THESIS APPROVAL

GRADUATE SCHOOL, KASETSART UNIVERSITY

Doctor of Engineering (Electrical Engineering)

DEGREE

Electrical Engineering — **FIELD**

Electrical Engineering — **DEPARTMENT**

TITLE: Outage Cost Assessment of Power Distribution System for Reliability Improvement

NAME: Mr. Chaliew Ketkaew

THIS THESIS HAS BEEN ACCEPTED BY

THESIS ADVISOR

(Assistant Professor Dulpichet Rerkpreedapong, Ph.D.)

THESIS CO-ADVISOR

(Assistant Professor Winai Plueksawan, Dr.Ing.)

DEPARTMENT HEAD

(Associate Professor Vichai Surapatana, M.Eng.)

APPROVED BY THE GRADUATE SCHOOL ON

DEAN

(Associate Professor Gunjana Theeragool, D.Agr.)

THESIS

OUTAGE COST ASSESSMENT OF POWER DISTRIBUTION SYSTEM FOR RELIABILITY IMPROVEMENT

CHALIEW KETKAEW

A Thesis Submitted in Partial Fulfillment of
the Requirements for the Degree of
Doctor of Engineering (Electrical Engineering)
Graduate School, Kasetsart University
2014

Chaliew Ketkaew 2014: Outage Cost Assessment of Power Distribution System for Reliability Improvement. Doctor of Engineering (Electrical Engineering), Major Field: Electrical Engineering, Department of Electrical Engineering. Thesis Advisor: Assistant Professor Dulpichet Rerkpreedapong, Ph.D. 80 pages.

This research presents assessment methods of outage cost on power distribution systems. Outage costs of electricity customers and utilities are an important factor used for decision making process on reliability improvement. Therefore, data of more than 400 industrial factories are surveyed by means of questionnaires to develop a customer damage function composed of duration outage cost and initial outage cost, which is used to evaluate the outage cost of each customer. However, to obtain the total outage cost of a distribution feeder, it is unlikely to survey all customers and get their customer damage functions. Consequently, outage cost modeling including fuzzy regression and conventional linear regression is proposed in this dissertation. First, all customer damage functions available are evaluated for their corresponding customers. Some of the resulting customer outage costs are then used as the output variable of the models being developed versus the corresponding input variables, which are the rate of production, cost of electricity bill and startup time. These three variables are selected as the inputs because they are helpful, and it is convenient to request them from the customers. Finally, model selection process is proposed for selecting the best model out of those resulted from fuzzy regression or conventional linear regression based on hypothesis testing. The practical methodology presented in this thesis can be used for high accuracy outage cost assessment of industrial customers.

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ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to Asst. Prof. Dr. Dulpichet Rerkpreedapong my thesis advisor for his support, encouragement, invaluable guidance and kindness for this research work. I sincerely thank Asst. Prof. Dr. Winai Plueksawan my thesis co-advisor for giving me experience, encouragement, and helpful recommendation.

I sincerely thank all teachers and staff at Department electrical engineering, Faculty of Engineering, Kasetsart University. I would like to thank people at Power Skill Development Project (PSDP), especially for Onurai Noohawm, a senior researcher for her kind encouragement.

I would like to thank the PEA-KU projects, BI roadmap project and Target-setting project. I would like to thank Provincial Electricity Authority (PEA), their engineers and technicians for giving me a chance of learning distribution system and their industrial customers for kind giving me the valuable data.

I would like to thank Rajamangala University of Technology Suvarnabhumi for funding my doctoral studies, and all friends at Suphanburi campus.

I deeply especially appreciate my beloved mother for her continuing encouragement. Finally, I am grateful to both of my parents, all teachers, preceptors and my beloved late teacher, Assoc. Prof. Dr. Jamnarn Horkierti, all who give me the opportunity for invaluable studies.

Chaliew Ketkaew

July 2014

TABLE OF CONTENTS

Page

LIST OF TABLES

LIST OF TABLES (Continued)

Table **Page**

LIST OF FIGURES

LIST OF ABBREVIATIONS

β_0 , β_1, ..., β_n	=	constants or the model partial regression coefficients
A_0 , A_1 , ..., A_n	=	fuzzy parameters
ANOVA	=	analysis of variance
C_i	=	energy consumption ratio of each customer type
CCDF	=	composite customer damage function
CEA	=	Canadian electrical association
CDF	=	customer damage function
CDF_k	=	CDF of customer k using duration outage cost (DC) in Baht/hour
COC_k	=	customer outage cost of customer k
DC	=	duration outage cost
EGAT	=	electricity generating authority of Thailand
EENS	=	expected energy not supplied
FCOC	=	feeder customer outage cost of interested feeder
IEAR	=	interruption energy assessment rate
ICPE	=	interruption cost per event
IC	=	Initial outage cost
i	=	customer type
j	=	number of customer # j
k	=	number of all customer of each customer type
LF_i	=	load factor of each customer type
MEA	=	metropolitan electricity authority
MAPE	=	mean absolute percentage error
n	=	number of customer type
N	=	number of interruptions on feeder that serves customer k
NSERC	=	the natural sciences and engineering research council
NVC	=	navanakron substation number III
NPL	=	Nhong-Pling substation
PEA	=	provincial electricity authority
PIC	=	partial insulated cable

LIST OF ABBREVIATIONS (Continued)

RCM	=	reliability centered maintenance
SAC	=	space aerial cable
SCDF	=	sector customer damage function
SAIDI	=	system average interruption duration index
SPP	=	small power producer
SIL	=	the Siam industrial land industrial real estate
t_i	=	duration of sustained interruption #i
u_i	=	random disturbance term
WTP	=	willing to pay
$X_1, X_2, ..., X_p$	=	independent variables
Y	=	dependent or response variable

OUTAGE COST ASSESSMENT OF POWER DISTRIBUTION SYSTEM FOR RELIABILITY IMPROVEMENT

INTRODUCTION

All electric power utilities in Thailand aim to provide services to their customers with high quality, reliability and safety. As a result, a number of megaprojects have been implemented on power distribution infrastructures such as smart grids, risk and asset management, overhead to underground system conversion and microgrids. Provincial Electricity Authority of Thailand (PEA) is the largest power distribution utility who serves electric energy to its customers all over the country, except Bangkok, Nonthaburi and Samutprakarn. Therefore, over billions of baht are spent each year to improve system reliability continuously. This will require the outage costs varying from area to area to support the decision making process on reliability project investment.

Outage cost is the economic losses due to a power outage, which affects both power utility and its customers. For example, PEA loses its revenues from selling electricity during the power outage. Also, commercial and industrial customers may lose their business opportunities, goods and services. The degree of damages resulted from a power outage depends on type of customers and duration of outage. To achieve a reliable outage cost assessment, data collection needs to be done carefully. First, questionnaires are designed, and later are used in customer surveys. Next, the gathered information is considered to develop the Customer Damage Function (CDF) of each customer, which describes both duration outage cost and initial outage cost.

To obtain the total outage cost of a power distribution feeder, the utility needs to add up all customer outage costs evaluated by the CDFs, and it is unlikely to be done because the utility has limited resources to survey all customers. This dissertation proposes the assessment method of customer outage costs using available and easy-to-find information based on Fuzzy regression and statistic linear regression techniques. First, the CDFs obtained from the collected information are evaluated to find the customer outage costs, and they are used as the output variable of the models to be developed in order to assess the outage cost of the unsurveyed customers. On the other hand, the rate of production, cost of electricity bill and startup time are used as the input variables of the models because they are practical and it is convenient to request them from the customers. Next, outage cost modeling can be done using both Fuzzy regression and statistic linear regression techniques. In addition, the selection criteria for the better outage cost model between both techniques is proposed using mean absolute percentage error (MAPE) and hypothesis testing by Analysis of Variance (ANOVA).

In this dissertation, industrial customers of six Thai Standard Industrial Classification (TSIC) groups with high energy consumption including foods, textiles products, chemicals and rubber, cements, iron and automotive parts are selected as case studies. The outage costs resulted from the proposed method are compared with the actual outage costs for effectiveness evaluation. The results obtained from outage cost assessment can be very helpful to power utilities to prioritize their distribution feeders or areas for reliability improvement projects.

OBJECTIVES

1. To study effects of power interruptions for utilities and their customers.

2. To develop a practical method for outage cost assessment for reliability improvement.

LITERATURE REVIEW

In many countries, outage cost are surveyed and assessed to find the appropriate results for outage cost evaluation method. General concepts are collecting data, creating sector customer damage function (SCDF), producing composite customer damage function (CCDF), using interruption records and EENS to calculate damage cost in interruption energy assessment rate(IEAR) and interruption cost per event (ICPE). Outage cost is an important tool for power system reliability improvement. Decreasing of outage cost and increasing of system reliability will be focused on economic investment consideration.

Mathematical models are used for outage cost assessment. Conventional regression or statistic regression as simple linear regression and multiple linear regression are used in outage cost assessment. Although there are many techniques as artificial intelligences will be concerned with helping calculation, regression methods are still favourable. Fuzzy concepts are applied for regression model to be alternative technique for statistic regression problems. Fuzzy linear regression and conventional regression are used to create customer outage cost models in this research.

Power distribution system maintenance is the powerful work can keep system to supply continuing energy. Maintenance activities are needed to enrich electrical system and reduce outage cost of utilities and their customers. Reliability centered maintenance (RCM) is modern technique applying for large industrial organization. RCM is being used to develop power distribution system and others.

1. Customer outage costs

There are two parts of outage cost that can be seen by utility and customer. Firstly, utility outage cost including loss of revenue from energy not supplied, loss of customer goodwill and so on. Secondly, customer outage cost of industrial customer including loss of manufacturer, damaged equipment, extra maintenance, etc. customer outage cost of residential customer about uncomfortable life such as spoiled deep frozen foods, heating and lighting cost. Consider total outage cost, found that utility outage cost is very less than customer outage cost. Most of total outage cost are from unavoidable and suffering cost of industrial customer such as lost of production process, damage of product, equipment failure, additional maintenance cost, etc. Unbearable cost of residential customer are rotten food, air conditioning, lighting and so on. Next is cost that hard to estimate as uncomfortable, making depressing hobby, loss of time for doing activities. Events are not desirable for example, burglary, crime and mayhem, loss of hospital service. There is a study of outage cost per kilowatt in function of time. Outage cost are a variable cost and a wide interval also depend on geography, small or large, industry, business or resident. It is no need to be a linear function. Because of general estimated cost is rerated to power demand or estimation by other indices. Relation of nonlinear outage cost should be looking for the appropriate function and taking to combine with probability distribution of duration time (Billinton and Allan, 1994).

Basic characteristic of modern power system is power and energy providing for power demand support and electrical energy service to customer with possible investment. Although cost of investment is limited, power system still has to acceptable reliability. Reliability worth assessment would be analyzed from overview cost and assessed in quantitative reliability. Calculation of reliability worth is very hard and sometime impossible. There are many reliability worth assessment methods to evaluate in monetary cost. Interruption cost are often used to measure reliability worth indirectly. It is important for visibility and this method is used for along time. Customer surveys are the data collection methods to calculate consequently effects from power interruption which customer can not be supplied for continuing energy. There are three favor customer groups as residential, commercial and industrial customer which can be used the surveyed results by relationship and rationality. First, outage cost are systematic surveyed in 1980- 1985 in on behalf of Canadian Electrical Association(CEA) by Saskatchewan University. Second, outage cost are survey in 1990-1992 by The Natural Sciences and Engineering Research Council (NSERC) and seven utilities in Canada. Surveyed data are classified by Sector Customer Damage

Functions (SCDF). SCDF of each sector are combined to create Composite Customer Damage Functions (CCDF). Reliability assessment of substation use analytical method and apply Monte Carlo method for helping calculation. Advantage of Monte Carlo is to provide data related to probability distributions of reliability indices. Simulation method can be used for understand complicated equipment repairing or distribution of repair time. These method is quite difficult so should be used a simulation method together with an analytical method in addition to assuming or something uncomplicated (Billinton and Li, 1994).

Customer cost of reliability are expense of customer facing with power interruption especially, when power outage in USA has damage cost more than 13,000 US dollar. It is cost without damaged products or equipment failure. So this is important things that utilities try to see both sides when they want to invest system themselves and they will consider loss of their customers. While System Average Interruption Duration Index (SAIDI) is increased, loss of customer will be increased. If utility want to decrease SAIDI, utility has to put the money for making system strongly. Then utility need to maintain, design and operate that will help to decrease customer loss appropriately in value-based planning. Investor, the owner of utility always want to get maximum profits more than well being or safety or security of sociality. Outage cost data become what is less important because money of customer is not important equal utility money. But thinking about outage cost of their customer will help utility better understanding their customer and propose economical services which can increase profit. So, thinking about customer outage cost will make investor understand their customers and offer appropriated economic services to customer for increasing customer profit and complacency (Brown, 2002).

