COMPREHENSIVE QUANTITATIVE DYNAMIC ACCIDENT MODELLING FRAMEWORK FOR CHEMICAL PLANTS

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To Almighty Allah for His Mercy and Blessings

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ABSTRACT

This thesis introduces a comprehensive accident modelling approach that considers hazards associated with process plants including those that originate from the process itself; human factors including management and organizational errors; natural events related hazards; and intentional and security hazards in a risk assessment framework. The model is based on a series of plant protection systems, which are release, dispersion, ignition, toxicity, escalation, and damage control and emergency management prevention barriers. These six prevention barriers are arranged according to a typical sequence of accident propagation path. Based on successes and failures of these barriers, a spectrum of consequences is generated. Each consequence carries a unique probability of occurrence determined using event tree analysis. To facilitate this computation, the probability of failure for each prevention barrier is computed using fault tree analysis. In carrying out these computations, reliability data from established database are utilized. On occasion where reliability data is lacking, expert judgment is used, and evidence theory is applied to aggregate these experts' opinion, which might be conflicting. This modelling framework also provides two important features; (i) the capability to dynamically update failure probabilities of prevention barriers based on precursor data, and (ii) providing prediction of future events. The first task is achieved effectively using Bayesian theory; while in the second task, Bayesian-grey model emerged as the most promising strategy with overall mean absolute percentage error of 18.07% based on three case studies, compared to 31.4% for the Poisson model, 22.37% for the first-order grey model, and 22.4% for the second-order grey model. The results obtained illustrated the potentials of the proposed modelling strategy in anticipating failures, identifying the location of failures and predicting future events. These insights are important in planning targeted plant maintenance and management of change, in addition to facilitating the implementation of standard operating procedures in a process plant.

ABSTRAK

Tesis ini memperkenalkan pendekatan pemodelan kemalangan yang komprehensif yang mengambilkira bahaya-bahaya yang berkaitan dengan loji proses termasuk yang bersumberkan proses itu sendiri, faktor manusia termasuk kesilapan pengurusan dan organisasi; bahaya bersumberkan kejadian alam semulajadi; dan bahaya dari aspek keselamatan dan tindakan yang disengajakan dalam kerangka pentaksiran risiko. Model ini berdasarkan satu siri sistem perlindungan loji, iaitu penghalang pencegahan bagi mengawal pelepasan, penyerakan, pencucuhan, ketoksidan, peningkatan dan pengendalian kerosakan dan pengurusan kecemasan. Enam penghalang pencegahan ini disusun mengikuti turutan biasa laluan penyebaran kemalangan. Berdasarkan kejayaan-kejayaan dan kegagalan-kegagalan penghalang-penghalang ini, satu spektrum akibat-akibat dihasilkan. Setiap akibat mempunyai kebarangkalian untuk berlaku yang unik yang dikira dengan menggunakan analisis pokok kesalahan. Bagi melaksanakan pengiraan ini, kebarangkalian kegagalan bagi setiap penghalang pencegahan dikira dengan menggunakan analisis pokok kesalahan. Dalam melaksanakan pengiraan ini, data kebolehpercayaan dari pengkalan data digunakan. Apabila data kebolehpercayaan tidak boleh didapati, pandangan pakar digunakan, dan teori bukti digunakan bagi mengagregatkan pandangan-pandangan pakar yang mungkin bertentangan. Kerangka permodelan ini juga menawarkan dua ciri iaitu; (i) kebolehan untuk mengemaskini kebarangkalian kegagalan bagi penghalang pencegahan secara dinamik berdasarkan data pelopor, dan (ii) memberikan ramalan kejadian masa hadapan. Tugas pertama dicapai dengan berkesan dengan menggunakan teori *Bayesian*, manakala bagi tugas kedua, model *Bayesian*-kelabu muncul sebagai strategi yang paling berjaya, dengan purata keseluruhan ralat ramalan 18.07 % berdasarkan tiga kes kajian, berbanding dengan 31.4 % bagi model *Poisson*, manakala 22.37% untuk model kelabu terbitan pertama, dan 22.4% untuk model kelabu terbitan kedua. Keputusan yang diperoleh menunjukkan potensi model yang dicadangkan dalam menjangka kegagalan, mengenalpasti lokasi kegagalan dan meramal kejadian masa depan. Maklumat mendalam ini penting dalam perancangan penyelenggaraan loji yang disasar dan pengurusan perubahan, selain daripada membantu perlaksanaan prosedur piawai operasi loji proses.

