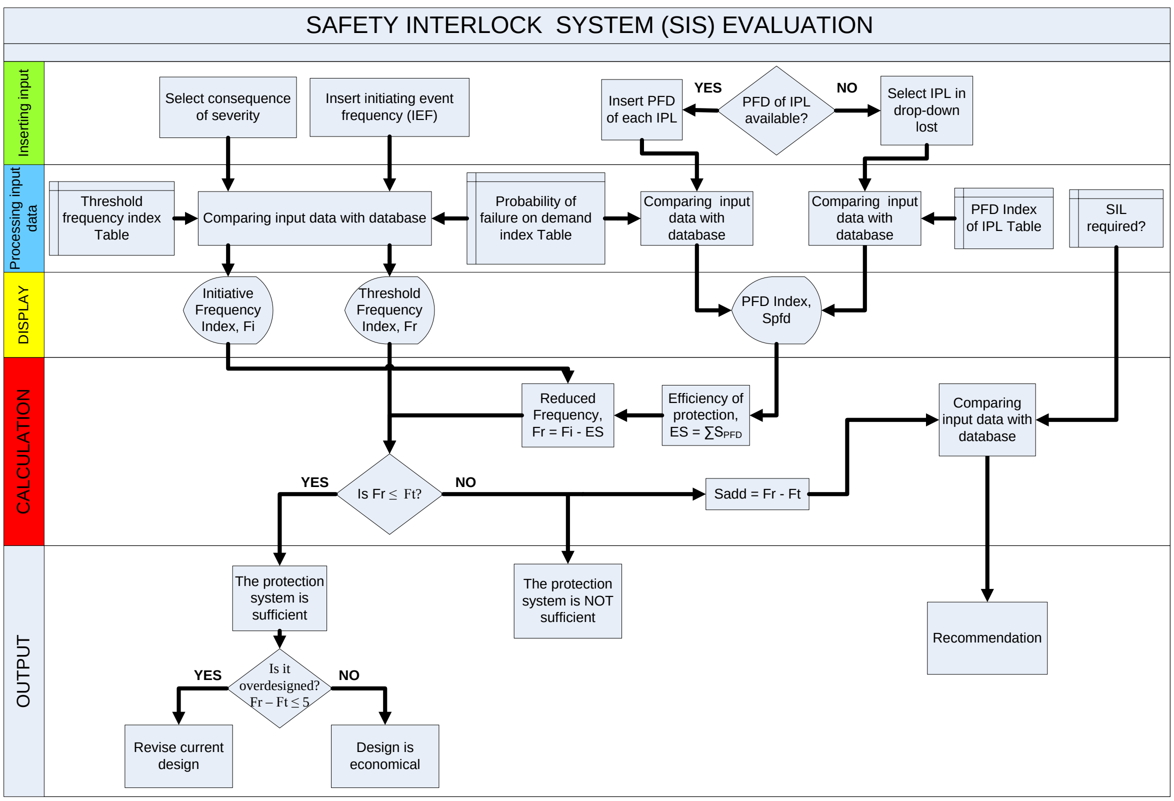


Figure 15: Flow chart of Safety Interlock System (SIS) Evaluation

CHAPTER 4

RESULT AND DISCUSSION

4.1 SIS Evaluation

In this chapter a complete simulation for SIL evaluation on SIS is discussed thoroughly. The simulation is built using the Microsoft Excel 2007 as the platform. The case study varies from different sources including literature reviews and industries. Several case studies are used in this study to test the simulation.

Case 1: Failure of level transmitter (LT) indicating a false high level in a high pressure sour gas amine treatment unit (Campa and Cruz-Gomez, 2009).

Figure 16 shows the simplified process flow of the absorber section of a high pressure sour gas amine treatment unit. Sour gas is a natural gas containing hydrogen sulfide (H_2S). Lean amine is used to remove H_2S in absorber column, T-1. Based on HAZOP study of the process as shown in Table 10, the following scenario is selected (Node: High pressure amine absorber (T-1) and Deviation: high level).