Outage cost is index to indicate importance(significance) of customer for utility serving energy by stability and reliability. Determination of customer significance not only utility has electrical reliability service but also country will have more investors. Helping industrial customer no need to find location only in city for getting good quality services. Damage of power interruption can be classified as damage of electrical utility, customers, public utilities and national security system.

Electrical utility damage is cost of energy not served. Customer damage are cost of number of interruption and cost of interruption duration. For using outage cost, it is presented to be calculated in feeder outage cost. Data collection by post mail surveyed method to send questionnaires to customers will only be responded six to seven percent but interview method is better. The author suggests collecting data as long as needed for considering. Questionnaires have to simple and have no more details and unnecessarily detailed question. It should not be asked for if electric interruption in 10, 20, 30, 45, 60 minute how much interviewee will get damage cost. Because customers have never been assessed themselves for these outage duration. The author suggest way for data management by considering relation between outage cost and industrial capacity and classified by distribution feeder. Utilities who have no surveyed of outage cost, they could not specify the important level of feeders should be maintained before and after. Maintenance program would only be corrective maintenance but not preventive maintenance (Horkierti, 2006).

Outage cost study in Thailand, there is first study in 1995-1996 by Energy Research Institute, Chulalongkorn University corporate with Electricity Generating Authority of Thailand (EGAT), Metropolitan Electricity Authority (MEA) and Provincial Electricity Authority (PEA). After past five years, outage cost were improved for appropriation of customers and electrical system condition at that time. Data collection had a target number more than 1,100 samples which were separated as industrial groups 300 samples, official and commercial group 400 samples and residential group 400 samples. Collecting field data and internet data were 2,238 samples. Data can be classified in to 7 types by tariff rate structure. Composite customer damage function (CCDF) was created from SCDF and weighting by energy consumption and load factor. CCDF was created in average model and fuzzy model. Outage cost assessment using CCDF and interruption records of utilities. Energy Not Supplied (ENS) can be evaluated from utilities interruption records. Finally unit interruption cost are composed of CCDF, interruption records and ENS used to create Interrupted Energy Rate (IER; Baht/kWh) and Interruption Cost Per Event (ICPE; Baht/event) for future outage cost estimation (Energy Research Institute, 2001).

Customer financial is put on electrical system reliability and is composed of important tool to determine for Grid investment. National Transmission Grid Study need this data identified status of growth of public and private sectors. Lead by the U.S. Department of Energy starting for finding to identify lack of necessary outage cost for reliability assessment from 24 case studies of 8 utilities in 1989 - 2002. Customer can be separated in residential customers, small and medium of business and industrial customers, large of business and industrial customers covering all area of country. Adjusting for common base by the 2002 CPI, Consumer Price Index included into same data base and separated in each scenario such as outage cost of weekday on the afternoon of on hour. They are independent case studies recorded to compare between nature of interruption and increasing of statistic analysis results. Customer damage function presents values of damage from electrical interruption of given outage scenario, customer class, time of day, consumption and business type. As results of one hour of power interruption on weekday afternoon for summer, residential customers have 3 dollars of outage cost, small and medium industrial and business customers have 1,200 dollars of outage cost and large industrial and business customers have 82,000 dollars of outage cost (Population Research Systems, 2003).

Consider of least-cost service that mean minimize of total of utility service cost and customer outage cost. Value of service (VOS) or outage cost is used the survey method to find expensed cost of customer facing with power interruption. Outage cost mean what customers willing to pay for reducing duration time. The aggregate VOS has 16 dollar per kilowatt-hour. In electrical system, there are important three parts such as transmission line, transformers and switching devices. Installing of switching devices will help to separate line section for reducing some problems of electrical supply interruption. Consider load profile, load curve will help to know when load is maximum, how many load capacity and frequency of occurring to resolve by changing which devices will be placed on the system (Stephenson and Barney, 1988).

Presenting of marginal costs forecasting to determine real time electricity pricing which marginal costs are consisted of marginal operation costs and marginal outage costs. Marginal operating costs assessment is cost of system improvement method for keeping system for stability, security, suitability and speed. Marginal outage costs assessment is economic evaluation with interruption events like using load-related probability to specify outage events (Kirsch *et al*., 1988).

For reliability worth, application of economic cost of system planning, the often using economic cost is to find losing money of customer from power system failure events as damage cost of unreliable system. There are unlimited methods and optional ways for suitable studies of outage cost depending on the notion. For finding results and usefulness for industrial customers more than other type of customers. In this paper presents the interruption cost survey and composite customer damage function (Wacker and Billinton, 1989).

This is marketing research project to study PG&E utility about selling, installing and maintaining of electrical generator for customer services. Prediction of outage cost assessment will help customer for making decision on investment to avoid affect of power interruption. From onsite report is founded customers who install reserved generator have to pay for maintenance cost amount 30 dollar per year and 40 percent of customers who install generator have no damage cost from power interruption (Leblanc, 1988).

In general, power distribution system is strong and flexible to supply electrical energy. Consideration of potentiality, economy, reducing losses, promoting reliability and improving appropriate design to environment for finding a useful and progressive tool for planning, operating, maintaining and documenting. This paper explains a structure of planning for solving reliability problems and analyzes cost minimization. Reliability is described with cost of operation and electricity prices consisting of electrical power and energy not supplied (Kjolle *et al*., 1990).

Optimal level of reliability for utility and customers is considered by measuring of an emergency operation in time. Data of customer damage cost are composed into probabilistic framework. This method suggested utility to plan for reliability level with Willing to Pay of customer (Burns and Gross, 1990) . Where Willing to Pay (WTP) is how much the customer would pay to avoid occurrence of power outage that mostly assessed from residential customer.

Reliability quantitative analysis was included as part of distribution system data. Outage rates, interruption duration and interruption cost are calculated and combined with data of distribution system, data of reliability of devices in distribution circuits and energy per-unit of expected energy not served. Using reliability program combined with other programs, studying of appropriate plan for distribution system developments, in this study integrated with technical limitations and overview costs of investment cost, loss and interruption events (Makinen *et al*., 1990).

This work presents system security with distance limitations of operation in electrical system including voltage collapse, stability limitations, conductors and overload transformers. Generation system limitation used point of collapse method based on singularity of power flow Jacobian to find operation limit boundary by converted distance to boundary in measuring system failure probability. System failure probabilities are normal condition system probability, expected demand not served, expected unserved energy and expected outage cost. Considering for sensitivity measurement of varying load and varying generation important for operation decision. a number of real time prices were presented from computer (Alvarado *et al*., 1991).

Composite generation and transmission system was considered of sufficient power demand. Appropriate planning for system expansion should think about investment cost, operation cost and damage cost. This paper presents the cost minimization for generation and transmission expansion. Operating cost and outage cost at load buses consisted of operating cost and outage cost at different load buses including simulation be duration of system status. Creating computer program provided conductor groups, load buses, generator buses and system index selected for appropriation system expansion planning at different level of load and load growth with IEEE reliability test system (Li and Billinton, 1993).

Basic method for reliability worth assessment is surveyed by post mail or interview each other. Results are converted into customer damage function by customer groups or types. Standard function would be substituted by duration. This paper show the three dimension of probability distribution. The results are used to analyze assessment of the adequacy of capacity for calculation interrupted energy assessment rate (IEAR) in dollar per kilowatt-hour. The results were higher than the conventional calculation results (Billinton *et al*., 1994).

This paper present model and method of probability distribution together with reliability indices of network. Outage cost assessment by probability distribution of interruption duration with CAIDI including analytical technique and Monte Carlo simulation using IEEE reliability test system (Allan and Silva, 1995).

Optimum design for minimization of investment cost, maintenance cost and outage cost which presents total of customer outage cost by considering power interruption from substation and difference of customer load of each bus. Interruption events at substation are calculated with probability estimation by Markov models (Satish and Billintion, 1995).

Residential customer outage survey by University of Manchester (UMIST), there are variables which effect to power interruption as interruption frequency, season, time period of each day, weekday and weekend (Kariuki and Allan, 1996).

Reliability of distribution system is a part of electrical network development, this paper identified the issues as customer outage cost represented reliability worth and criterion for planning policy, design and operation by analysing 33 kV of two networks (Kariuki and Allan, 1996).

This paper showed 210 large industrial and commercial customers by observation structure of plant, service and product, production process, generator and equipment design for power security and quality. Statistical method is used to estimate outage cost by regression models (Sullivan *et al*., 1997).

Using evolution programming for global optimum to find minimization cost, outage cost, feeder line loss and fixed cost. Evolution programming is used for complicated and nonlinear problems (Lin *et al*., 2000).

Approximate methods are presented for customer outage cost evaluation based on interruption events at distribution feeders from specific outage event. This method used data groups classified by customer types as commercial, industrial and residential customers. This paper presents simple estimation to reduce complication of former method. This method are provided for practical outage cost evaluation from specific outage events (Billinton and Wangdee, 2005).

This paper presents economic impact assessment in Sri Lanka by selecting 150 number of industrial factories from 3,074 factories. Then, percentage of outage cost compared with Gross Domestic Product (GDP). Finally, there are calculations of outage cost from temporary interruption, planed outage and interruption from other causes, installed reserved generator and others(Wijayatunga and Jayalath, 2003).

Composite customer damage functions (CCDF) of four countries as Canada, Japan, England and Thailand are used to analyse and consider interruption cost (ECOST) and interrupted energy assessment rate (IEAR) using reliability test system Bus-4 of Roy Billinton (RBTS). The results found that England model has higher reliable than other countries (Goel, 2007).

2. Fuzzy linear regression

There was proposed linear regression analysis with fuzzy model in 1982. The authors used fuzzy concept by considering fuzzy linear functions of Zadeh. The general regression models are measured deviations with observed values and estimated values. But this proposed the deviations are supposed to depend on indefiniteness of the system structure which is devised a fuzzy linear regression analysis. The authors regard deviations as the fuzziness of system parameters which are reflected in a linear function with fuzzy parameters (Tanaka *et al*., 1982).

Many papers are analyzed by using fuzzy regression following Tanaka approach. A fuzzy output, fuzzy coefficients and an non-fuzzy input vector are included in their regression models. This article purposed revisiting of fuzzy regression portion and discussed the Tanaka approach related issues. Beside, fuzzy least-squared regression models are considered. Classical statistic linear regression problems is mentioned that can happen in the situations as small data set, vagueness in the relationship between output and input variables and so on (Shapiro, 2005).

Fuzzy regression analysis is used for peak load estimation in distribution system. This work presents application of fuzzy regression to power distribution system calculations. A substation peak load as daily peak load and a set of customers features(explanatory variables) as daily energy consumption are expressed in regression model. Finally, comparison of fuzzy regression model and standard linear regression model by average error. Consideration of the spread of fuzzy models does not depend on sample size and the width of confident interval in standard regression models depends on sample size (Nazarko and Zalewski, 1999).

The 30 experiments of transfer moulding which is the process to perform microchip encapsulation for electronic packages are used to develop fuzzy regression models. There are three models including quality characteristics (dependent variables) and significant process parameters (independent variables). The results of two validation tests are calculated from fuzzy regression models as less than 5 percent of prediction errors (Ip *et al*., 2003)

The development of learning system prediction by computer-based forecasting model by using fuzzy regression. This study used data of the oral cancer database resource from faculty of dentistry, University of Malaya. Input data as patients demographic profile and risk habits such as age, sex, cigarette smoking habits, alcohol drinking habits, betel-quid chewing habits, DNA, etc. Output data are the health state as cancer or healthy. An adaptive prediction model for binary output based on fuzzy regression is the main contribution of the research (Dom *et al*., 2008).

Oil consumption data of Canada, United States, Japan and Australia between 1990-2005 are used to develop forecasting model by flexible fuzzy regression algorithm. Input data as annual population, cost of crude oil import, gross domestic production(GDP) and annual oil production. Output data is annual oil consumption. The data of World Bank (2006) are used to identify the preferred model to estimate and forecast oil consumption. Fuzzy regression, conventional regression, analysis of variance(ANOVA) and mean absolute percentage error(MAPE) are consisted of the proposed algorithm (Azadeh *et al*., 2009).

3. Reliability Centered Maintenance(RCM)

RCM is the maintenance management methodology which focused on critical components for reliability improvement. RCM can help for suitable preventive maintenance activity selection with economic maintenance cost. Commercial aircraft industry initially produced RCM to improve the Boeing 747 preventive maintenance planning. In 1978, United Airlines firstly presented the initial RCM bible by Nowland Stanley and Howard Heap. This method was taken into nuclear power plant in 1980 and hydro power plant in 1990 (Smith and Hinchcliffe, 2004).

MATERIALS AND METHODS

Materials

1. Personal Computer
2. Microsoft Windows and Microsoft Office Program
3. SPSS, MATLAB and Freeware Program

Methods

This research work is to study effects of power interruption for utilities and their customers, to develop a practical method for outage cost assessment for reliability improvement. There are six sections in this chapter. The explanation of the power distribution system of PEA is presented in section 1, the data surveyed and data collection of industrial customers are presented in section 2, the customer damage function is presented in section 3, the customer damage model of TSIC classification is presented in section 4, the outage evaluation is presented in section 5 and the application of outage cost in maintenance planning is presented in section 6.