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LIST OF ABBREVIATIONS

AGO	-	Accumulated Generation Operator
AM	-	Accident Model
ASP	-	Accident Sequence Precursor
BN	-	Bayesian Network
CCA	-	Cause-Consequence Analysis
CIMs	-	Consequence Impact Models
CPI	-	Chemical Process Industry
CPI-CPA	-	CPI- Comprehensive Prevention Accident methodology
CPT	-	Conditional Probability Table
DC&EMB	-	Damage Control and Emergency Management Barrier
DPB	-	Dispersion Prevention Barrier
DRA	-	Dynamic Risk Assessment methodology
DRM	-	Dynamic Risk Management methodology
DSAMs	-	Dynamic Sequential Accident Models
DST	-	Dempster–Shafer Theory

EAMs	-	Epidemiological Accident Models
EPB	-	Escalation Prevention Barrier
ETA	-	Event Tree Analysis
FAM	-	Formal Accident Model
FTA	-	Fault Tree Analysis
HBA	-	Hierarchal Bayesian Approach
IPB	-	Ignition Prevention Barrier
M&OF	-	Management and Organizational Factor
MAPE	-	Mean Absolute Percentage Error
MC_error	-	Computational accuracy of the mean
MCMC	-	Markov Chain Monte Carlo simulation
Na-Tech	-	Natural Hazard Triggering Technological Disasters
OLS	-	Ordinary least square method
PHPAMs	-	Process Hazard Prevention Accident Models
QRA	-	Quantitative Risk Assessment
RBD	-	Reliability Block Diagram
RM	-	Risk Management
RPB	-	Release Prevention Barrier
SAMs	-	Sequential Accident Models
Sd	-	Standard deviation
SHIPP	-	System Hazard Identification Prediction and Prevention methodology

SyAMs`	-	Systematic Accident Models
TPB	-	Toxic Prevention Barrier

LIST OF SYMBOLS

Bel	-	The Belief function
BG(1,1)	-	First-order single variable Bayesian-grey model
Bpa	-	Basic probability assignment function
E	-	Evidence
E(x)	-	The mean of the distribution of *x*
f	-	Number of failures
f(data\x)	-	The likelihood distribution function
f(x)	-	The prior distribution function
f(x\data)	-	The posterior distribution function
G(1,1)	-	First-order single variable grey model
$g(X_{k1},X_{k2})$	-	The coupling function of safety barrier *x* that has to sub-systems k_1 and k_2
i	-	Release class
k	-	The number of safety sub-systems in event tree model
k_{dc}	-	The measure of degree of conflict between experts
$m(p_k)$	-	The degree of evidence in the set p_k

$m(x)_{fb}$	-	The number of occurrence of end-state events that branched from failure of safety barrier *x*
$m(x)_{sb}$	-	The number of occurrence of end-state events that branched from success of safety barrier *x*
m_1	-	First expert
m_2	-	Second expert
P	-	Power set
$p(x\|y)$ *and* $f(x\|y)$	-	Conditional probability function of *x* given *y*
$Pa\ (A_i)$	-	The parent nodes
Pi	-	A subset of power set P
Pl	-	The Plausibility function
s	-	Number of successes
t	-	Time interval
x	-	Prevention barrier
$X^{(0)}$	-	The time series data at time *t*
z	-	Random variable

Greek Letters

$\sum$	-	Summation
θ	-	The unknown parameter
ϖ	-	Discernment frame of cardinality

