MODELING AND ANALYSIS OF PROCESS FAILURES USING PROBABILISTIC FUNCTIONAL MODEL

MOHAMED ABDEL RAHIM KHALIL SIDDIG

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To Almighty Allah for His Mercy and Blessings

To my beloved mother and to my dear wife for their supporting supplications and love

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ABSTRACT

Failure analysis is an important tool for effective safety management in the chemical process industry. This thesis applies a probabilistic approach to study two failure analysis techniques. The first technique focuses on fault detection and diagnosis (FDD), while the second is on vulnerability analysis of plant components. In formulating the FDD strategy, a class of functional model called multilevel flow modeling (MFM) was used. Since this model is not commonly used for chemical processes, it was tested on a crude distillation unit and validated using a simulation flowsheet implemented in Aspen HYSYS (Version 8.4) to demonstrate its suitability. Within the proposed FDD framework, probabilistic information was added by transforming the MFM model into its equivalent fault tree model to provide the ability to predict the likelihood of component's failure. This model was then converted into its equivalent Bayesian network model using HUGIN 8.1 software to facilitate computations. Evaluations of the system on a heat exchanger pilot plant highlight the capability of the model in detecting process faults and identifying the associated root causes. The proposed technique also incorporated options for multi – state functional outcomes, in addition to the typical binary states offered by typical MFM model. The second tool proposed was a new methodology called basic event ranking approach (BERA), which measures the relative vulnerabilities of plant components and can be used to assist plant maintenance and upgrade planning. The framework was applied to a case study involving toxic prevention barriers in a typical process plant. The method was compared to some common importance index methodologies, and the results obtained ascertained the suitability of BERA to be used as a tool to facilitate risk based decisions in planning maintenance schedules in a process plant.

ABSTRAK

Analisis kegagalan adalah salah satu teknik penting dalam pengurusan keselamatan dalam industri proses kimia. Tesis ini mengaplikasikan pendekatan kebarangkalian dalam mengkaji dua teknik analisis kegagalan. Teknik yang pertama memberi tumpuan kepada pengesanan dan diagnosis kerosakan (FDD), manakala yang kedua pula memfokuskan kepada analisis kelemahan komponen kilang. Dalam merumuskan strategi FDD, satu kelas model fungsi iaitu model aliran bertingkat (MFM) telah digunakan. Oleh kerana model ini jarang digunakan bagi proses kimia, ianya telah diuji ke atas unit penyulingan mentah dan disahkan dengan menggunakan simulasi carta alir menerusi perisian Aspen HYSYS (Versi 8.4) bagi membuktikan kesesuaiannya. Dalam kerangka FDD yang dicadangkan, maklumat kebarangkalian telah ditambah dengan mengubah model MFM kepada model kesalahan pokok yang setara. Model ini seterusnya ditukar kepada model rangkaian Bayesian dengan menggunakan perisian HUGIN 8.1 bagi memudahkan pengiraan. Penilaian ke atas sistem loji perintis penukar haba telah menunjukkan keupayaan model dalam mengesan kesalahan proses dan mengenal pasti punca yang berkaitan. Teknik yang dicadangkan ini juga menyediakan pilihan untuk mendapatkan keputusan berasaskan pelbagai keadaan sebagai tambahan kepada keadaan binari yang biasanya ditawarkan oleh kebanyakan model MFM. Kaedah kedua yang dicadangkan adalah suatu kaedah baru yang dikenali sebagai pendekatan penarafan acara asas (BERA), yang mengukur kelemahan relatif komponen kilang dan boleh digunakan untuk membantu perancangan penyelenggaraan dan menaik taraf loji. Rangka kerja ini telah digunakan untuk kajian kes yang melibatkan halangan pencegahan toksik yang digunakan di kebanyakan loji proses. Kaedah ini telah dibandingkan dengan beberapa kaedah biasa indeks kepentingan, dan hasil yang diperoleh membuktikan kesesuaian BERA untuk digunakan sebagai teknik bagi memudahkan pembuatan keputusan berasaskan risiko dalam perancangan jadual penyelenggaraan loji proses.