1. Power distribution system of PEA

This section presents the overview of PEA power distribution system including physical conditions of system, important data for outage cost assessment and general maintenance activities of power distribution system.

1.1 Physical conditions of PEA

Provincial Electricity Authority (PEA) is the largest power distribution utility who serves electric energy to its customers all over the country, except Bangkok, Nonthaburi and Samutprakarn. The capital city, Bangkok and two perimeter provinces are responsibility area of Metropolitan Electricity Authority (MEA). Mostly, PEA is purchased electrical energy from Electricity Generating Authority of

Thailand (EGAT) for selling electrical energy to their customers. Although PEA can purchase alternative energy sources from Very Small Power Producer (VSPP). Normally, the power distribution systems compose of many equipment, starting from substation which can be categorized as outdoor and indoor type, sub-transmission line 115 kV and distribution line 22 kV and 33 kV (for only the southern of Thailand). In several areas, such as in the northeastern and the southern, the distribution feeders are very long which have more than 40 circuit-km. The main equipments of PEA power distribution lines are overhead cables, protection or switching equipments such as SF6 circuit breaker, recloser and the cable supported equipments such as insulators, cable spacers. There are several types of PEA overhead distribution lines which are bare conductors, partial insulated cable (PIC) and fully insulated cable or space aerial cable (SAC) conductors. In addition, there are also many different types of trees along the distribution lines which caused the power interruptions in the power system.

1.2 Data for reliability improvement

General information of power distribution utility for reliability improvement are required as data of substation, feeder, load, single line diagram, transformer sizing, tariff rate, interruption records, customer types and maintenance activities, etc.

1.3. Maintenance activities in power distribution system

There are several appropriate maintenance activities in power distribution system to reduce number of interruptions from failure causes. In general case, the preventive maintenance (PM) activities are preferred because these PM activities can protect system from failures, but sometimes, the improvement maintenance (IM) activities such as cable changing are also needed for system operation. The example activities of PM are shown as follow:

1.3.1 Transformer maintenance

1.3.2 Thermal inspection by thermal viewer

1.3.3 Insulator cleaning

1.3.4 Tree trimming

1.3.5 Installation of animal guards

1.3.6 Visual inspection or Patrol

1.3.7 Equipment changing

1.3.8 Improving the power line configuration

1.3.9 Creating landmark for reducing accident as painted pole, guard rail installation

2. Data surveyed and data collection of industrial customers

In this survey-based method, the samples of customer are random to collected the data for customer outage cost assessment. There are two basic approaches as direct measurement and imputation. Direct measurement has outage scenarios that describe composition of outage event characteristics. Three main approaches in outage cost survey as Direct Worth, Willingness to Pay (WTP) and Willingness to Accept Compensation (WTAC) are surveyed by using the interruption scenarios. Direct Worth is cost estimation that customers are inquired about various factors such as cost of production lost, cost of rescheduling, damage costs and so on. This research uses Direct Worth approach for outage questions in direct measurement approach of survey-based method. Survey methods of outage cost assessment are collected data by on-site interview and post mail.

2.1 Survey method by on-site interview

The on-site interviews are used in the survey-based method to estimate the industrial outage costs. The Nhong-Pling (NPL) substation in the responsibility of PEA Saraburi office located in the Siam Industrial Land (SIL) industrial real estate in Saraburi province and the Navanakorn III (NVC) substation in the responsibility of PEA Rungsit office located in Navanakorn industrial real estate in Pathumtani province have been selected as case studies. The individual customer damage functions that represent the interruption and duration outage costs are developed as a mathematical equation from data surveyed. Next, the industrial customer outage costs of distribution feeders from both substations are calculated from the customer damage functions using interruption records as the input.

The data of NPL and NVC substation were collected by on-site interviews that required high operation cost and long period of interview. However, such a method results in the better accuracy than the mail survey that generally has a return rate about 10%. Outage cost data is collected by the on-site survey in order to obtain the precise information. The procedure of customer interview is explained as follows.

2.1.1 General Information

Prior to on-site interview, the survey team must be provided general information of all industrial customers as follows: address, location, telephone number, type of products, rated power of transformer and monthly electricity charge. Interruption records of feeders of the power substation that dispatches energy to the SIL industrial customers are also required. Types of interruptions (lockout trip or momentary trip) should be specified in the records together with their duration and causes.

2.1.2 Customer Appointment

Individual industrial customers must be contacted for an appointment. The interviewee should be a person who understands the whole process of production, and impacts due to the power interruptions

2.1.3 Interview Questions

There are two types of interruptions to be understood by the interviewee, which are momentary and sustained interruptions. Momentary interruption is a power outage whose duration is less than 1 minute. Sustained interruption is power outage whose duration is equal or longer than 1 minute. The interviewee may evaluate production losses due to a momentary interruption in Baht per interruption. Next, he/she should evaluate production losses due to sustained interruptions in Baht per hour.

If he/she feels difficult to evaluate the production losses in monetary unit, the interviewer may interview him/her to illustrate the whole production process step by step. In the meantime, the interviewer may extract the following things from the information given by the interviewee:

(1) Costs of input material being used at each stage of production

(2) Costs of machine parts or tools that may be broken due to line interruptions

(3) Rated of production units such as piece per hour, ton per day

(4) Unit sale price of products

(5) Number of workers in the line of production and their wages.

The above items can be later used to estimate the production losses in monetary unit by the survey team.

2.2 Survey method with the questionnaires by post mail

The survey-based method with the questionnaires by post mail is used to estimate the outage costs for the industrial customers by collecting data from questionnaires. There are many ways to collect data such as by mail survey, telephone, internet and interview. Although, the interview method is very effective that can get responses more than 60 percent but rather expensive. The mail survey is cheaper but it generally gets data back less than 10 percent. This section presents the details of data collection by mail survey.

The data of ten industrial customer groups mostly were collected by post mail. The questionnaires used in mail survey are same as those used in the interview method in order to collect similar data, and good comparisons can be done. The questionnaires consist of three parts including the general information of industrial customer, details in production (number of employees, working time and duration, production process illustrated step by step, production rate, unit sale price of products, startup time of production process, availability of backup generators, etc.) and type of interruptions (momentary and sustained interruptions). Data can be classified by industrial types categorized by Thai Standard Industrial Code (TSIC). There are 9 industrial groups, which are TSIC 31- 39.

2.2.1 Questionnaire design

Interview questionnaire is developed to be post mail questionnaire for sending to industrial customers. They are created from interviewed experiences at onsite. Data from the questionnaires are used to find customer damage function. The advantage of developed questionnaire are simple to understand, saving time and concise document for covering questions because of regard to respondents who may refuse to answer.

2.2.2 Sending and responding to questions

Preparing customer addresses and questionnaires documents with survey reply, including a sender address and a replied envelope with post office stamped. Observing respondent emails can be completely replied in two to four weeks. Then data from questionnaires should be consider about the outlier samples may cause problems during data analysis. After recording data, customer damage functions, customer damage models and outage cost assessments can be continued the processes respectively.

2.3 Survey Results

Collected data from industrial customer outage cost survey can be separated into 3 groups as

2.3.1 Data from onsite-interview are used to prioritize feeder services.

2.3.2 Data from post mail are used to created outage cost model classified by 6 TSIC groups.

2.3.3 Data from post mail are used to created outage cost model for the only one Sub-TSIC (rice mill industry).

3. Customer damage function

3.1 Individual Customer Damage Function (ICDF(t) or CDF(t))

$$CDF(t) = DC.t + IC \qquad (1)$$

where CDF is Customer damage function.

IC is Initial outage cost.

DC is Duration outage cost.

t is Duration of power outage (hr. or min.).

3.2 Sector Customer Damage Function (SCDF)

$$SCDF(t) = \frac{\sum_{j=1}^{k} ICDF_j(t)}{\text{Total Peak Load}} \quad \text{Baht / kW}_{peak} \qquad (2)$$

where

j is Number of customer # j

k is Number of all customer of each customer type

3.3 Composite Customer Damage Function (CCDF)

$$CCDF(t) = \sum_{i=1}^{n}\left(\frac{C_i \times SCDF_i(t)}{LF_i}\right) \quad \text{Baht / kW}_{avg} \qquad (3)$$

where

i is Customer type

n is Number of customer type

C_i is Energy consumption ratio of each customer type

LF_i is Load factor of each customer type

4. Customer damage model classified by TSIC

The customer outage cost models of the six TSIC groups in the outage cost in Baht per interruption. The models would be created for simple way to apply, maybe some of input variables are not available. Especially for fuzzy regression models, the constant parameter (A_0) alone can be used to assess the outage costs with an acceptable error. Also, outage cost models classified by TSIC will offer a higher accuracy that is very helpful to electric utilities for making a decision on maintenance planning and reliability improvement projects.

5. Mathematical for modeling

5.1 Conventional linear regression

Conventional regression or statistic regression is regression analysis. This method is based on the analysis of relationship between the variables. Simple linear regression could be modeled from dependent variables and independent variables. If there are many independent variables it would be modeled by multiple linear regression as presented by equation (4).

$$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_p x_p \qquad (4)$$

where Y is dependent or response variable

x_0, x_1, ..., x_n are independent variables

β_0, β_1, ..., β_n are constants or the model partial regression coefficients

p is number of independent variables

5.2 Fuzzy linear regression

Fuzzy linear regression is first developed by Tanaka *et al*. This method is based on the principle of fuzzy sets (L.A. Zadeh). Statistic regression is based on probability theory, while fuzzy regression is based on possibility theory and fuzzy set theory. Equation (5) shows the fuzzy regression model.

$$Y = A_0 + A_1 x_1 + A_2 x_2 + \ldots + A_n x_n \qquad (5)$$

where Y are fuzzy outputs or dependent variables
$A_0, A_1, \ldots, A_n$ are fuzzy parameters
$x_0, x_1, \ldots, x_n$ are independent variables

The fuzzy parameters or fuzzy coefficients are represented in the form of triangular fuzzy numbers with membership function is defined as:

$$\mu_{A_j}(a) = \begin{cases} 1\text{-}\dfrac{|\alpha_j - a_j|}{c_j}, & \alpha_j - c_j \le a_j \le \alpha_j + c_j \\ 0 & \textit{otherwise} \end{cases}$$

where a_j is the center value of fuzzy number and c_j is the spread, and represented as shown in Figure 1.

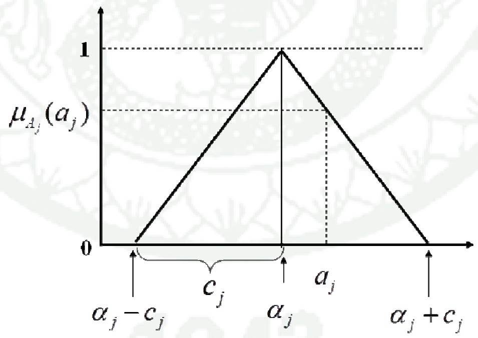


Figure 1 Symmetrical fuzzy parameters

Therefore, the fuzzy linear regression model can be rewritten as:

$$y = (\alpha_0, c_0) + (\alpha_1, c_1)x_1 + (\alpha_2, c_2)x_2 + \ldots + (\alpha_n, c_n)x_n$$

Then, linear programming is used to optimize the performance index (J) as shown in equation (6).

$$Minimize \quad J = \sum_{j=0}^{N}\left(c_j \sum_{i=1}^{M} \left| x_{ij} \right| \right)$$

$$Subject\ to \quad \sum_{j=0}^{N} \alpha_j x_{ij} + (1-h)\sum_{j=0}^{N} c_j \left| x_{ij} \right| \ \geq y_i \qquad (6)$$

$$\sum_{j=0}^{N} \alpha_j x_{ij} - (1-h)\sum_{j=0}^{N} c_j \left| x_{ij} \right| \ \leq y_i$$

$$c_j \geq 0, \quad \alpha_j \in \Re, \quad j = 0, 1, 2, ..., N \quad x_{i0} = 1, \quad i = 0, 1, 2, ..., M \quad 0 \leq h \leq 1$$

The performance index J is minimized subject to constraints as given in (6) where h as the membership value between 0 and 1 is the threshold level, and determines the degree of fitting with human decision making. C_j is the width or spread, and α_j is the center of triangle base. For fuzzy parameters, x is independent variables, and y is dependent variables where M is the number of data and N is the number of x (independent variable).

5.3 Analysis of variance

Single factor analysis of variance (ANOVA) or one way ANOVA is the analysis of differential level of data by considering only one factor. The objective of analysis of variance is the test of the several means of populations to compare between the groups of populations. The number of population groups have to be equal or greater than three groups of populations or treatments .

First, determine the null hypothesis H0: $\mu_1 = \mu_2 = \mu_3 = \mu_n$. Next, write the alternative hypothesis H1: $\mu_i \neq \mu_j$ at least one pair of means, $i \neq j$, i,j = 1, 2, ..., n. Then, specify the α level: α = 0.05. Lastly, calculate the appropriate statistic

where μ_1, μ_2, μ_3 and μ_n are the means of populations
n is number of group of populations
α is the significance level.