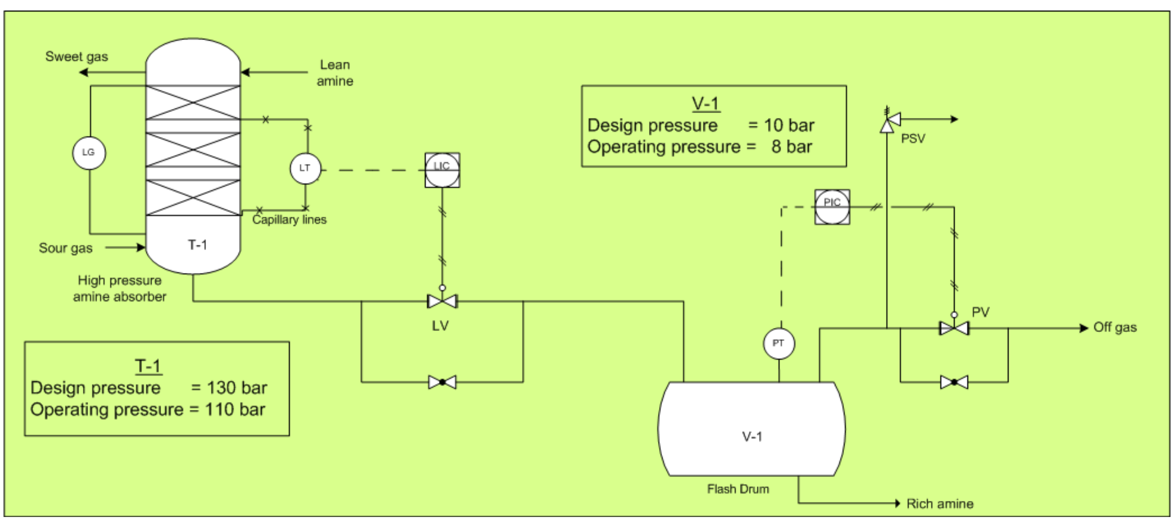


Figure 16: Process Flow diagram of for the absorber section of a sour gas treatment unit (Campa and Cruz-Gomez, 2009)

From Table 10, the essential information can be extracted and shown in Table 11. All the input data gained is then keyed in into the Safety Interlock System (SIS) Evaluation.

Table 10: Hazards and Operability (HAZOP) study of the process

Cause	Consequence	Safeguards	Recommendations
Failure of LT indicating a false high level	LV fully opens Loss of liquid seal in T-1 column (LG indication is unreliable in this case)	High pressure alarm in V-1 PIC and operator response	Consider adding a SIS and implement a SIF for this scenario
	High pressure gas flows to low pressure flash tank V-1 is not designed for this scenario		Lock LV bypass valve in closed position
	LV bypass valve could be erroneously opened in an attempt to control the 'high level' in t-1, worsening the scenario		Update emergency operation procedures with this scenario and train operators accordingly
	Potential explosion of V-1		

.

Table 11: Input data of case 1

Consequence Description/Category	Assuming Facility spacing is adequate. Personal concentrated in bunker control room at sufficient distance. **Category 4: Major** (Based on risk matrix)
Initiating event frequency	Failure of a level transmitter indicating false high level (0.1)
Independent Protection Layers	
1. BPCS alarm and Human Action	1×10^{-1}
2. Level Gauge (LG)	LG indication is unreliable in this scenario
3. PSV	PSV in the absorber is not designed for this scenario.