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LIST OF ABBREVIATIONS

AIM	-	Asset Integrity Management
BERA	-	Basic Event Ranking approach
BI	-	Birnbaum Importance
BN	-	Bayesian Network
CDU	-	Crude Distillation Unit
CI	-	Criticality Importance Factor
CPI	-	Chemical Process Industries
DIM	-	Differential Importance Measure
ETA	-	Event Tree Analysis
FAST	-	Function Analysis System Technique
FBD	-	Functional Block Diagram
FDD	-	Fault Detection and Diagnosis
FM	-	Functional Modeling
FMEA	-	Failure Mode and Effect Analysis
FT	-	Fault Tree
FV	-	Fussel-Vesely
GT- ST	-	Goal Tree – Success Tree
HAZOP	-	Hazard and Operability Analysis
HBA	-	Hierarchical Bayesian Approach
HIPO	-	Hierarchy plus Input – Process – Output Chart
HRA	-	Human Reliability Analysis
HSE	-	Health, Safety and Executive

IDEF0	-	Integration Definition for Function Modeling
IM	-	Importance Measure
MCMC	-	Markov Chain Monte Carlo
MCS	-	Minimal Cut – Set
PSM	-	Process Safety Management
RA	-	Risk Analysis
RAW	-	Risk Achievement Worth
RRW	-	Risk Reduction Worth
SADT	-	Structured Analysis and Design Technique
TPB	-	Toxic Prevention Barriers
VA	-	Vulnerability Analysis

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CHAPTER 1

INTRODUCTION

1.1 Background

History has shown the potential of process plant in causing catastrophic damages resulting in multiple injuries and fatalities, as well as substantial economic, property, and environmental damages. Today, it is still a major concern following series of accidents that have put legislators and investors alike on high alert. This is because not only that some of these incidents have involved multiple fatalities and devastating financial implications, they also instilled public fear and concerns especially to those who are directly related to chemical process industries (CPI). As a response to this challenging scenario, there is a clear need to enhance preventive and mitigating measures to improve safety and to reduce public worries. These requirements along with the needs for the plant to be more energy efficient and environmentally benign require systematic actions throughout the project life cycle, which can be realized by fully adopting the concept of inherent and engineered safety and process safety management (PSM).

There is therefore a need of full understanding of all hazards associated with the process operation and proper controls to prevent harm to employees, processing facilities as well as the surrounding communities. Based on these understandings, safety can be assessed and inherent measures can be proposed and implemented. The choice of raw materials and the sequence of reactions that converts them to the desired product is a key early design decision that influences the inherent safety of a plant. Nevertheless, various engineering and economic constraints do not permit ideal requirements to be fully implemented and compromises are therefore required. In such cases, the process of decision making would be of paramount importance to avoid unwanted oversight since scenarios requiring safety related decisions are oftentimes complex and risky. To minimize the likelihood consequence of catastrophic incidents, the evaluation of the likelihood of occurrence and the resulting consequences involved are an important part in the design and implementation of safety systems (Gabbar, Suzuki and Shimada, 2001; Zhao *et al.*, 2009).

Analyses of major accidents in the process industries revealed that four major elements as the main root causes (Kidam and Hurme, 2013a; Kidam and Hurme, 2013b). These are equipment/component failure, human error, natural disaster and terrorism or sabotage. Since natural disasters and terrorisms are relatively more difficult to predict and handle, strategies to reduce the number of accidents in the process industries can be better achieved by preventing potential failures that are associated with process equipment or human errors.

Focussing on equipment failures, among others, there are two important things that can be exploited to address the issue of equipment failures. The first is the needs to address process failures effectively during plant operations. This can be accomplished through effective early warning system and faults management. The second important aspect is plant maintenance which include activities to preserve the safety, performance and reliability of the plants assets to ensure smooth performance of their intended function. This is however challenged by the needs for maintaining profitability despite of difficult economic conditions. Mechanisms to manage targetted maintenance are therefore needed.

1.2 Statement of the Problem

There are two important aspects of failures of process plant components during plant operations, which may ended up as plant accidents. The first is the failure of plant components during operations begins with failure of the inner layer of plant protection system, which is the process control function. This is designed to be supported by the successive layers of protection including alarms, interlocks and relief functions. On the technological development, there is a need to develop effective early warning system and faults management. The second important aspect is plant maintenance which includes activities to preserve the safety, performance and reliability of the plants assets to ensure smooth performance of their intended function. Therefore, there is a gap in researches on an integrated system safety and risk assessment method to systematically identify cause and consequences of a failure based on qualitative functional modeling.