5.4 Test of hypothesis

If the significance level in ANOVA results less than 0.05, the null hypothesis will be rejected. Tukey test is chosen for hypothesis test because it is the pairwise comparison method to test significant differences between groups . For Tukey test, John W. Tukey proposed the method for multiple comparison procedure in 1953. The test depends on studentized range distribution to show significant levels of group comparisons .

5.5 Mean absolute percentage error (MAPE)

MAPE is shown by the following equation .

$$MAPE = \frac{100}{N}\sum_{i=1}^{N}\frac{\left|y_i - \hat{y}_i\right|}{y_i} \qquad (7)$$

Where N is the number of data

$\hat{y}_i$ is the estimated value

y_i is the observed value

6. Application of outage cost in maintenance planning

RCM is the maintenance management methodology which focused on critical components for reliability improvement. RCM can help for suitable preventive maintenance activity selection with economic maintenance cost. Commercial aircraft industry initially produced RCM to improve the Boeing 747 preventive maintenance planning. In 1978, United Airlines firstly presented the initial RCM bible by Nowland Stanley and Howard Heap. This method was taken into nuclear power plant in 1980 and hydro power plant in 1990 [5-9]. RCM steps are shown in Figure 2.

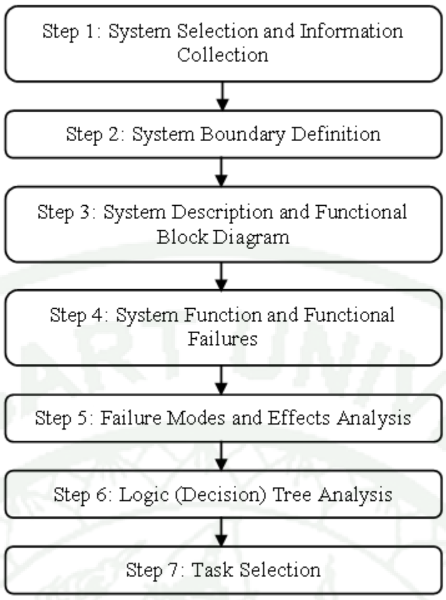


Figure 2 RCM process

7. Case study

There are the cases of the study in this thesis as feeder prioritization by customer outage cost, customer damage model selection of 6 TSIC groups of high energy consumption industries and one sub-TSIC as rice mill industries group. The maintenance planning are shown with economy maintenance activities prioritization.

7.1 Feeder prioritization by customer outage cost

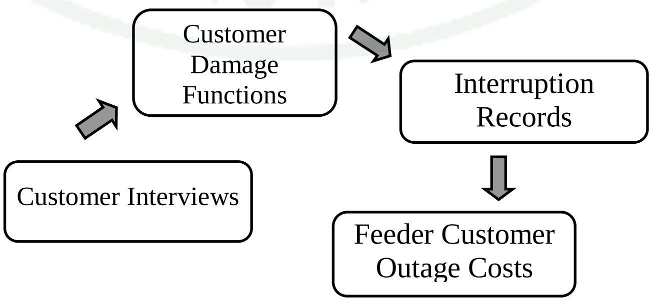


Figure 3 Feeder customer outage cost

7.2 Customer damage model selection

The algorithm of selecting model between conventional regression and fuzzy regression are used in forcasting oil consumption by Azadeh *et al*.

RESULTS AND DISCUSSION

Results

1. Customer damage function for outage cost assessment

To assess the customer outage costs, the customer damage functions and interruption records are together required as illustrated in Fig. 1. The interruption records are normally available, and can be obtained from the power substation.
In this section, the customer damage functions (CDF) are developed as a mathematical equation in (1) from information collected during the customer interviews.

The customer damage function is basically used to represent the damage costs of customers as a result of power outages. The functions can be very different from one industrial customer to another depending on type, method, and size of productions. Normally, a customer damage function is composed of two components, which are interruption cost (Baht per interruption) and duration outage cost (Baht per hour or minute).

1.1 Initial Outage Cost

Interruption cost represents sudden losses and product impairment of industrial customers when the line production is interrupted due to both momentary and sustained interruptions. In this dissertation, the interruption cost is expressed in Baht per interruption, associated with the following damages:

1.1.1 Raw material damages such as plastic melt in the mold cavity becomes frozen during a power outage.

1.1.2 Product damages in the middle of production process due to improper installation and operation caused by a power outage.

1.1.3 Loss of production opportunity during restart process.

1.2 Duration Outage Cost

Duration outage cost represents duration losses caused by only sustained power interruptions including

1.2.1 Loss of production opportunity during a period of power outages.
1.2.2 Labor costs for over-time shift.
1.2.3 Fuel cost for back-up generators.

1.3 Development of Customer Damage Functions

The customer damage functions (CDF) can be developed after their interruption and duration outage costs are found. Features of individual customer damage functions depend upon types of products and their manufacturing processes. Some industrial customers may be affected by only sustained interruptions. Therefore, the CDF of these customer groups do not include the interruption cost (IC). For example, if the duration outage cost (DC) of an industrial customer equals 315,807 Baht/hour, its CDF can be expressed by (8).

$$CDF(t) = 315,807.t \tag{8}$$

Nevertheless, most industrial customers are likely to be affected by momentary and sustained outages. In this case, the customer damage function includes both interruption and duration outage costs. For example, if an industrial customer has IC of 20,000 Baht/interruption and DC of 172,067 Baht/hour, its CDF can be expressed by (9).

$$CDF(t) = 172,067.t + 20,000 \tag{9}$$

In some manufacturing processes, a customer's production losses that include costs of raw materials damaged during power outages and costs of restart process are augmented, when outage duration lasts longer than a period of time. In this case, the customer damage function is depicted as a discontinuous curve with at least a jump discontinuity at the end of the specified period. For example, this type of CDF can be expressed by the following (10a), (10b) and (10c).

$$(0 \le t < 20\,\text{min}) \quad CDF(t) = 223,500.t + 3,275 \qquad (10a)$$

$$(20 \le t < 30\,\text{min}) \quad CDF(t) = 223,500.t + 7,275 \qquad (10b)$$

$$(t \ge 30\,\text{min}) \quad CDF(t) = 223,500.t + 234,775 \qquad (10c)$$

As described above, the customer damage function of an industrial customer can be developed when the interruption and duration outage costs are available. Using information obtained from on-site interviews, for example, the individual customer damage functions of SIL industrial customers on service feeder (NPL08) of NPL substation are plotted in Figure 4. and the individual customer damage functions of Navanakorn industrial customers on service feeder (NVC01) of NVC substation are plotted in Figure 5.

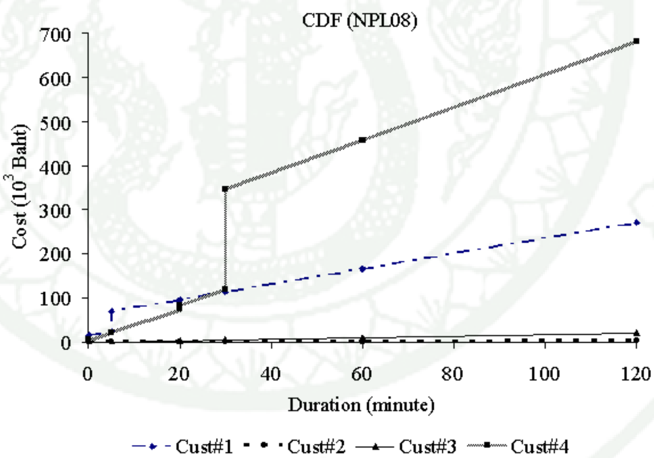


Figure 4 Customer Damage Functions of Feeder NPL08.

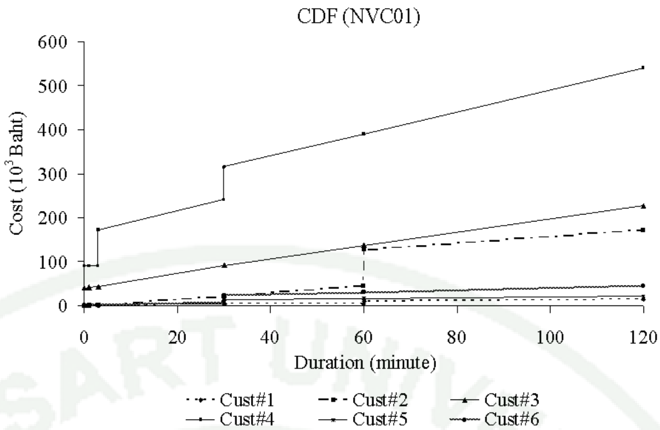


Figure 5 Customer Damage Functions of Feeder NVC01.

On feeder NPL08, 7 out of 9 customers are interviewed. Only five interviews result in complete information. However, only four customer damage functions are plotted because the other customer is slightly affected by power outages.

2. Feeder Prioritization by Outage Cost

2. 1 Data from onsite-interview are used to prioritize feeder services.

After the on-site interviews are finished, completeness of collected information must be first evaluated. Table 1 and Table 2 show the survey results of SIL industrial customers and NVC industrial customers grouped by distribution feeders**.** For the NPL substation, distribution feeders 1, 3 and 4 do not dispatch electrical energy, and feeder 5 is reserved for a small power producer (SPP). The NVC substation, feeders 7 and 10 do not serve energy to customer.

Table 1 Survey Results by Feeders of NPL Substation

Feeder	Industrial Customers	Interviewed Customers	Complete Interviews	%
NPL01	N/A	-	-	-
NPL02	9	9	9	100
NPL03	N/A	-	-	-
NPL04	N/A	-	-	-
NPL05	Reserved	-	-	-
NPL06	2	2	1	50
NPL07	3	3	3	100
NPL08	9	7	5	71
NPL09	3	3	3	100
NPL10	8	7	6	86

Note: % = Percentage of Complete Interviews

Table 2 Survey Results by Feeders of NVC Substation

Feeder	Industrial Customers	Interviewed Customers	Complete Interviews	%
NVC01	10	7	6	86
NVC02	9	9	8	89
NVC03	12	7	4	57
NVC04	8	8	5	63
NVC05	1	1	1	100
NVC06	15	10	7	70
NVC07	N/A	-	-	-
NVC08	3	2	1	50
NVC09	10	8	8	100
NVC10	N/A	-	-	-

Note: % = Percentage of Complete Interviews

Table 1 and Table 2 show that the industrial customers on feeder NPL09 are affected the most by power outages in the Siam Industrial Land (SIL) industrial real estate and on feeder NVC04 are affected the most by power outages at the area of NVC substation in Navanakorn industrial real estate respectively. All feeders in Table 1 are ranked by their FCOC. The resulting priority together with the number of customers of each feeder is illustrated in Figure 5. Surprisingly, feeders NPL02, NPL10 and NPL08, which have a lot of industrial customers, are ranked at the bottom of the priority chart. It shows that only the number of customers on each feeder cannot tell how much that feeder is affected by power outages.

Consequently, the feeder customer outage costs in Table 1 can be very useful for power utilities in maintenance planning and scheduling because the utilities can use them for decision making on maintenance management and investment.

2.2 Process for feeder customer outage cost

To calculate the feeder customer outage costs, interruption records of all feeders are collected from the substation to be used with the customer damage functions determined in the previous section. Table 3 shows the example of historical records of interruptions in 2005 that the NPL substation has recorded.

Table 3 Interruption Records of NPL Substation

Trip	Number of interruptions	Cause of outages
Lockout Trip	3	Unknown (2) Equipment failure (1)
Momentary Trip	11	Unknown (2) Equipment failure (6) Trees (1) Animals (2)

For all feeders, the customer outage cost (COC) of each industrial customer must be first determined using the interruption records in Table III. For example, if customer k is served electrical power by feeder NPL05 (N_m = 5, N_s = 1), the COC_k can be calculated by (11).

$$\begin{aligned} COC_k &= \sum_{i=1}^{N} CDF_k\left(t_i\right) \\ &= \sum_{i=1}^{N}\left[DC_k(t_i) + IC_k\right] \\ &= \sum_{i=1}^{N} DC_k(t_i) + N.IC_k \end{aligned} \tag{11}$$

where COC_k is customer outage cost of customer k

CDF_k is CDF of customer k using duration outage cost (DC) in Baht/hour.

N is number of interruptions on feeder that serves customer k

t_i is duration of sustained interruption #i

Once the COC of all customers on an interested feeder is calculated using (11), the feeder customer outage cost (FCOC) can be determined by (12).

$$FCOC = \sum_{k=1}^{N_C} COC_k \tag{12}$$

$$\because \; COC_k = N.IC_k + \sum_{i=1}^{N} DC_k(t_i)$$

$$\begin{aligned} FCOC &= \sum_{k=1}^{N_C}\left[\sum_{i=1}^{N} CDF_k\left(0\right) + \sum_{i=1}^{N} DC_k\left(t_i\right)\right] \\ &= FCOC_{momentary} + FCOC_{sustained} \end{aligned}$$

where $FCOC$ is feeder customer outage cost of interested feeder

N is number of customers on interested feeder

$FCOC_{momentary}$ is a portion of FCOC caused by momentary interruptions

$FCOC_{sustained}$ is a portion of FCOC caused by sustained interruptions

From (11) and (12), the feeder customer outage costs of all service feeders in each substation are calculated using the customer damage functions developed and interruption events. In Table 1 and Table 2, the FCOC of each feeder is tabulated, and both momentary and sustained portions of the FCOC, as determined by (12), are also given.