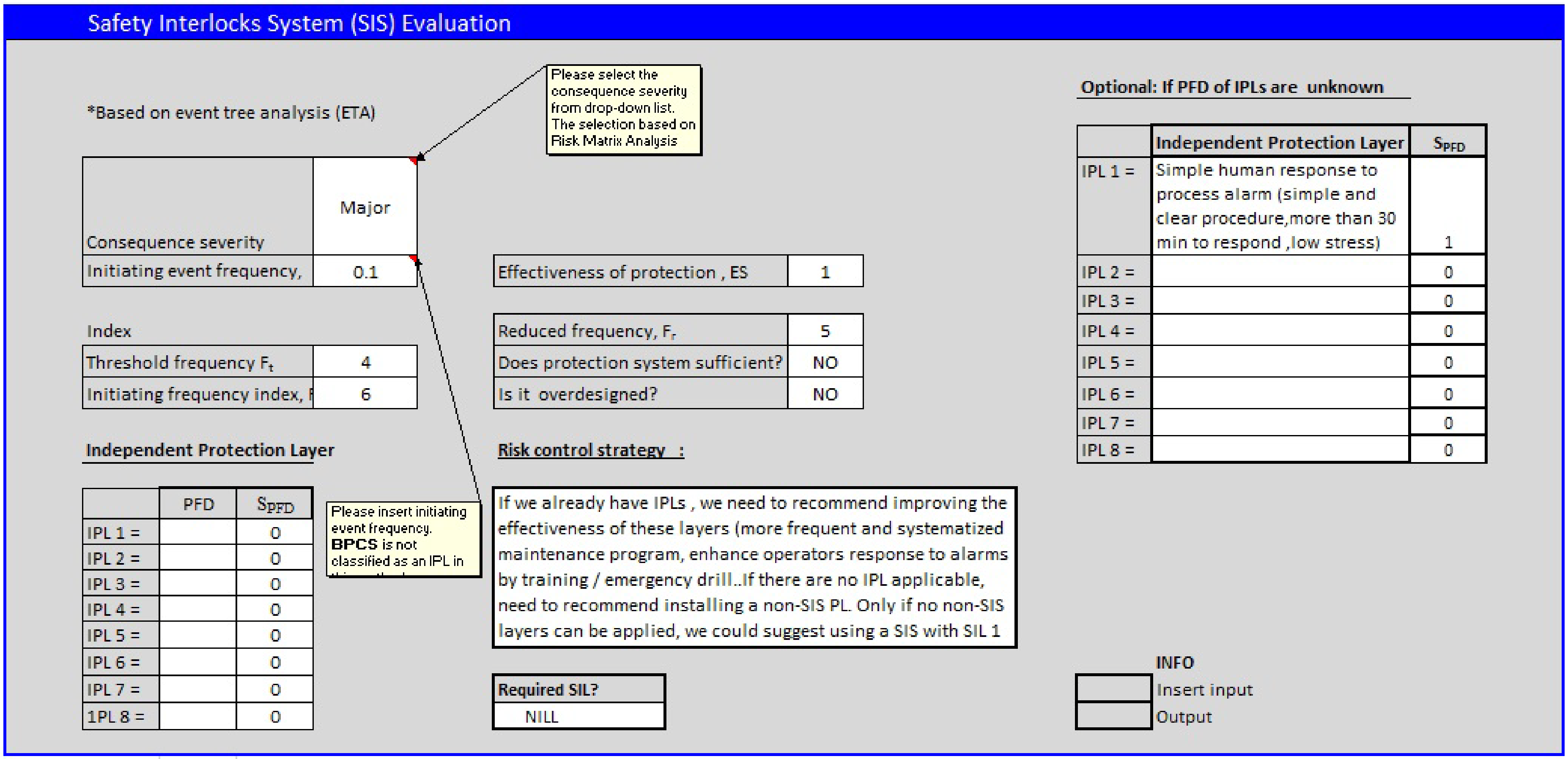


Figure 17: Result for Case 1

The consequence severity assigned is category 4: Major. It is categorized based sizes of release and consequences of production and facilities according to Figure 13 and 14. The initiating frequency for this scenario is 0.1, which give clear information of high probability of occurrence in plant lifetime and the corresponding index frequency denoted as 6.

Although there are 3 IPLs as stated in Table 11, only one is applicable. Whereas, another two IPLs are not applicable due to reasons as already mentioned in Table 11. The only applicable protection is process alarm associated with operator response that yield a low effectiveness (S_{PFD} = 1). Just one IPL with low S_{PFD} number, the protection system is insufficient which cause the reduced frequency index is greater than threshold frequency index based on Figure 17. Due to insufficient protection system, the risk control strategy plays essential role to counter the problem.

In this case, the program gives solutions which are arranged systematically as listed below:

- If IPLs already exist, improve the protection layers (more frequent and systematized maintenance program, enhance operators response to alarms by training /emergency drill.
- If there are no IPL applicable, need to recommend installing a non-SIS Protection Layer.
- Only if no non-SIS layers can be applied, suggesting on using a SIS with SIL 1.

The solutions are arranged in that manner is means to reduce the cost and to achieve ALARP philosophy.

In response to the suggestion given in the SIS Evaluation program, assume that the preventive maintenance is already being applied systematically and scheduled training and emergency drill have been carried out and no non-SIS is available, thus SIS with SIL 1 is recommended. SIL 1 is selected because the effectiveness required (frequency reduction), S_{ADD} is 1. The SIF is to shut down the emergency shutdown valve (ESV) which is installed in series. In normal practice, single valve will not be enough to meet SIL 1 requirement. Therefore, another ESV is need based on redundancy philosophy. A solenoid 3-way valve is needed on air pressure control line to control both ESVs installed in series. The conceptual design is shown in Figure 18.