λ	-	The average number of abnormal events
Ω	-	The conflict mass of ignorance
Φ	-	A null set

CHAPTER 1

INTRODUCTION

1.1 Motivation

The chemical process industry (CPI) involves process plants of various complexities that deal with variety of hazardous materials, and diverse equipment. The advent of new designs aiming at achieving high product quality and operation performance further complicates the condition as they are typically configured with higher degree of heat integrations and built with lower over-design margin. This leads to higher performance process plants that are more difficult to manage. In ensuring that the objectives of plant operations are achieved, process plants are equipped with several layers of protection that includes various automated features and management procedures. At the base level, comprehensive process control functions are configured and installed to ensure the smoothness of operation and eliminate deviations from the intended operating conditions so that the desired performance is achieved and unwanted incidents are prevented. This is backed up by alarms to alert the plant operators when deviations are larger than allowable limits. Should these two main plant operation functions failed, the plant would be protected by safety interlock functions and relieve devices to enable more aggressive recovery from the unintended deviations. Nevertheless, despite all these measures, deviations continue to happen, some of which result in materials and/or energy releases. For this reason, process plants are also aided by mitigating measures in the form of protection barriers to prevent further escalation of hazards in the event of materials and/or energy releases. Unfortunately, history has shown that accidents continue to happen impacting the livelihood of workers and the surrounding community in different ways including casualties, enormous property damages, loss of business opportunities as well as others. Examples of these are provided in the next chapter.

It is generally accepted that although zero accident situation cannot be achieved in real life as there are many sources of potential errors within the plant system as well as external factors that can serve as triggering factors; their occurrences can be made less frequent with impact being mitigated. This calls for new initiatives at various stages of plant life cycles beginning from the design, installation, commissioning and operations. However, what is more urgently needed is to address the safety performances of existing plants, especially those that have been in service for some number of years. In this perspective, the issue of maintenance, upgrade and management of change are of paramount importance, and one important process safety tool that can facilitate such efforts is accident modelling.

Over the years, many forms accident models have been proposed and these models can be classified into four main categories e.g., sequential, epidemiological, systematic, and formal. The capabilities and limitations of the developed accident models are varying depending on purpose, focuses, and area of application. However, models that deal with process hazards and chemical process plant are rare (Rathnayaka *et al.*, 2011a). Among these few, a class of the Dynamic Sequential Accident Modelling (DSAM) known as SHIPP model is considered most promising as it integrates release events involving process hazards with typical plant safety mitigation barriers in a systematic manner (Al-shanini *et al.*, 2014a). However, upon scrutiny, SHIPP model is found lacking from a number of perspectives. Since it was formulated focussing on fire and explosion, it lacks the ability to deal with toxic releases. It is also unable to handle simultaneous failure events involving multiple categories, which is quite often the case in real situations. Furthermore, the accident sequence is also dependent on how the failure case was deduced, and as such reducing the applicability of the model when an abrupt failure occurs. For example, if explosion occurs abruptly as the first triggering event, the logical flow of the proposed prevention barriers falls apart. The model also neglects the potential hazards due to intentional manmade (sabotage/terrorism) acts and unwanted natural events related hazards.

Owing to the potential of this model despite the current weaknesses, it is proposed that this model be extended, improved, and reformulated into something more comprehensive, generic, and accurate to be used in the CPI. Having such models, more accurate and valuable outputs can be obtained, which can then be used to improve the prevention plans of accident through supporting risk-based decision for safer chemical plants.

1.2 Objectives of the Research

The main objective of this study is to develop a generic and comprehensive process hazards accident model for the chemical industry based on SHIPP methodology. The objective can be detailed out as follows:

1. To investigate the use of SHIPP model in analysing accidents in selected case studies as a proof of concept on the applicability of DSAM in the CPI.
2. To formulate a comprehensive dynamic accident model that considers all plausible hazards; process hazards, natural events related hazards, intentional manmade & security hazards, and the interaction between them in one framework.
3. To propose a methodology to overcome uncertainties arising from human (or expert) judgement on failure rates using evidence theory.
4. To improve the predictive capability of the proposed accident model by evaluating prediction methods for effective use in data-scarce environment.

