MODELLING AND REASONING OF LARGE SCALE FUZZY PETRI NET USING INFERENCE PATH AND BIDIRECTIONAL METHODS

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To

all my family members

who support me spiritually throughout my life

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ABSTRACT

The state explosion problem has limited further research of Fuzzy Petri Net (FPN). With the rising scale of FPN, the algorithm complexity for related applications using FPN has also rapidly increased. To overcome this challenge, this research proposed three algorithms, which are transformation algorithm, decomposition algorithm and bidirectional reasoning algorithm to solve the state explosion problems of knowledge-based system (KBS) modelling and reasoning using FPN. Based on the goal of this research, the entire research is separated into two tasks, which are KBS modelling and reasoning using FPN. In modelling, a transformation algorithm has been proposed while in reasoning, decomposition and bidirectional reasoning algorithms have been proposed. In transformation, the algorithm is proposed to generate an equivalent large-scale FPN for the corresponding large-size KBS using a novel representation method of Fuzzy Production Rule (FPR). In decomposition, the algorithm is proposed to separate a large-scale FPN into a group of sub-FPNs by using a presented index function and incidence matrix. In bidirectional reasoning, the algorithm for optimal path is proposed to implement inference operations. Experimental results show that all proposed algorithms have successfully accomplished the requirements of each link of KBS modelling and reasoning using large-scale FPN. First, the proposed transformation algorithm owns ability to generate the corresponding FPN for the large-size KBS automatically. Second, the proposed decomposition owns ability to divide a large-scale FPN into a group of sub-FPNs based on the inner-reasoning-path. Lastly, the proposed bidirectional reasoning algorithm owns ability to implement inference for the goal output place in an optimal reasoning path by removal of irrelevant places and transitions. These results indicate that all proposed algorithms have ability to overcome the state explosion problem of FPN.

ABSTRAK

Masalah ledakan keadaan telah merghadkan kajian lanjutan ke atas Rangkaian Petri Kabur (FPN). Dengan penambahan skala FPN, kerumitan algoritma terhadap aplikasi yang berkaitan dengan FPN juga telah bertambah. Bagi menangani cabaran ini, kajian ini mencadangkan tiga algoritma iaitu algoritma transformasi, algoritma penghuraian dan algoritma penaakulan dwiarah bagi menyelesaikan isu ledakan keadaan terhadap pemodelan dan penaakulan sistem berasaskan pengetahuan (KBS) menggunakan FPN. Berdasarkan matlamat kajian ini, kajian dibahagikan kepada dua bahagian iaitu pemodelan dan penaakulan KBS dengan FPN. Dalam pemodelan, satu algoritma transformasi telah dicadangkan manakala dalam penaakulan, algoritma penghuraian dan dwiarah telah dicadangkan. Dalam transformasi, algoritma dicadangkan untuk menjana kesepadanan FPN berskala besar bersesuaian dengan KBS berskala besar menggunakan kaedah perwakilan baru bagi Peraturan Penghasilan Kabur (FPR). Dalam penghuraian, algoritma dicadangkan untuk mengasingkan FPN berskala besar menjadi kumpulan sub-FPN menggunakan fungsi indeks dan matriks insiden. Dalam penaakulan, algoritma dwiarah bagi laluan optimum dicadangkan untuk melaksanakan operasi inferens. Keputusan eksperimen menunjukkan semua algoritma yang dicadangkan berjaya melaksanakan keperluan bagi setiap sambungan pemodelan dan penaakulan KBS FPN berskala besar. Pertama, algoritma transformasi yang dicadangkan mampu menjana kesepadanan FPN untuk KBS berskala besar secara automatik. Kedua, algoritma penghuraian yang dicadangkan mampu membahagikan FPN berskala besar kepada sub-FPN berdasarkan laluan-penaakulan-dalaman. Akhirnya, algoritma penaakulan dwiarah yang dicadangkan mampu melaksanakan inferens bermatlamat tempat output dalam laluan penaakulan optimum secara penyingkiran tempat dan peralihan yang tidak relevan. Keputusan ini menunjukkan semua algoritma yang dicadangkan mampu menangani masalah ledakan keadaan FPN.