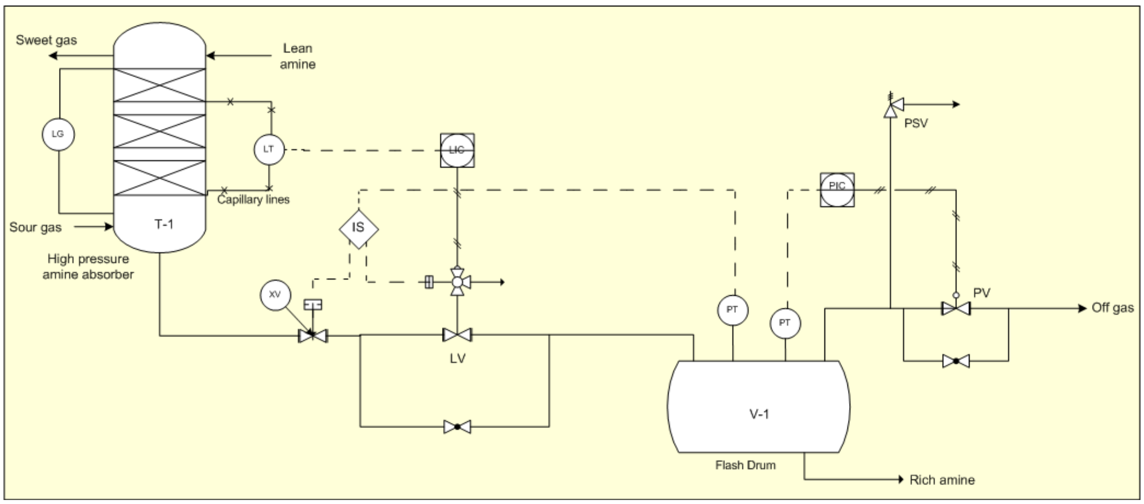


Figure 18: Revamped Design Piping & Instrumentation diagram (P&ID)

Case 2: Cooling water failure with runaway reaction and potential for reactor overpressure, leakage, rupture, injuries and fatalities. Agitation is assumed (Crowl and Louvar, 2002)

Figure 19 shows a safety system in a certain chemical reactor. The reactor contains a high-pressure alarm to alert the operator in the event of dangerous reactor pressures. It consists of a pressure switch within the reactor connected to an alarm light indicator. An automatic high-pressure reactor shutdown system is installed. The system is activated at a pressure higher than the alarm system and consists of a pressure switch connected to a solenoid valve in the reactor feed line. The automatic system stops the flow of reactant in the event of dangerous pressures.

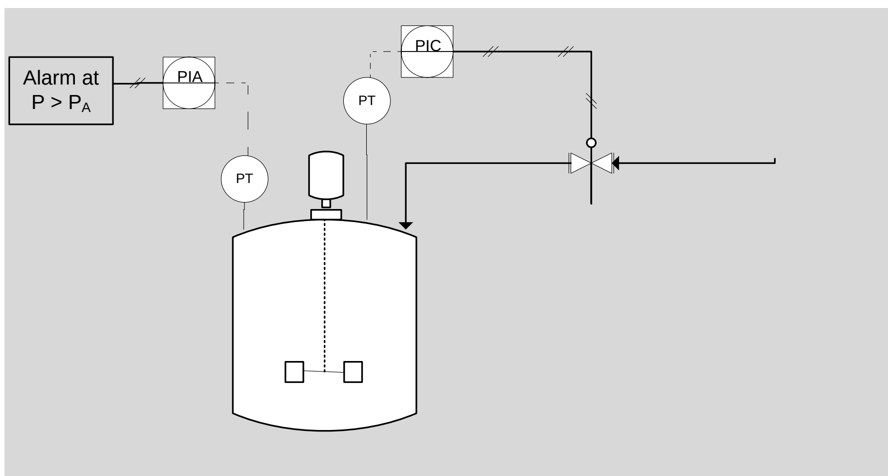


Figure 19: Chemical reactor with an alarm and an inlet feed solenoid

Table 12: Input data for case 2

Consequence Description/Category	Runaway reaction and potential for reactor overpressure, leakage, rupture, injuries and fatalities. **Category 5: Catastrophic**
Initiating event frequency	BPCS instrument loop failure (0.1)
Independent Protection Layers	
1. Inherent safe design	1×10^{-1}
2. Operator response	1×10^{-2}