5. To develop dynamic risk management methodology for vulnerability ranking of system's basic elements to improve the efficiency of risk-based decision activities.

1.3 Research Scope

To satisfy the objectives of this study, the scope and limitation of this research works are as follows:

i) Computation of Probability for Failure Cases

Failure probabilities of all prevention barriers are causally modelled using Fault Tree Analysis (FTA). On occasion of lack of data, expert's opinions are used, and this brings uncertainty and conflict as expert's opinion can be subjective. To minimize this impact, evidence theory is used.

ii) Modelling of Consequence Horizon

The consequence horizon resulting for all failure cases are generated using Event-Tree Analysis (ETA).

iii) Modelling of Barrier's Dynamic Vulnerability

The probability of failures of all prevention barriers changes over time dynamically. To track these changes, a dynamic updating algorithm of barriers failure probabilities based on plant precursor data are developed using Bayesian statistics on the ET model. In doing so, the trend of barrier failure probabilities can be observed.

iv) Improving Accident Prediction

As alternatives to Poisson model, the use of time series grey model, and Bayesian-grey models are explored. Performance evaluation is carried out against Poisson model on selected case studies.

v) Formulation of Comprehensive Framework

The comprehensive model proposed extends the SHIPP methodology. In addition to process hazards used in SHIPP, natural disaster and manmade hazards are included.

vi) Case Studies

A number of case studies are used in this study. The choice is made based on suitability of the issues addressed and availability of data. The case studies include hydrogen stations (both offsite and onsite stations) for evaluating SHIPP model, LNG plant for evaluating comprehensive model and the dynamic risk methodology, CSTR and vessel processing precursor data as well as IC data for evaluating the prediction study.

vii) Computation Tools

A number of computation tools are used. All Bayesian network computations are carried out externally using open source Markov Chain Monte Carlo simulation software (WinBUGS). Grey model computations are carried out using MATLAB R2010b software.

1.4 Research Significance/Contribution

This research hopes to develop a comprehensive, generic, and systematic accident model for chemical plants. The model intensively considers all plausible hazards roots that could cause CPI accidents. It provides the following capabilities:

i. Estimation of failures probability of all prevention barriers
ii. Identification of the relative vulnerability of the barriers over time
iii. Predictions of future incidents

These capabilities would facilitate process safety management efforts so that targeted maintenance program can be designed, thus reducing the overall cost of plant operation.

In addition, three important features are also introduced:

i. Better prediction
ii. Evidence theory to overcome experts' opinions uncertainty raised from conflict and ignorance

iii. The application of hierarchical Bayesian approach (HBA) and Bayesian network (BN) to reliability analysis techniques

The publications offered from this work contribute to the overall body of knowledge in process safety management. They are as listed in the Appendix.

1.5 Layout of Thesis

The organization of thesis is summarized in Figure 1.1. Following this introductory chapter, a detailed literature review on the subject is presented, focussing on accident models that are well suited for the CPI. The general classification of accident models are provided and explained, however; more extensive analyses and discussions are given to the Dynamic Sequential Accident Modelling approach. In chapter 3, the application of the SHIPP model to hydrogen stations is explained. Two case studies were considered, i.e. off-site station where hydrogen is supplied using trucks, and an on-site station where hydrogen production facility is included onsite. Chapter 4 elaborates on the proposed comprehensive preventive and predictive accident model. The model has been implemented into LNG facility includes pipeline, lignification facility, and offshore export port. Next in chapter 5, efforts to improve the accident prediction capability of the unwanted consequence, in data-scarce environment, has been taken place. This is followed by an effort to introduce dynamic risk management methodology as ranking tool to prioritize plant's plans, this is in chapter 6. Finally, in chapter 7, findings of this thesis are concluded, and recommendations for future works have been suggested.