1.3 Objective of the Research

This research is proposed to close the gaps mentioned in the problem statements. The detailed objectives are as follows:

i. To apply functional modeling strategy as an approach for developing tools associated with process safety.
ii. To formulate a fault detection and diagnosis method based on functional model and Bayesian Network.
iii. To develop an effective method of vulnerability analysis to facilitate targeted maintenance planning as a means of improving asset integrity management.

1.4 Scope of the Research

This study focuses on the use of functional modeling techniques in developing tools for process safety. Different case studies are used in this study consist of the crude distillation unit (CDU), heat exchanger pilot plant and Toxic Prevention Barriers (TPB). All the plant's specifications and data shall be obtained from the plants, literatures, textbooks, and published papers. To fulfill the objective of this study the scope of work is as follows:

i. MFM model is developed using Crude distillation unit (CDU) and validated using Aspen HYSIS Software.
ii. To include probabilistic information on process components, fault tree analysis model is used. In this case, fault tree (FT) of the heat exchanger pilot plant from the functional model is mapped into its equivalent fault tree (FT).
iii. Convert the fault tree (FT) of the heat exchanger pilot plant to the Bayesian Network (BN) model, to formulate fault detection and diagnosis (FDD).
iv. Updating the failure probability of the basic events using hierarchical Bayesian approach (HBA) and Markov Chain Monte Carlo simulation (MCMC) software (Open BUGS) for dynamic Importance Measure.
v. Developing a new methodology for Importance measure to rank the components of the system and comparison anew model with the common importance measures for static and dynamic states.

1.5 Layout of Thesis

This thesis comprises 6 chapters. Chapter 1 introduces the overall problem and thesis objectives, followed by literature review on the importance of failure analysis in process safety, modeling tools for failure analysis which consist of Functional Modeling (FM), Fault Tree (FT) and Bayesian Network (BN), Vulnerability Analysis (VA) and Importance Measure (IM) were discussed in Chapter 2. Chapter 3 consists of an application of cause and consequence reasoning methodology of functional modeling description. The crude distillation unit was considered as a case study. In chapter 4, binary and multi – state system fault detection and diagnosis using probabilistic MFM were elaborated. The model has been implemented into the heat exchanger pilot plant. The new methodology of Importance Measure (IM) for ranking the system's components was developed to the static and dynamic risk importance measure, this chapter deals with the Toxic Prevention Barriers (TPB) as a case study, and finally the conclusion and recommendations for future works of the study is presented in Chapter 6.

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APPENDIX A

LIST OF PUBLICATIONS

1. Mohamed A. R. Khalil, Arshad Ahmad, Tuan Amran Tuan Abdullaha, Ali Al-Shatri, Ali Al-Shanini. (2016). MULTI–STATE ANALYSIS OF PROCESS STATUS USING MULTILEVEL FLOW MODELLING AND BAYESIAN NETWORK. Jurnal Teknologi. Volume 78: 8–3 (2016) 33–41. (SCOPUS journal).
2. Mohamed A. Khalil, Arshad Ahmad, Tuan Amran T. Abdullah and Ali Al-shanini. (2016). Failure Analysis Using Functional Model and Bayesian Network. Chemical Product and Process Modeling. Failure Analysis Using Functional Model and Bayesian Network. Volume 11, Issue 4, Pages 265–272, ISSN (Online) 1934-2659, ISSN (Print) 2194-6159, DOI: 10.1515/cppm-2016-0007 . (SCOPUS journal).
3. Mohamed A.R.KHALIL, Arshad AHMAD, Ali AL – SHANINI, Amirah NORANI. Assessing the Influence of Plant Components in a Failure Case using Basic Event Ranking Approach . The 7th International Symposium on Design, Operation and Control of Chemical Processes (PSE Asia 2016), Tokyo, Japan, July 24-27 (2016).
4. Mohamed A. Khalil, Arshad Ahmad, Amirah A. Norani and Ali Al-Shanini. (2016) - Dynamic Importance Measure for Vulnerability Analysis of Plant Components. Reliability Engineering and System Safety (RESS) - ISI index. Impact factor:2.498 , (Under Review).
5. Mohamed A.R. Khalil, Arshad Ahmad, Tuan Amran Tuan Abdullah, Ali Al-Shatri, Ali Al-Shanini – (2016) - The Causal Dependency in Crude Distillation Unit Using Multilevel Flow Modeling - Chemical Product and Process Modeling (CPPM). (Prepare to submit).