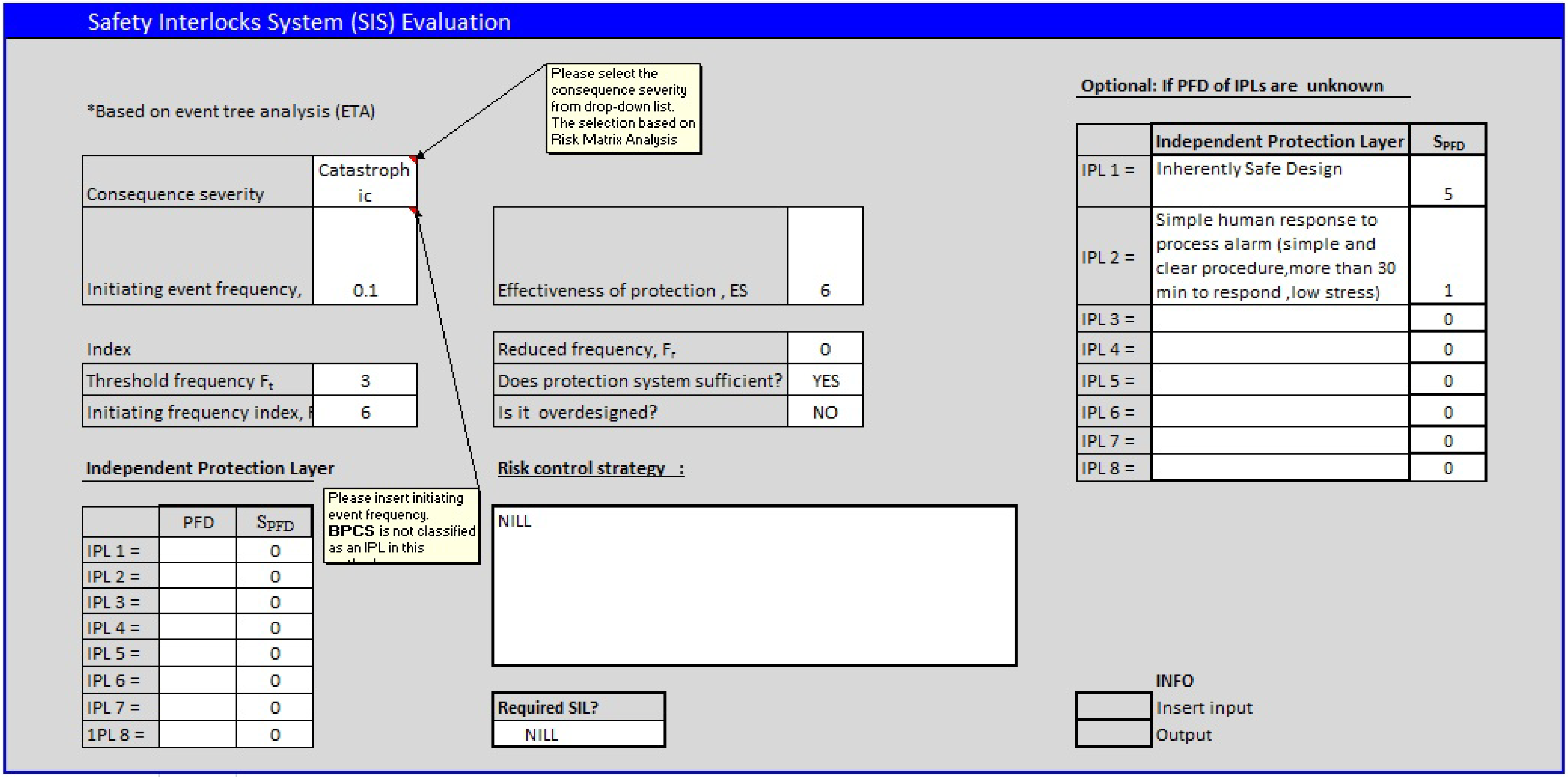


Figure 20: Spreadsheet interface and result of case 2

Figure 20 shows the result of the case 2. For case 2, the result indicates that the protection system is adequate to mitigate the undesired scenario. In the consequence severity box, catastrophic category is selected from the drop-down list which is shown in Figure 9. The corresponding threshold frequency index will then appeared which give the maximum acceptability criteria. The initiating event frequency inserted is 0.1, a medium probability of occurrence in the plant lifetime. The corresponding index 6 appears in the cell.