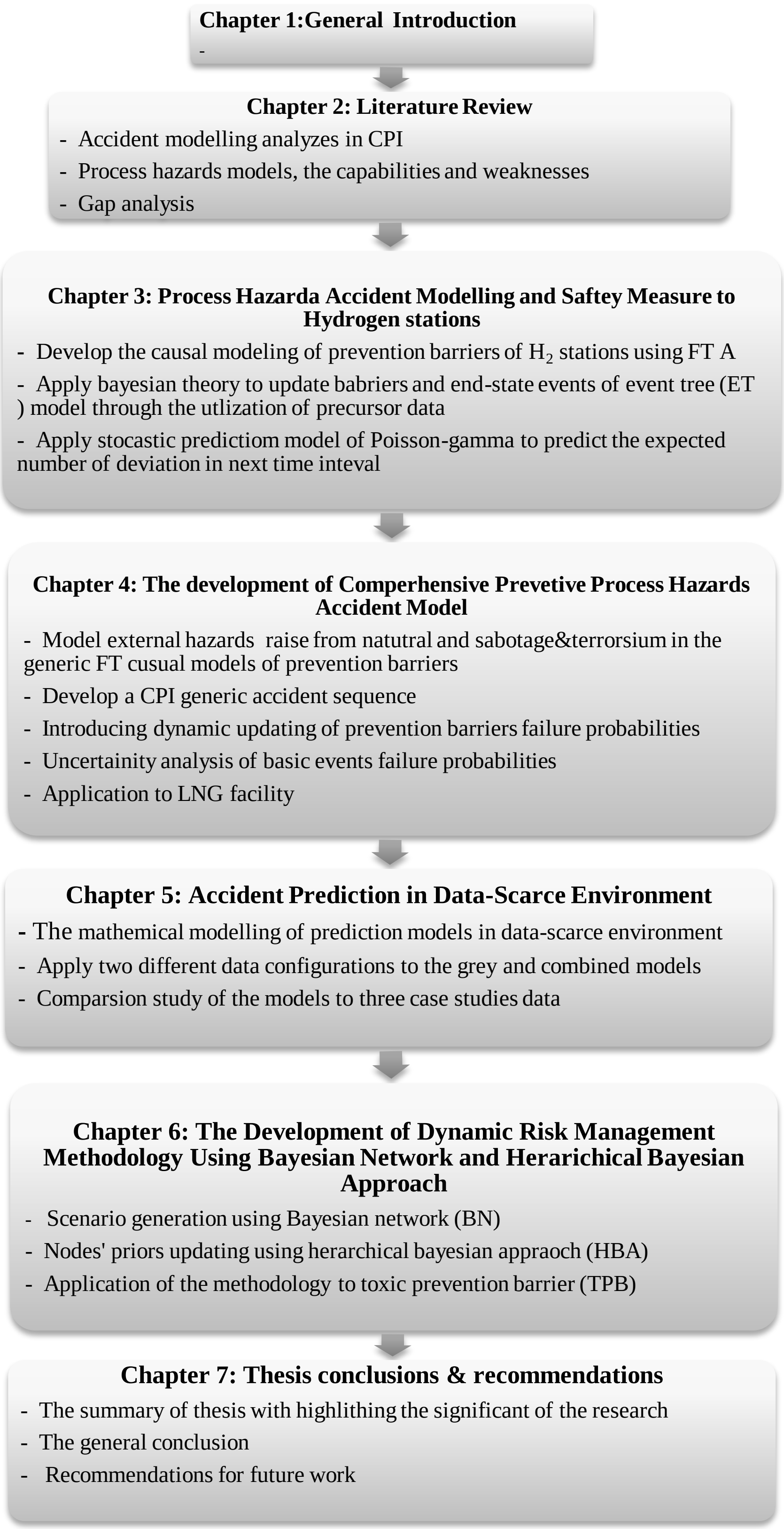

Figure 1.1 Flow chart showing Thesis organization

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