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LIST OF ABBREVIATIONS

ACO	-	Ant Colony Optimization
ANN	-	Artificial Neural Network
CPN	-	Colored Petri Net
EN_system	-	Element System
FCPN	-	Fuzzy Colored Petri Net
FPN	-	Fuzzy Petri Net
FPR	-	Fuzzy Production Rule
FSPN	-	Fuzzy Stochastic Petri Net
FTPN	-	Fuzzy Time Petri Net
GA	-	Genetic Algorithm
HLFPN	-	High Level Fuzzy Petri Net
HLPN	-	High Level Petri Net
IFPN	-	Intutionistic Fuzzy Petri Net
KBS	-	Knowledge-based Systems
KR	-	Knowledge Representation and Reasoning
PN	-	Petri Net
PSO	-	Particle Swarm Optimization
P/T Net	-	Place/Transition Net
SPN	-	Stochastic Petri Net
TPN	-	Time Petri Net

LIST OF SYMBOLS

D	-	A finite set of propositions in the KBS,
CF_{ji}	-	Support strength
H	-	Incidence matrix
I	-	Input matrix
$IRS(p_i)$	-	Immediate reachability set of p_i
M	-	A vector of fuzzy marking
M'	-	Succeed marking
$M[t>$	-	Enable
O	-	Output matrix
P	-	A finite set of places
$RS(p_i)$	-	Reachability set
T	-	A finite set of transitions
w	-	Weight
X	-	Place Vector
Y	-	Transition Vector
μ	-	Threshold
β	-	An association function that reveals the relationship between places and propositions
${}^{\bullet}x$	-	Pre-set or input set of x
$x^{\bullet}$	-	Post-set or output set of x

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CHAPTER 1

INTRODUCTION

1.1 Overview

The purpose of this study is to research how to model and reason large-size knowledge-based system (KBS) by using fuzzy Petri net (FPN).To fulfill the purpose above, this study consists of two main missions, which are generating large-scale FPN for the corresponding large-size KBS (modelling task) and executing inference operation on the obtained large-scale FPN (reasoning task). This chapter overviews some essential modules of this study, includingresearch background, problem statement, research objectives, research significance, and thesis organization.

1.2 ResearchBackground

Knowledge representation and reasoning (KR) is an area of artificial intelligence (AI) to discuss how to represent information about the real world in a form and how to ensure computer systems can resolvecomplicated tasks utilizing theobtainedinformation.Over past decades, some formalisms were proposed to achieve the goals of KR. Typical formalisms of knowledge representation includesemantic nets,systems architecture,Frames, Rules, and ontologies; examples of automated reasoning engines are composed of inference engines,theorem provers, and classifiers (Chen et al., 1990).

Among the proposed formalisms, FPN is an appropriate tool for both of portrait fuzzy knowledge and executing approximate reasoning for knowledge-based system (KBS) or system with uncertainty. Firstly, due to the graphical description ability of FPN, fuzzy production rule (FPR) in KBS could be completely presented in the form of FPN. For example, Chen et al. (1990) utilized the FPNs to depict different types of FPRs, which includes ‘Simple’ rule, ‘OR’ rule, ‘AND’ rule, and multi-condition rule. Moreover, Gao et al. (2003) used a different proposition to stand for the proposition with the negation operator in the FPN. In addition,multi-output places were referred to the IF–THEN and IF–THEN–ELSE rules in KBS by Shen (2006). On the other hand, because of the parallel operation ability inherited from Petri net (PN), FPN is also broadly employed to performthe approximate reasoning for KBS (Amin and Shebl, 2014; Chen et al., 2014; Fenton et al., 2007; Gong and Wang, 2012; Hu et al., 2011; Lee et al., 2009; Liu et al., 2010; Luo and Kezunovic, 2008;Wai and Liu, 2009; Wai et al., 2010; Wu and Hsieh, 2012).According to the existing literature, inference mechanism using FPN couldbe roughly classified into three types, which areinference using reachability tree, inference usingalgebraic operation, and inferenceusing high level of FPN (HLFPN) (Ting et al., 2008; Sharma et al., 2008; Peters et al., 2009; Cheng et al., 2009; Sharma et al., 2010; Asthana et al., 2011; Abdulkareem et al., 2011; Barzegar et al., 2011; Rajpurohit et al., 2012; Liu et al., 2013a; Liu et al., 2013b; Ding et al., 2013; Wai and Lin, 2013;Bharathiet al., 2013; Chen et al., 2014; Shen et al., 2014; Chen et al., 2014).

From the viewpoint of industrial practices, the entire application process using FPN could be separated into three phases. The goals of these three phases aregenerate corresponding, propose reasoning algorithm rooted in the application background, and implement reasoning operation on relation industrial areas, respectively. The generalindustrialpractice process using FPN is depicted as shown in Figure 1.1.