A protection with low S_{PFD} number gives an indication that it is low effectiveness and has a high probability of failure in case it is needed. The first IPL in this case is inherently safe design. Assumption made is that if it is properly implemented, the design can eliminate scenarios or significantly reduce the consequences associated with a scenario. That is among the reason why the index for inherent safe design is high which give high reliability of the IPL. The second IPL is human response to alarm assuming that the procedures are clearly understood, with low stress. The S_{PFD} is 1 indicating that it has low effective and has high probability of failure when it is in demand since it involves many external factors like lack of operation training and inadequate or nonexistent of management of change. .

However, the protection system is still sufficient as Frequency reduction, F_r is less than Threshold frequency, F_t. Thus, no risk control strategy and SIL required. If F_r is low than F_t, the protection system is overdesigned. Another question arises when it comes to 'how much protection layer really needed?', 'is it overdesigned?'. It is vital for everyone to know the minimum IPL needed as noticed that any additional IPL will skyrocketing the investment cost. There are no such references that give the minimum criteria value to be considered as overdesigned. Every company has their own standard value. In this case, the spreadsheet is set to allow any changes to ensure it meets the standard, one required.

Release Characteristic	0.5 to 5 kg	5 to 50 kg	50 to 500 kg	500 to 5,000 kg	5,000 to 50,000 kg	More than 50,000 kg
Extremely toxic above BP	Critical: Category 3	Major: Category 4	Catastrophic: Category 5	Catastrophic: Category 5	Catastrophic: Category 5	Catastrophic: Category 5
Extremely toxic below BP or highly toxic above BP	Minor: Category 2	Critical: Category 3	Major: Category 4	Catastrophic: Category 5	Catastrophic: Category 5	Catastrophic: Category 5
Highly toxic below BP or flammable above BP	Minor: Category 2	Minor: Category 2	Critical: Category 3	Major: Category 4	Catastrophic: Category 5	Catastrophic: Category 5
Flammable below BP	Negligible: Category 1	Minor: Category 2	Minor: Category 2	Critical: Category 3	Major: Category 4	Catastrophic: Category 5
Combustible liquid	Negligible: Category 1	Negligible: Category 1	Negligible: Category 1	Minor: Category 2	Minor: Category 2	Critical: Category 3

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BP, atmospheric boiling point.

Figure 21: Semi-quantitative guide for consequence category selection based on size of release (Campa & Cruz-Gomez, 2009)

Facility Type	Mechanical Damage to Spared or Nonessential Equipment	Plant Outage for Less Than 1 Month	Plant Outage for 1 to 3 Months	Plant Outage for Less/More Than 3 Months	Vessel Rupture 3,000 to 10,000 gal 100–300 psi	Vessel Rupture >10,000 gal >300 psig
Large plant, main product	Minor: Category 2	Critical: Category 3	Major: Category 4	Major: Category 4	Major: Category 4	Catastrophic: Category 5
Small plant, by-products	Minor: Category 2	Minor: Category 2	Critical: Category 3	Major: Category 4	Major: Category 4	Catastrophic: Category 5

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Figure 22: Semi-quantitative guide for consequence category selection according to consequence on production and facilities.

(Campa & Cruz-Gomez, 2009)

CHAPTER 5

CONCLUSION AND RECOMMENDATION

Prior determination of the appropriate SIL on a particular SIF requires one to evaluate thoroughly the concept of independent protection layer (IPL) to avoid intentionally incorporating an IPL failure into the initiating event frequency which will jeopardize the entire analysis. A concept of semi-quantitative risk analysis is used throughout the study where it involves combination of HAZOP, LOPA technique and concept of SIL and SIS. Prior estimating the consequence and severity, HAZOP is used to select the most severe consequence which initiated by an event. Then, initiating event frequency can be specified. The system developed gives user two alternative in specifying the IPLs. In case of PFD value is not available, there are many types of IPLs can be selected from the drop down list. Otherwise, user can key in the PFD value in the designated column. All the input data is converted from exponent number into index number for ease of adding the multiplication of probabilities. Analysis on the SIS is performed to check on the reliability and economical of the design. Recommendation is given based on the sufficiency of the protection. If the protection is insufficient, several strategies will be given - improving existing layer, installing non-SIS protection layer and installing a SIS with specific SIL. It is not always necessary to have a lot protection layer. Most scenarios can be catered by enhancing the existing design and instrumentation which minimizes the magnitude and frequency of deviation of the process. Therefore, dependency on safety system can be reduced. The tool developed can be used either in decision making which related in investment in additional of safety protection layer or improving the existing protection layer. Future study shall be continued to enhance the relevancy and reliability of the tool by considering more parameters in assessing a case. Thorough discussion with experts from industries is required to ensure the study is relevant and applicable in industry.