2.3 Results of feeder prioritization

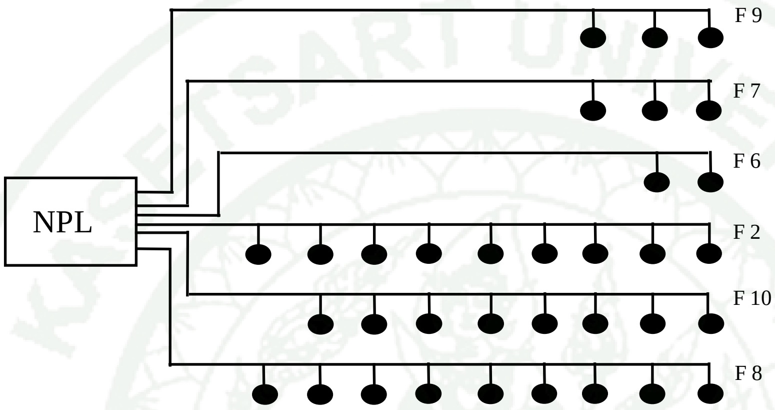


Figure 6 Results of feeder prioritization

2.4 Apply for maintenance activities

Reliability improvement should be considered against cost of maintenance and outages. Cost of outages is categorized into customer and utility sides. In the customer side, there are costs of planned and unplanned outages. In Table 1, cost of planned outages of the service area in industrial estate is neglected because the hotline technicians can perform uninterrupted maintenance using bypass conductors. In addition, the yearly maintenance can be scheduled in advance and will be later performed during a long weekend (New Year holidays) that customers stop the production process. Utility outage cost can be calculated from load of feeder with a duration of power outage in terms of the expected energy not supplied (EENS).

Table 4 Cost of outages

Substation	Customer Outage Cost (Baht)		Utility Outage Cost (Baht)
	Unplanned	Planned	
NPL (2005)	3,821,605	-	4,619
NVC (2006)	10,073,849	-	117,165

Before making a decision on maintenance investments, utilities should find out what are causes of interruptions. According to interruption records of NPL substation, the causes include animals, trees, equipment failures and natural disasters. Suspected animals in this area are birds and snakes. Equipment failures include insulators, cable spacers, transformers, connectors, overhead lines, etc.

There are several appropriate maintenance activities to reduce number of interruptions such as transformer maintenance, thermal inspection by thermal viewer, insulation cleaning, tree trimming, and installation of animal guards. From feeder observations, feeders NPL07, NPL08, NPL09 and NPL10 still use bare conductors, which can be easily contacted by animals and branches of trees. Design-out maintenance is also an option such as replacing bare conductors with spaced aerial cables (SAC), but it is costlier than other methods. Therefore, when a utility wants to perform maintenance activities, the payback period (PB) should be determined to see if the investment costs are worth a decrease in feeder customer outage costs. For the NPL substation, the PB of each feeder is calculated by (13), and the results are shown in Table 4 .

Table 5 Total Maintenance Cost against FCOC and PB

Costs & Activities	NPL07	NPL08	NPL09	NPL10
FCOC (Baht)	1,131,895	91,375	1,208,335	162,549
SAC (Bath)	2,930,007	2,138,113	1,583,788	3,009,197
Thermal scan (Baht/year)	32,000	32,000	32,000	32,000
Tree trimming (Baht/year)	444	324	240	456
Insulation cleaning (Baht/year)	30,000	30,000	30,000	30,000
Total investment costs (Baht)	2,992,451	2,200,437	1,646,028	3,071,653
PB (year)	3	24	1	19

Table 6 Load of NPL Feeders

Feeder	Load (MW) year 2005
NPL02	3.20
NPL06	4.60
NPL07	6.40
NPL08	8.10
NPL09	6.30
NPL10	4.40

$$Simple\ PayBack = \left(\frac{Total\ investment\ \cos ts}{FCOC}\right) \qquad (13)$$

When making a decision for maintenance, the above results are taken into consideration as follows:

2.4.1 FCOC: In Figure 6, feeder NPL09 has the highest FCOC, and feeder NPL07 is the second highest.

2.4.2 PB: In Table 5, feeder NPL09 has the shortest payback period, and feeder NPL07 is the second shortest.

2.4.3 Load: In Table 6, if load of each feeder is considered, feeders NPL08, NPL07 and NPL09 will be affected the most due to an opportunity loss for energy sale.

According to the above consideration, feeders NPL09 and NPL07 are the first priority for maintenance improvement. After the bare conductors of feeders NPL09 and NPL07 were replaced with the spaced aerial cables (SAC) in 2006, an evaluation on the FCOC of each feeder on NPL substation is proceeded to observe the effectiveness of design-out maintenance. Table 7 shows a significant reduction in FCOC for feeders NPL09 and NPL07.

Table 7 Reducing of FCOC

Feeder	FCOC (2005)	FCOC (2007)	RCost
NPL02	240,000	60,000	180,000
NPL06	987,450	923,070	64,380
NPL07	1,131,895	0	1,131,895
NPL08	91,375	288,711	-197,336
NPL09	1,208,335	0	1,208,335
NPL10	162,549	87,600	74,949
Total	3,821,605	1,359,381	2,462,224

Note: RCost = Reduced FCOC

2.5 Power Tap Line Replacement

Power tap line is employed to connect between the main feeder and the metering system at the customer load point. The bare conductors as the tap line had been widely used in PEA distribution systems. Nevertheless, interruption records

showed that a number of power interruptions were caused by tree and animal contacts associated with the tap lines. As a result, the PEA Rungsit office decided to replace the bare conductors with the partial insulated cables (PIC) to reinforce the system performance. There were 9 industrial customers whose power tap lines were bare conductors: 3 customers on feeder NVC01 and 6 customers on feeder NVC06.
The cost of tap line replacement was 33,066 Baht which included the costs of material and labor. From the results in Table 6, it was worth to do so since if the momentary interruption of feeder NVC01 was decreased by 1 time, the PB period would be no more than 3 months.

The tap lines were replaced before the rainy season in April, 2007.
The interruption records associated with the causes of tree, animal and unknown of NVC substation in April to June between 2006 and 2007 are compared. However, the number of interruptions between the two periods is the same. Meanwhile, the interruption records of both Navanakorn I (NVA) and Navanakorn II (NVB) which are the neighboring substations in 2007 are higher than 2006 as shown in Figure 7 from the above results, we may not confidently claim that tap line replacement prevents NVC from an increase in interruptions, but it surely reduces the risk of interruptions.

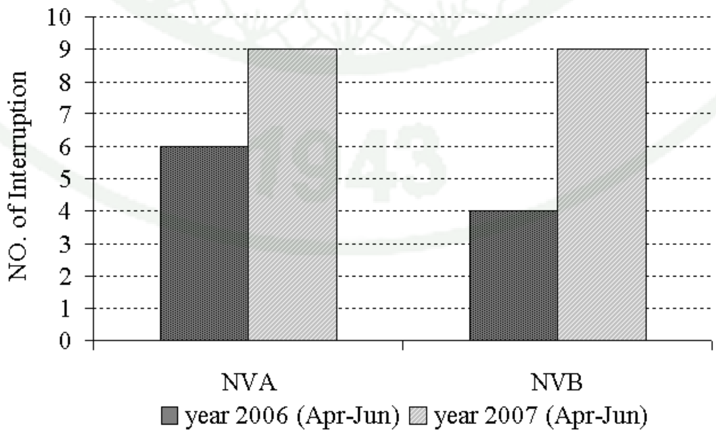


Figure 7 Interruption Records of NVA&NVB Substations

3. Customer damage model selection with 6 TSIC groups of high energy consumption industries

3. 1 Data from post mail for classification by 6 TSIC groups.

Table 8 Survey results

Year	Interviewed Customers	Completed Responses	%
2006-2007	134	90	67
Year	Mail Surveys	Completed Responses	%
2008	2926	212	7

Table 9 Number of Customer

Supply Voltage	Number of Industrial Customers	%
115-kV	26	9
22-kV	276	91

Table 10 Data classified by TSIC

TSIC	Type	Frequency	Valid Percent
31	Food, beverage & tobacco	55	18.2119
32	Textiles & leather products	24	7.9470
33	Wood and wood products	1	0.3311
34	Paper and paper products	6	1.98676
35	Chemical and rubber	85	28.1457
36	Non metallic mineral	17	5.6291
37	Basic material	22	7.2848
38	Fabricated metals	76	25.1656
39	Other manufacturing	2	0.6623
41	Gas and Electricity	1	0.3311
50	Construction	1	0.3311
61	Whole sales	3	0.9934
62	Retail sales	1	0.3311
71	Warehouse and transportation	2	0.6623
92	Public health services	5	1.6556
95	Individual services	1	0.3311
Total		302	100

The data are mostly collected from industrial customers who are supplied by 22-kV distribution feeders. On the other hand, the customers who require a large amount of electrical power for their production are supplied by 115-kV sub-transmission lines. The scatter graph in Fig. 1 represents the values of two parameters, DC and IC, of the 22-kV and 115-kV customers.

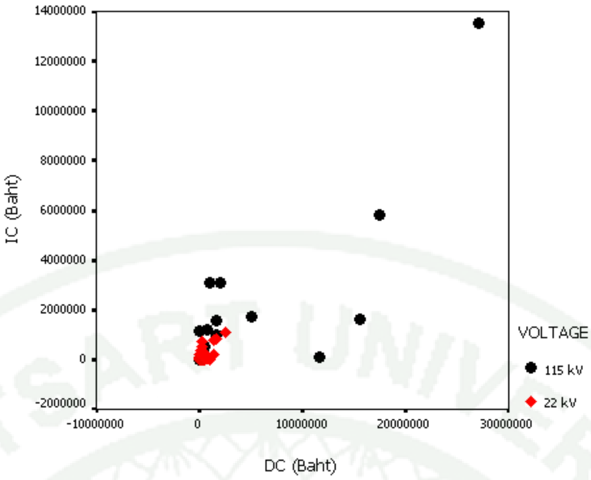


Figure 8 Scatter plot of IC and DC (DC is calculated at average duration time of interruptions in central region 36.12 minutes

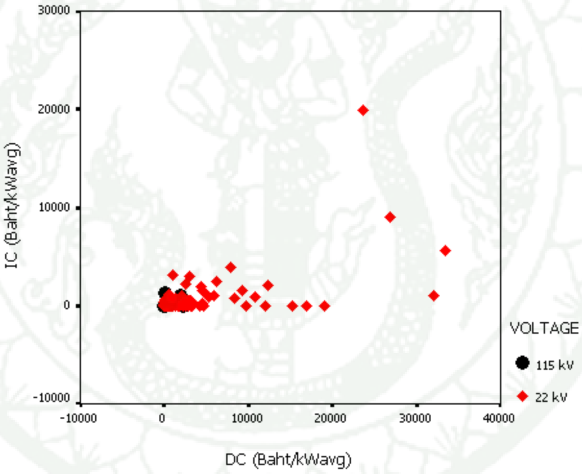


Figure 9 Scatter plot of IC and DC normalized by capacity (kWavg)

In Figure 9, the results are the values of IC and DC normalized by their capacity. Then, the customer damage function (CDF) can be developed by using these normalized results.

However, the COC data first need to be grouped since those data are rather varied by characteristic of productions. After classification using statistical analysis, the data are classified into 6 groups of industrial type by Thai Standard Industrial Code (TSIC). The classified data for each group yield better correlation for developing the customer damage function (CDF).