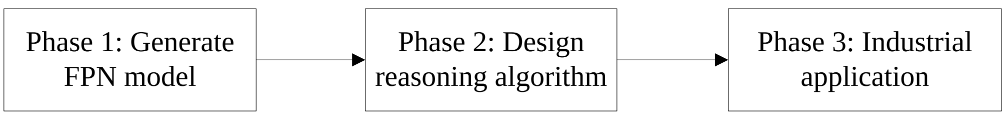

Figure 1.1 Generalindustrial practice process using FPN

Figure 1.1 demonstrates the application practice process using FPN. The process includes three phases. In Phase 1, an equivalent FPN will be generated for the corresponding KBS. Then, regarding the characteristics ofindustrial application, a fitting reasoning strategy will be presented. Finally, the presented algorithm will be applied into relevant industries (fault diagnosis, target recognize, traffic control, etc.) in Phase 3.

Although FPN and related practices have successfully attained the initial goals and expectations of researchers, however, the further studies of FPN are hindered by an enormous neck-bottle, namely the state explosion problem, because FPN and related industrial practices are based upon an exhaustiveenumeration of all possible marking by firing all enable transitions (Chen et al., 1990; Li et al., 2000; Gao et al., 2000; Gao et al., 2003; Gao et al., 2004). Hence, this study tries to solve the state explosion problem of FPN surrounding two aspects: generate large-scale FPN for the corresponding large-size KBS automaticallyand execute reasoning for the appointed output place in a large-scale FPN effectively.

1.3 Problem Statement

Despite the FPN received increasing attention from researchers and obtained fruitful results in various fields (Rajpurohit et al., 2012; Sharma et al., 2012;Gong et al., 2012; Chen et al., 2014), however, the existing modelling and reasoning techniques algorithm using FPN will be difficult to execute for large-scale FPN because of space explosion problem.

State space method is widely employed to execute automatic analysis and verification of the behavior for concurrent systems (Valmari, 1998). In a boardersense, this kind of method is based on constructing a structure that consists of all states that a system can reach, and all transitions that the system can make between those states. This structure is often called the state space. However, as the number of state variables in the system increases, the size of the system state space grows exponentially. This is called the ‘state explosion problem’ (Clarke and Grumberg, 1987; Valmari, 1991; Kress-Gaziet al., 2011; Clarke et al., 2011).

To overcome the state explosion problem, various strategies were proposed by scholars over past years, such as state space reductions, storage size reductions, parallel and distributed computation, and randomized techniques and heuristics (Pel ́anek, 2009). Specific to PN area, the main approach to handle state explosion problemwas called decomposition algorithm, which has the function to divide a large-scale PN into a series of small-scale PNs by sharing consist ofsame dynamic or structure properties (Zaitsev, 2004; Zeng and Duan, 2007; Nishi and Tanaka, 2012; Wisniewski, et al., 2014; Nishiand Matsumoto, 2015).

In recent years, the main obstacle in applying FPNis also the state explosion problem. The influences of state exposition problem in industrial practices using FPN could be summarized into following three aspects:

i. Despite the corresponding FPN of each fundamental type FPR was discussed and generated by engineers (Zhong, 2008; Xu et al., 2011; Wu et al., 2012; Wu and Hsieh, 2012). However, with the rapidly increasing size of KBS, the number of FPR in expert systems is also growing sharply. It also indicates that the current manual transformation approach is difficult to generate the corresponding FPN from a complex, large-size KBS rooted in the proposed fundamental FPN modules (Milinković et al., 2013; Bharathi et al., 2014; Khan et al., 2014; Khoukhi, et al., 2014; Yusof and Latif, 2014).
ii. With the growing scale of the FPN, the number of requisite parameters is also raised. The literature illustrates that the values of parameters directly affect the accuracy of reasoning result (Sharma et al., 2010; Asthana et al., 2011; Abdulkareem et al., 2011). Hence, the accuracy of the reasoning resultbecomes moredifficult to gatherwith the increasing size of FPN (Barzegar et al., 2011; Vuran et al., 2011; Rajpurohit et al., 2012; Talouki and Motameni, 2013; Zhao et al., 2014).
iii. The dimensions of the reachability tree or related matrices/vectors also depend on the scale of the FPN (Pang et al., 1995; Pantelopoulous and Bourbakis, 2010; Parhi and Mohanta, 2011; Pan et al., 2012).The existing algorithms are difficult toimplementreasoning for a large-size FPN due to the dramaticallyincreasing dimensions of related matrices or vectors. Meanwhile, the optimal reasoning path of an appointed output place is also hard to be recognized in a large-size FPN (Asthanaet al., 2011; Barzegaret al., 2011;

Rajpurohit et al., 2012; Milinković et al., 2013; Khan et al., 2014; Khoukhi, et al., 2014).