REFERENCE

Andrew, J. D. and Bartlett, L. M. (2005). A Branching Search Approach method to Safety System Design Optimization, Reliability Engineering and System Safety, 87, 1, pp23-30.

Baybutt, P. (2003). Layer of Protection Analysis for Human Factor (LOPA-HF): An improved method for addressing human failure in process hazard analysis. *American Society of Safety Engineer* , 163-175.

Campa, H. J., and Cruz-Gomez, M. (2009). *Determine SIS and SIL using HAZOPS.* Mexico City: Wiley Interscience.

CCPS. (2001). *Layer of Protection Analysis : Simplified Process Risked Assessment.* New York: CCPS.

Connor, M. K. (2009, November 3-4). Safety Integrity Level verification. Texas, USA.

Crowl, D. A., and Louvar, J. F. (2002). Risk Assessment. In J. F. Daniel A.Crowl, *Chemical Process Safety: Fundamentals with Application* (pp. 471-507). New Jersey: Pearson Prentice Hall.

Dowell, A. M., and Hendershot, D. C. (2002). Simplified Risk Analysis : Layer of Protection Analysis. *AIChE National Meeting* , 1-6.

Group Safety User. (2007, August). SIL : Tools and references. San Jose, California, USA.

Gulland, W. G. (2004). Requirement Pro and Con. In W. G. Gulland, *Method of Determining Safety Integrity Level* (pp. 1 - 16).

Guo, H. and Yang, X. (2007). A Simple Reliability Block Diagram method for Safety Integrity level Verification, Reliability Engineering and System Safety, 92, 9, pp1267 - 1273.

Kosmowski, K. T. (2006). Functional Safety Concept for Hazardous Systems and New Challenges, Journal of Loss Prevention in the Process Industries, 19, 2-3, pp 298-305.

Lassen, C. A. (2008). *Layer of Protection Analysis (LOPA) for Determination of Safety Integrity Level (SIL)*. Snaroya: Norwegian University of Science and Technology.

Magnetrol Bulletin. (2009). *Understanding Safety Integrity Level*. USA: Magnetrol International.

Mannan, M. S., Wang, Y., and West, H. H. (2004). The Impact of Data Uncertainty in Determining Safety Integrity Level , Process Safety and Environmental Protection, 82, 6, pp 393 - 397.

Markowski, A. S. and Mannan, M. S. (2009). Fuzzy Logic for Piping Risk Asessment (pfLOPA), Journal of Loss Prevention in the Process Industries, 22, 6, pp 921 - 927

Marszal, E. M., and Scharpf, E. W. (2002). *Safety Integrity Level Selection: Systematic Methods Including Layer of Protection Analysis*. United States: Instrumentation, Systems and Automation (ISA).

PETRONAS Group Technology Solution. (2009). Layer of Protection Analysis (LOPA) Briefing package. *Layer of Protection Analysis (LOPA) Briefing package* . Kuala Lumpur, Malaysia: PETRONAS Group Technology Solution.

Scott, M. D. *Burner Management Safety Integrity Level Selection*. Greenville: AE Solution.

Stavrianidis, P and Bhimavarapu, K. (1998). Performance-based Standards: Safety Instrumented Functions and Safety Integrity Level, Journal of Hazardous Materials, 71, 1-3, pp 449-465.

Summers, A. E. (2003). Introduction to layer protection analysis. *Journal of Hazardous Materials* , 163 - 168.

Wei, C., Rogers, W. J., and Mannan, M. S. (2008). Layer of protection analysis for reactive chemical risk assessment. *Journal of Hazardous Material* , 19-24.

Zatil, A. R. (2009). *Using Layer of Protection Analysis (LOPA) to Determine Safety Integrity Level (SIL) for Hazardous Installation*, Bachelor Thesis, Universiti Teknologi PETRONAS, Malaysia.