3.2 Process in model selection

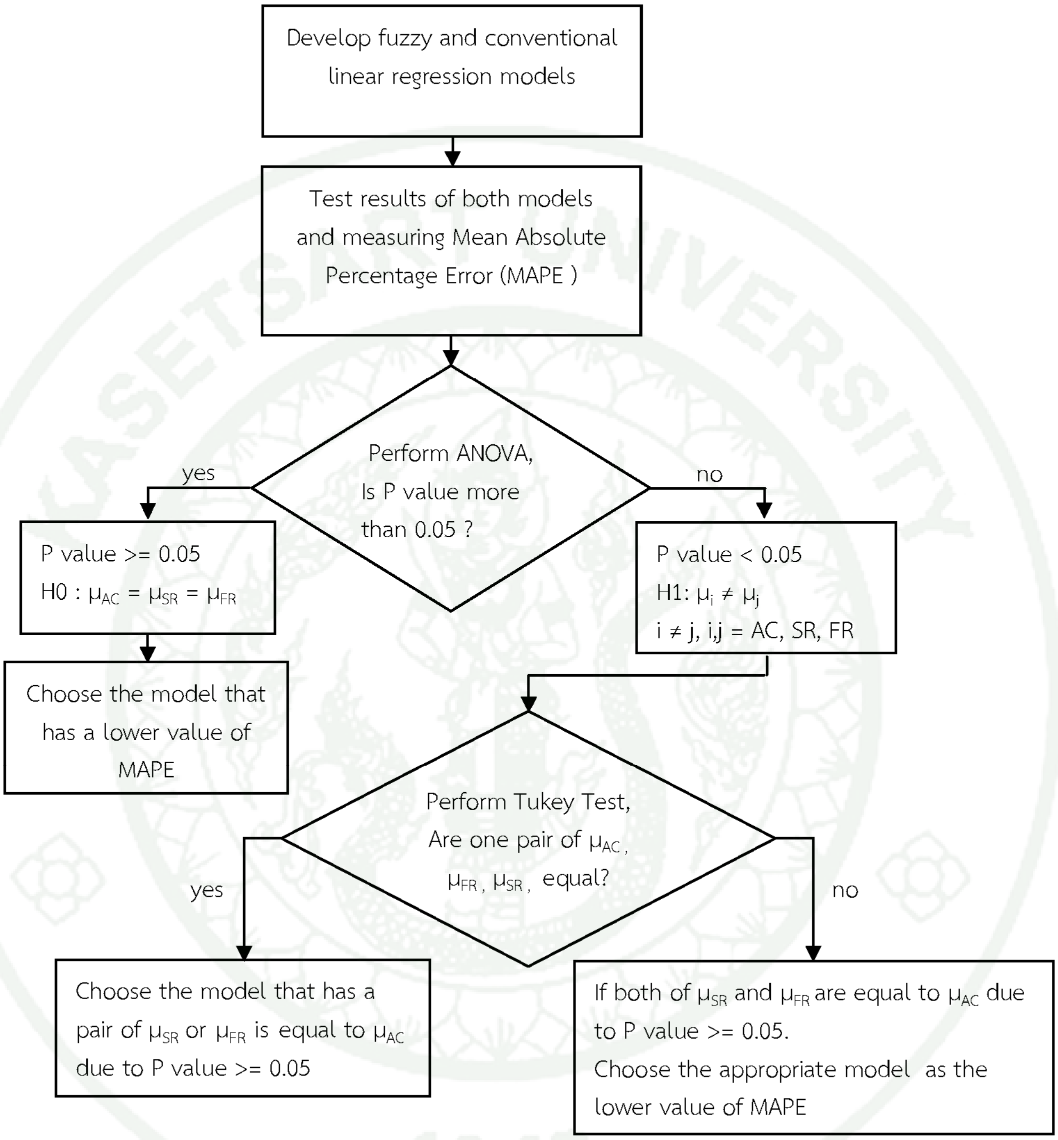
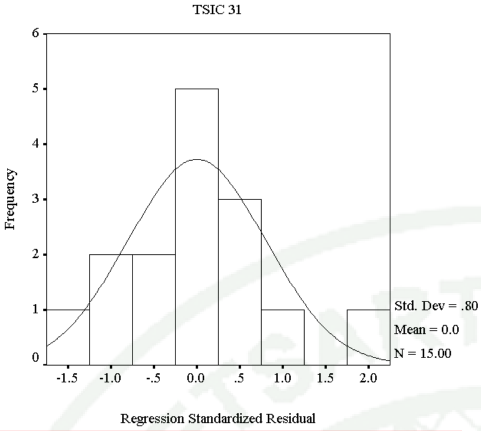
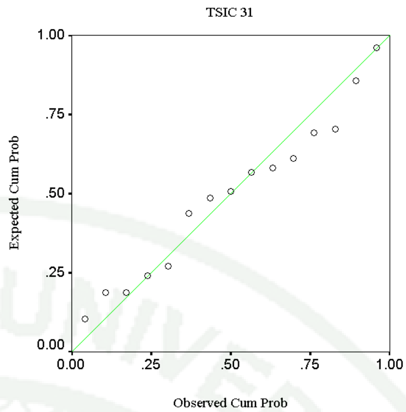


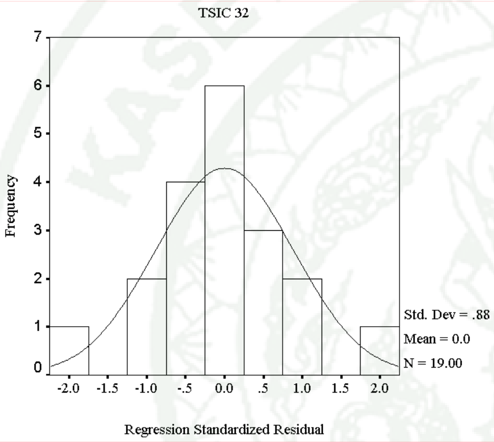
Figure 10 Selection of customer damage model

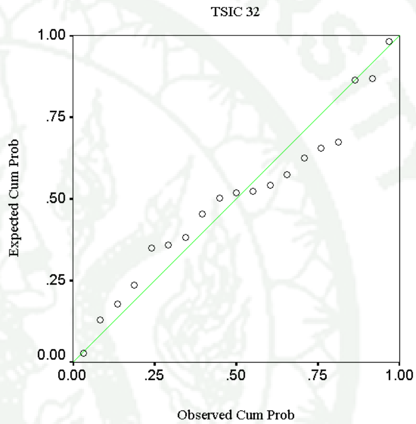
3.3 Results of model selection

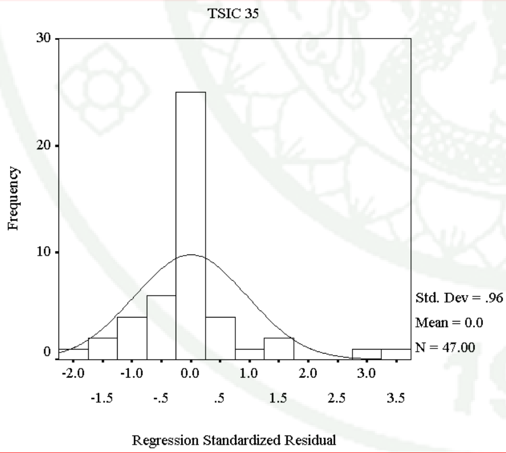
The histograms and probabilities plots of dependent variable or $y_{TSIC\ i}$ are shown in Figure 10 to display the line of normal curve of dependent variable for each TSIC group from multiple linear regression.

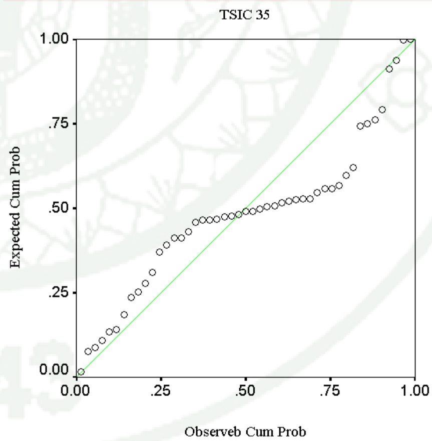

TSIC 31
Frequency
Std. Dev = .80
Mean = 0.0
N = 15.00
Regression Standardized Residual


TSIC 31
Expected Cum Prob
Observed Cum Prob


TSIC 32
Frequency
Std. Dev = .88
Mean = 0.0
N = 19.00
Regression Standardized Residual


TSIC 32
Expected Cum Prob
Observed Cum Prob


TSIC 35
Frequency
Std. Dev = .96
Mean = 0.0
N = 47.00
Regression Standardized Residual


TSIC 35
Expected Cum Prob
Observeb Cum Prob

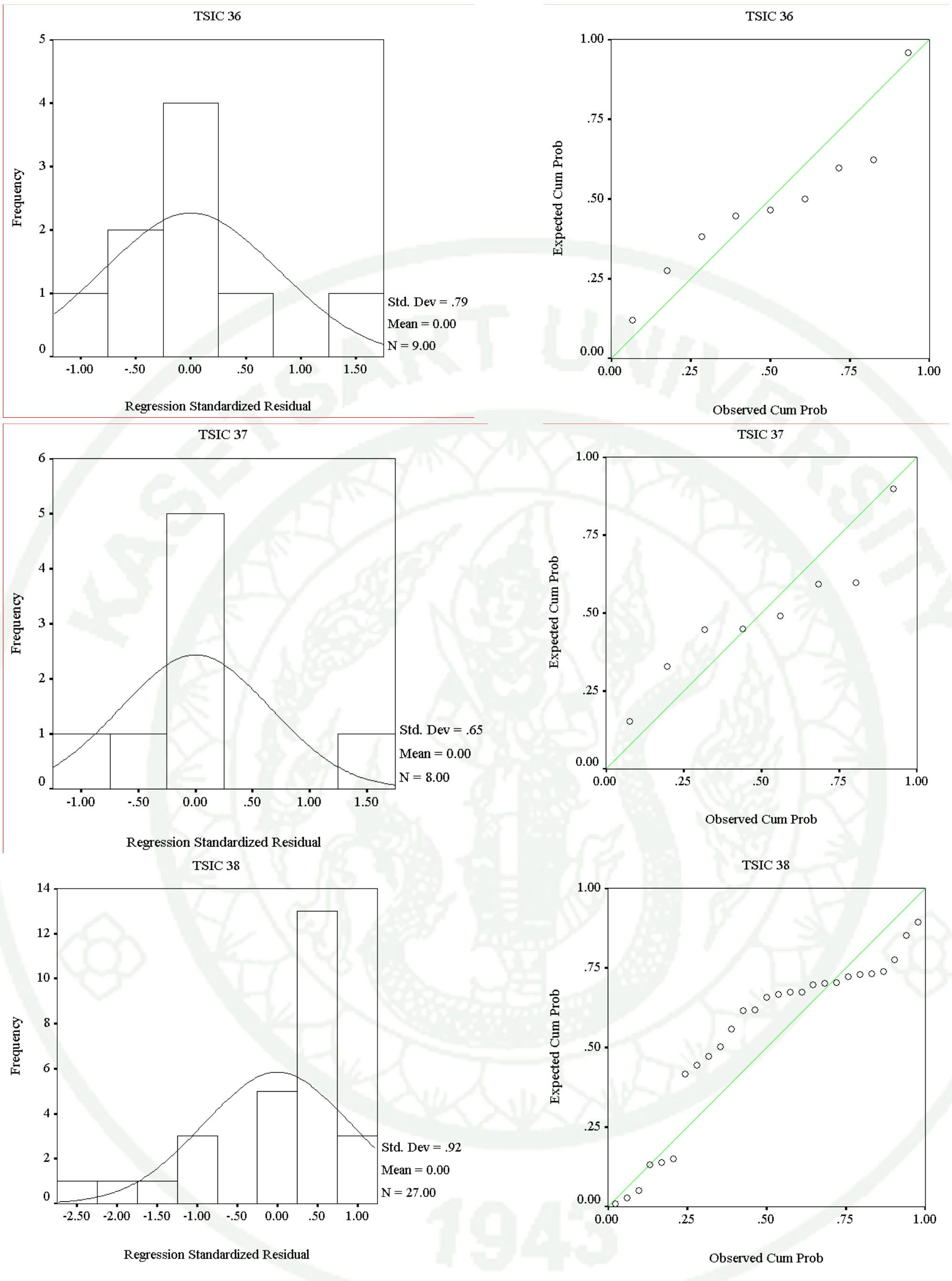


Figure 11 Distribution histogram and probability plots

Table 11 Mean Absolute Percentage Error

TSIC Code	Mean Absolute Percentage Error (MAPE)	
	Fuzzy Regression	Statistic Regression
31	13.07	7.93
32	127. 83	14.86
35	24.33	6.61
36	4.30	3.40
37	316.64	524.36
38	34.33	122.45

After the customer outage costs of six TSIC groups are modeled using fuzzy regression and statistic regression, the MAPE resulted from both models are calculated and presented in Table 11. In case of MAPE more than one hundred percent, it can happen in the case that has a large difference between the estimated and observed data. For example, The MAPE in TSIC 37 models is more than one hundred percent. Because of the internal complicated data of industry group which are several sub-categories in this TSIC such as TSIC 37110 as manufacturer of basic iron and steel, TSIC 37120 as casting iron and steel and TSIC 37200 as casting of non-ferrous metals which they are much different in production process.

A summary of statistical values of industrial customer outage costs from AC, FR, and SR for each TSIC group are shown in Table 12, Table 14, Table 16, Table 18, Table 20 and Table 22.