Although various decomposition algorithms have already been proposed to overcome state explosion problem, but these algorithms are not suitable to decompose the large-scale FPN. It is because that there are a group of inner-reasoning-paths among places and transitions in FPN. If the large-scale FPN is divided into a group small-scale FPNs with considering the inner-reasoning relationship, the inner-reasoning-paths of FPN also will be destroyed. Thereby, the reasoning operation is also impossible to implement on the decomposed small-scale FPNs. Therefore, facing with the state explosion issue of FPN, this study tries to settle following research questions, which are:

i. How to generate an intact large-scale FPN for the corresponding large-size KBS on the promise of keeping the inner-reasoning-relationships among enormous number of FPRs.
ii. How to decompose the large-scale FPN into series small-scale sub-FPNs on the promise of protecting all completeness inner-reasoning-paths among places and transitions in large-scale FPN?
iii. How to execute reasoning algorithm on an optimal inference path for the appointed output placeon the promise of removing allirrelevant places and transitions of the goal placeina large-scale FPN?

1.4 Research Objectives

According to the proposed research questions, objectives of this study are listed below, which are:

i. To propose a transform algorithm for generatingan equivalentlarge-scale FPN from the corresponding large-size KBS automatically on the promise of keeping inner-reasoning-relationships among FPRs.
ii. To propose abidirectional decomposition algorithm for dividinga large-scale FPN into small-scale sub-FPNs by using an incidence matrix and index

function based on the each completeness inner-reasoning-paths among places and transitions of large-scale FPN.

iii. To propose a bidirectional adaptive reasoning algorithm for executing inference process on the optimal path for the appointed output place in a large-scale FPN via removing all irrelevant places and transitions.

1.5 Research Scopes

To fulfill research objectives of this study, research scopes of this study are listed as follows:

i. FPR is utilized to represent information in KBS.

ii. Dynamic properties (including reachability, boundedness and safeness, liveness, and fairness) of FPN are discussed forkeeping the correctness of decomposition operation of large scale FPN.

iii. Pre-set and post-set of each place are applied into calculate the number of reasoning path in a FPN.

iv. Incidence matrix is used to decompose the large-scale FPN.

v. Backward searching is exploited to seek a completed reasoning path from the appointed output place in any given FPN.

vi. A classical forward reasoning operation is chosen to execute inference from input place(s) to a signal goal output place in the simplest inference path.

1.6 Research Significance

Focusing on the state explosion problem of FPN, this study tends to:

i. Generate large-scale FPN for the corresponding large-size KBS automatically on the promise of maintaining the completeness inner-reasoning-relationships among FPRs.

ii. Simplify the reasoning processof the goal output place in a large-scale FPN effectively on the promise of keeping completeness of optimal reasoning path.

The study makes a useful attempt to solve state explosion problem of FPN. Focusing on the different task of each phase in the practical process using FPN, three algorithms are proposed to fulfill the research questions, which are transform algorithm, decomposition algorithm, and bidirectional reasoning algorithm.

First, transformation algorithm owns ability to generate large-scale FPN for the corresponding large-size KBS automatically via the inner-reasoning-relationships among FPRs. This algorithm helps researcher or engineersavoid missing any possible inner-reasoning-relationships among copious amount of FPRs on generating corresponding FFP for a complex, large-sizeKBS.

Second, decomposition algorithm owns ability to divide a large-scale FPN into a group of small-scale sub-FPNs via each inner-reasoning-path of FPN. In this algorithm, each decomposed sub-FPN represent a completed reasoning process from input place(s) (initial causes of inference process) to signal output place (finial result of inference process). This algorithm helps researchers and engineers easily understand the interior reasoning component or process for a large-size, complex system.

Last but not least, bidirectional reasoning algorithm owns ability to seek an optimal reasoning path for the appointing output place via removing all irrelevant places and transitions. This algorithm helps researchers and engineers easily obtain the optimal reasoning path for the appointed output place among various possible reasoning path. This algorithm also can reduce the algorithmcomplexity of the reasoning operations.

1.7 Thesis Organization

This thesis makes up of seven chapters. Chapter 1 discusses the basic components of this study. Chapter 2 reviews FPN and related reasoning algorithms.

Chapter 3 analyzes the research methodology of this study. Chapter 4 presents a transfer approach to generate the equivalent FPNfrom the corresponding KBS automatically. In Chapter 5, a novel algorithm is carried out to decompose the large-scale FPNbased on the theoretical discussion of dynamic properties of FPN. Moreover, a proven theorem is presented to calculate the number of reasoning paths in FPN. Chapter 6 proposes a bidirectional inference algorithm by FPN to simplify the reasoning process and to reduce the algorithm complexity automatically for an appointed output place. Finally, Chapter 7 includes the conclusion, contributions and potential upcoming research to be conducted as derived from this thesis.

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