Table 12 Statistical values of TSIC 31

Groups	Count	Sum	Average	Variance
AC	55	12,259,514	222,900	379,370,284,797
FR	55	16,402,109	298,220	221,789,199,603
SR	55	5,303,731	96,431	210,807,647,982

Table 13 ANOVA results of TSIC 31

Source of Variation	Sum square	Degree of freedom	Mean square	F	P-value
Between Groups	1,143,745,430,683	2	571,872,715,342	2.1129	0.1242
Within Groups	43,846,225,148,604	162	270,655,710,794		
Total	44,989,970,579,287	164			

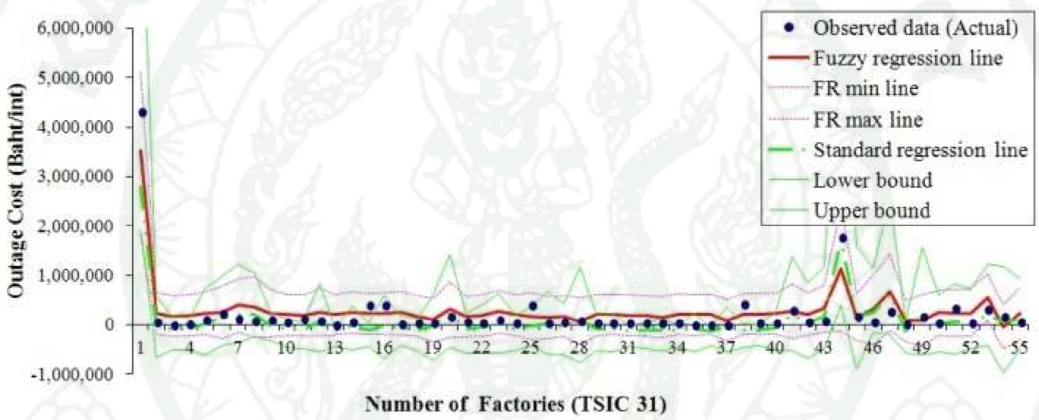


Figure 12 FR and SR Estimation for TSIC 31

According to ANOVA results in Table 13, the P-value is greater than 0.05 so the null hypothesis is accepted for TSIC 31. Then, MAPE of statistic regression in Table 11 is found lower than that of fuzzy regression, so the SR model is selected for TSIC 31 customer group.

Table 14 Statistical Values of TSIC 32

Groups	Count	Sum	Average	Variance
AC	24	1,597,643	66,568	14,450,594,062
FR	24	3,761,034	156,710	37,013,285,472
SR	24	1,083,947	45,164	3,426,610,590

Table 15 ANOVA results of TSIC 32

Source of Variation	Sum square	Degree of freedom	Mean square	F	P-value
Between Groups	168,207,583,377	2	84,103,791,688	4.5966	0.0134
Within Groups	1,262,481,272,873	69	18,296,830,042		
Total	1,430,688,856,250	71			

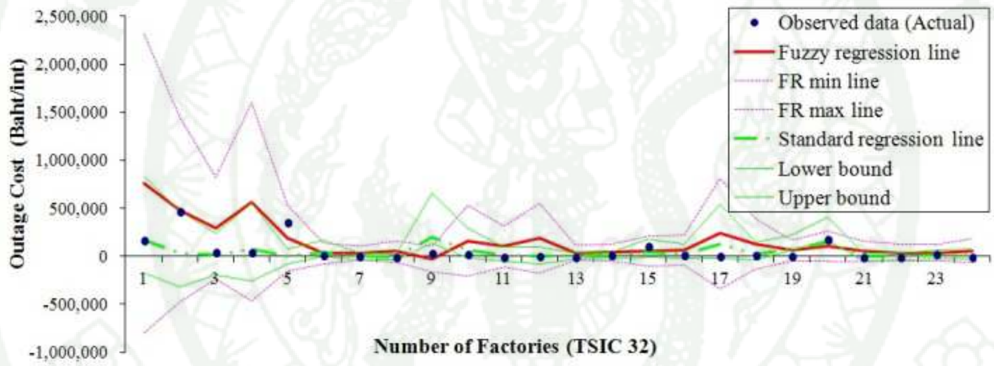


Figure 13 FR and SR Estimation for TSIC 32

According to ANOVA results in Table 15, the P-value is less than 0.05 so the null hypothesis is rejected for TSIC 32. Thus, the hypothesis testing by Tukey method is used to compare the pairs of treatments. The results are shown as follows:

	P-value	Result
AC and FR	0.0613	$\mu_{AC} = \mu_{FR}$
AC and SR	0.8478	$\mu_{AC} = \mu_{SR}$
FR and SR	0.0154	$\mu_{FR} \neq \mu_{SR}$

The significant results of pairs AC and FR, AC and SR have the P-value greater than 0.05 so both statistic and fuzzy regressions are applicable. However, the model resulted from statistic regression is better recommended for TSIC 32 customer group because of a lower of P-value.

Table 16 Statistical Values of TSIC 35

Groups	Count	Sum	Average	Variance
AC	85	5,447,058	64,083	19,666,687,385
FR	85	18,682,428	219,793	228,580,296,986
SR	85	7,545,328	88,769	134,504,363,257

Table 17 ANOVA results of TSIC 35

Source of Variation	Sum square	Degree of freedom	Mean square	F	P-value
Between Groups	1,190,638,241,045	2	595319120522	4.6661	0.0102
Within Groups	32,151,113,200,718	252	127583782543		
Total	33,341,751,441,762	254			

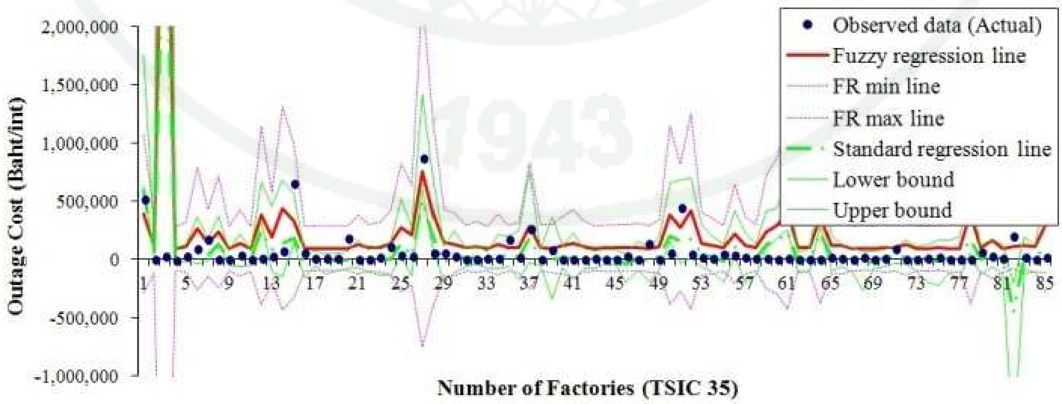


Figure 14 FR and SR Estimation for TSIC 35

According to ANOVA results in Table 17, the P-value is less than 0.05 so the null hypothesis is rejected for TSIC 35. Thus, the hypothesis testing by Tukey method is used to compare the pairs of treatments. The results are shown as follows:

	P-value	Result
AC and FR	0.0134	$\mu_{AC} \neq \mu_{FR}$
AC and SR	0.8942	$\mu_{AC} = \mu_{SR}$
FR and SR	0.0460	$\mu_{FR} \neq \mu_{SR}$

The significant result of pair AC and SR has the P-value greater than 0.05 so the model resulted from statistic regression is selected for TSIC 35 customer group.

Table 18 Statistical Values of TSIC 36 ANOVA results of TSIC 36

Groups	Count	Sum	Average	Variance
AC	17	9,379,412	551,730	1,126,985,471,107
FR	17	9,024,046	530,826	991,094,786,265
SR	17	9,116,261	536,251	1,133,541,051,991

Table 19 ANOVA results of TSIC 36

Source of Variation	Sum square	Degree of freedom	Mean square	F	P-value
Between Groups	4,000,718,421	2	2,000,359,210	0.0018	0.9982
Within Groups	52,025,940,949,810	48	1,083,873,769,788		
Total	52,029,941,668,231	50			

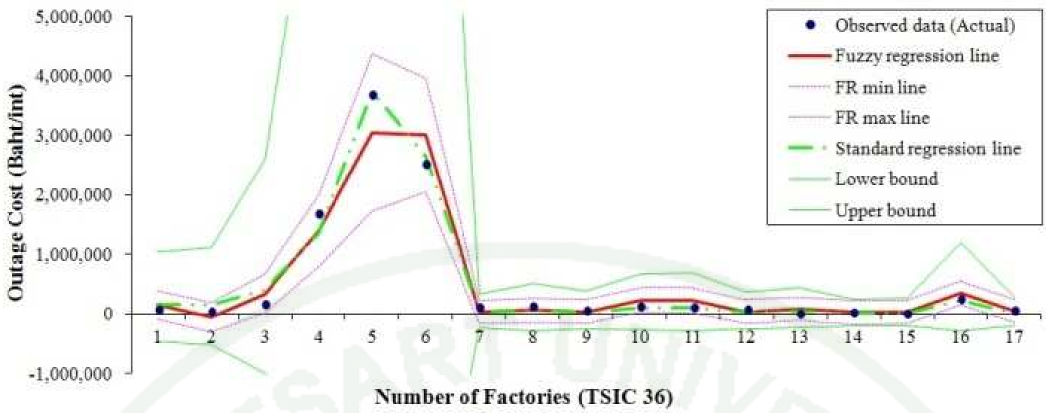


Figure 15 FR and SR Estimation for TSIC 36

According to ANOVA results in Table 19, the P-value is greater than 0.05 so the null hypothesis is accepted for TSIC 36. Thus, MAPE in Table 11 is considered. It is found that the MAPE of statistic regression is lower than that of fuzzy regression, so the SR model is selected for TSIC 36 customer group.

Table 20 Statistical Values of TSIC 37

Groups	Count	Sum	Average	Variance
AC	22	11,727,237	533,056	2,445,715,349,382
FR	22	14,957,018	679,864	1,652,806,416,678
SR	22	-9,587,286	-435,786	959,107,950,584

Table 21 ANOVA results of TSIC 37

Source of Variation	Sum square	Degree of freedom	Mean square	F	P-value
Between Groups	16,169,139,959,289	2	8,084,569,979,645	4.7955	0.0115
Within Groups	106,210,224,049,522	63	1,685,876,572,215		
Total	122,379,364,008,811	65			

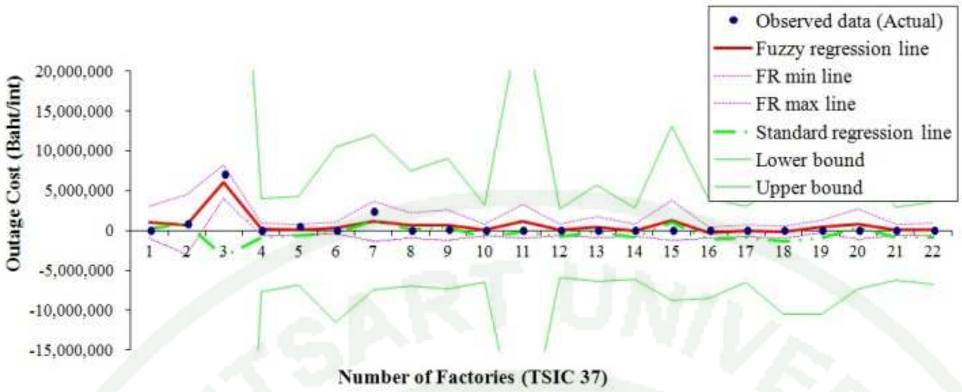


Figure 16 FR and SR Estimation for TSIC 37

According to ANOVA results in Table 20, the P-value is less than 0.05 so the null hypothesis is rejected for TSIC 37. Thus, the hypothesis testing by Tukey method is used to compare the pairs of treatments. The results are shown as follows:

	P-value	Result
AC and FR	0.9255	$\mu_{AC} = \mu_{FR}$
AC and SR	0.0419	$\mu_{AC} \neq \mu_{SR}$
FR and SR	0.0161	$\mu_{FR} \neq \mu_{SR}$

The significant result of pair AC and FR has the P-value greater than 0.05 so the model resulted from fuzzy regression is selected for TSIC 37 customer group.

Table 22 Statistical Values of TSIC 38

Groups	Count	Sum	Average	Variance
AC	76	73,361,764	965,286	16,286,343,096,486
FR	76	96,958,818	1,275,774	5,898,747,682,194
SR	76	30,497,494	401,283	11,862,743,385,749

Table 23 ANOVA results of TSIC 38

Source of Variation	Sum square	Degree of freedom	Mean square	F	P-value
Between Groups	29,874,008,986,360	2	14,937,004,493,180	1.3161	0.2702
Within Groups	2,553,587,562,332,150	225	11349278054810		
Total	2,583,461,571,318,510	227			

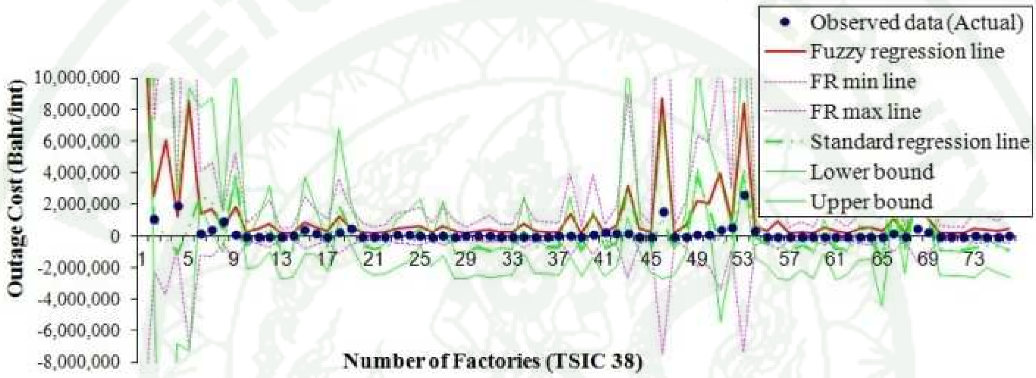


Figure 17 FR and SR Estimation for TSIC 38

According to ANOVA results in Table 22, the P-value is greater than 0.05 so the null hypothesis is accepted for TSIC 38. Thus, MAPE in Table 11 is considered. It is found that the MAPE of fuzzy regression is lower than that of statistic regression, so the FR model is selected for TSIC 38 customer group.

4. Rice Mill Industries and Economical Maintenance Activities

4.1 Data from post mail for classification by only one Sub-TSIC.

All of the rice mill plant production capacity between 100 to 2,000 ton per day of 318 factories are surveyed by questionnaires to collect the data for outage cost studying and reliability improving for electrical system of distribution utility and customer in 2011 as Table 24.

The questionnaire are developed from onsite interview about the effect of plant outage by electrical system both internal and external failures from rice mill study plant in the central region of the country. The main items include four parts. First part is personal information of responders for the necessary case of calling back. Second part are general information of the plant like product, number of staff, working period and week, season, production price rate, production process and diagram. Third part are electrical system data like utility customer id, voltage level, transformer kVA, peak load, reserved generator, etc. The fourth are the effect of momentary and sustain interruption, production process diagram, etc.

Thailand industrial customers can be categorized in to nine groups follow as Thailand standard industrial code (TSIC ID 31-39). For rice mill industry can be classified and are in TSIC31 which is food, beverage and tobacco and TSIC code of rice mill industry is TSIC31161.

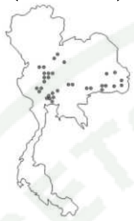
Production process of rice mill industry mostly like the process in Figure 21. The process is started with cleaning of paddy, warming to reduce humidity, milling to remove husk and winnowing to separate husk from rice kernel. The rice grain getting from this process is the rice with inner layer or bran. Some paddy will be returned to milling process. Rice with inner layer will be removed bran in whitening polish process. Final process, swaying sieve will separate full seed, broken seed and bran for storing and selling.

Besides, the data are shown in Table 22 along with rice mill plant location, breeding rice, production activities, interruption causes and electrical system. First of all, locations are name of provinces and amount of factories in each province. Then, breed of rice, there are several breeding rice in the country but some rice breeds are very popular for growing and consuming. Next, production rates are included many related factors for example productive capacity, working day and restarting time. After that, interruption causes from internal and external as though tree, animal, equipment and natural disaster. Last, electrical system are very interesting to know about momentary interruption and sustained interruption, reserved generator installation, maintenance activity planning, interesting of changing voltage level connection from medium voltage (22 kV, 24 kV) to sub-transmission voltage (69 kV, 115 kV) and becoming very small power producer (VSPP) for own energy producing from husk. VSPP are promoted by the Thai government to increase the renewable energy power plants about 4,000 MW that energize through low voltage or medium voltage of distribution line to sale the energy for Metropolitan Electricity Authority (MEA) or Provincial Electricity Authority (PEA). MEA and PEA are state enterprise distribution utility that PEA take responsibility for the most areas of the country except Bangkok, Nonthaburi and Samut Prakan.

Table 24 Surveyed Result of Rice Mill Plant

TSIC	Type	Surveys (Factory)	Responses (Factory)	Percentage (%)
31161	Rice mill Industry (100-2,000 ton/day)	318	33	10.38

Table 25 Data Collection of Rice Mill Customer

Data collection	Result
Location (number) 	Central: Bangkok(1), Nonthaburi(3), Ayutthaya(1), Saraburi(1), Pathum Thani(1), Chainat(1), Suphanburi(3) North: Phitsanulok(2), Nakhon Sawan(5), Phetchabun(1), Kamphaeng Phet(2) North-east: Roi Et(1), Nakhon Ratchasima(2), Buriram(2), Yasothon(1), Sisaket(1), Surin(3), Ubon Ratchathani(2)
Breed of rice	Rice paddy such as Thai jasmine, Pathumtani, Phitsanulok1, Suphanburi2, Chainat1, etc.
Production	Milling, packaging, selling or exporting Production rates 100 – 2,000 ton/day 7 days/week and 24 hr 70 % 6 days/week and 24 hr 18 % Only daytime or nighttime 12 % Average of restarting time 28.73 min
Interruption causes	External: tree, car accident, natural disaster like rain, lightning, storm Internal : rat, snake and bird making fault at transformer and drop out fuse (D/F) melting
Electrical System	Average momentary interruption 18 times per year Average sustained interruption 11 times per year Reserved generator installation 3 % 54 % of customers with have preventive maintenance activities 52 % of customers are interested in voltage level changing to be 115 kV 15 % of customers are very small power producer

* the number of data collection is 33 data

4.2 Process of outage cost assessment

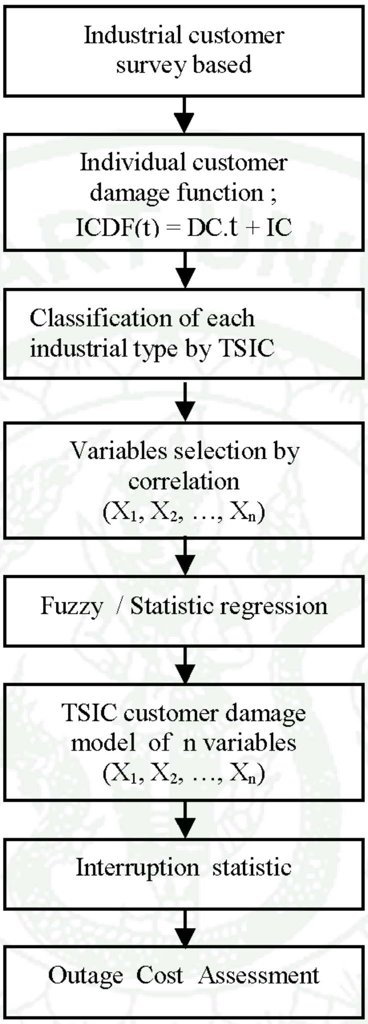


Figure 18 Outage cost evaluation

4.3 Results of the test model factories, model selection, example of feeder prioritization

Table 26 Statistical coefficients

Coefficients	Center
β_0	38413.3079
β_1	-27.4679
β_2	191.2611
β_3	93.0173
β_4	0.0323
β_5	865.8824

It is strongly encouraged that the authors may use SI (International System of Units) units only.

Table 27 Factories for data testing

Name	x_1 (kVA)	x_2 (ton/day)	x_3 (kW)	x_4 (Baht/month)	x_5 (min)
Factory 1	1,000	420	174	150,000	30
Factory 4	500	400	230	130,000	60
Factory 10	1,500	200	1,436	400,000	20
Factory 14	1,500	400	1,000	550,000	30

Table 28 Test results of fuzzy model

Name	Outage cost of fuzzy regression model (Baht / interruption)			Actual outage cost (Baht/interruption)
	Spread	Center	Interval	
Factory 1	269,464	100,189	0 to 369,654	481,250
Factory 4	452,455	111,167	0 to 563,622	395,352
Factory 10	273,281	170,073	0 to 443,354	261,333
Factory 14	346,736	185,908	0 to 532,644	403,333

Table 29 Test results of statistical model

Test data	Outage cost of statistic regression model (Baht / interruption)			Actual outage cost (Baht/interruption)
	Spread	Estimate	Confident interval	
Factory 1	489,734	138,280	0 to 766,293	481,250
Factory 4	561,058	178,728	0 to 918,514	395,352
Factory 10	772,102	199,269	0 to 1,170,640	261,333
Factory 14	784,734	210,467	0 to 1,205,669	403,333

In Figure 19 shows the confident interval of statistic or standard regression and Figure 20 presents upper bound and lower bound of fuzzy regression. Comparison of standard regression and fuzzy regression is presented in figure 21.

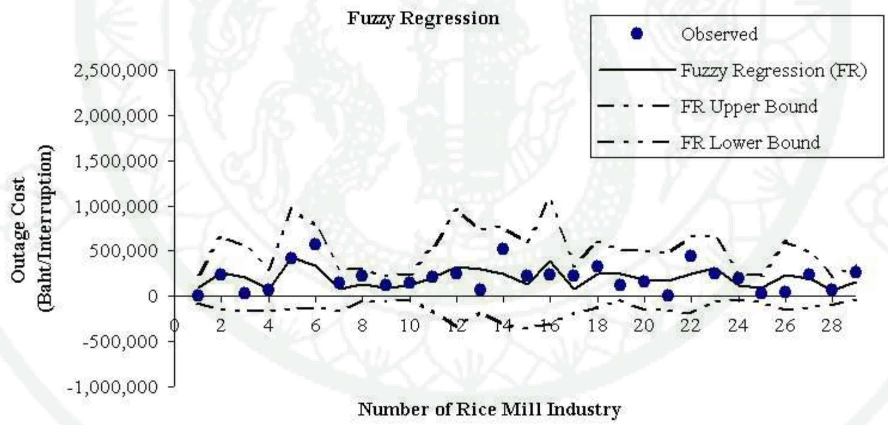


Figure 19 Plot of fuzzy regression

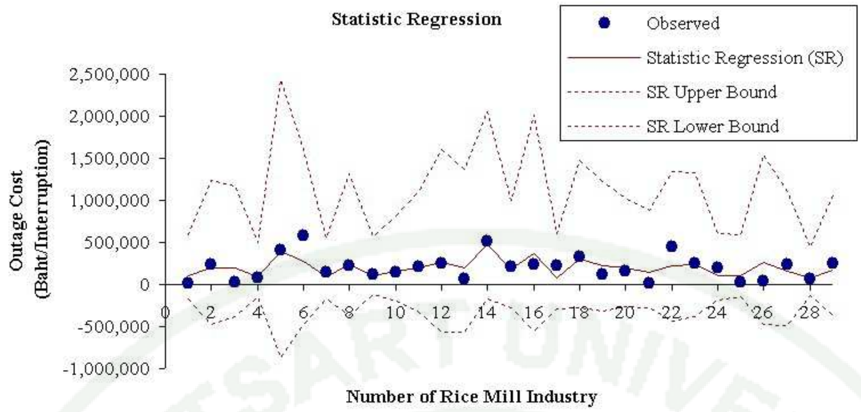


Figure 20 Plot of statistic regression

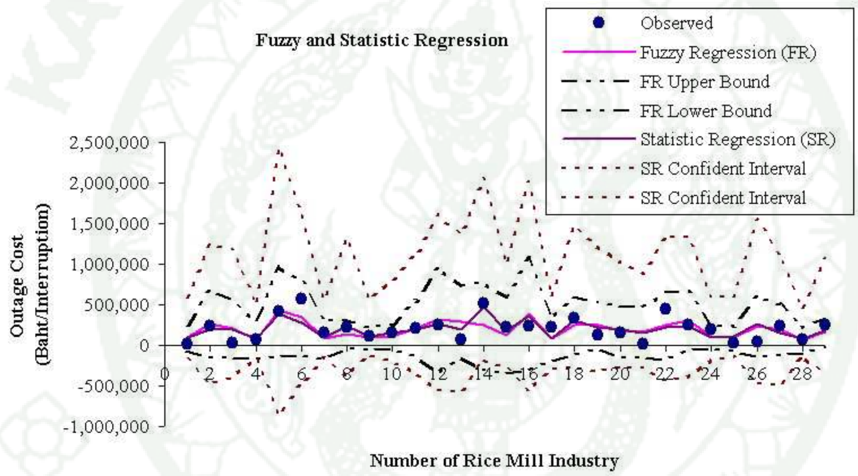


Figure 21 Plot of fuzzy regression and statistic regression

4.4 Apply for maintenance activities by RCM

Reliability Centered Maintenance Process (RCM) of rice mill industry maintenance planning is shown by the following RCM steps.

Step 1 System Selection and Information Collection

a) System Selection

System selection of rice mill can be considered into 2 parts, the first one consists of electrical system, drying system and milling process and the second one consists of equipments that comprise transformer, main distribution board, circuit breaker, capacitor and motor, etc.

b) Information Collection

The significant data of the rice mill study plant are: production rate, machine capacity, kVA of transformer, outage event data of plant failure such as drop out fuse melting from animal making short circuit, etc.

Step 2 System Boundary Definition

The system boundary of this case study consists of the electrical system and the production process as shown in Figure 22.

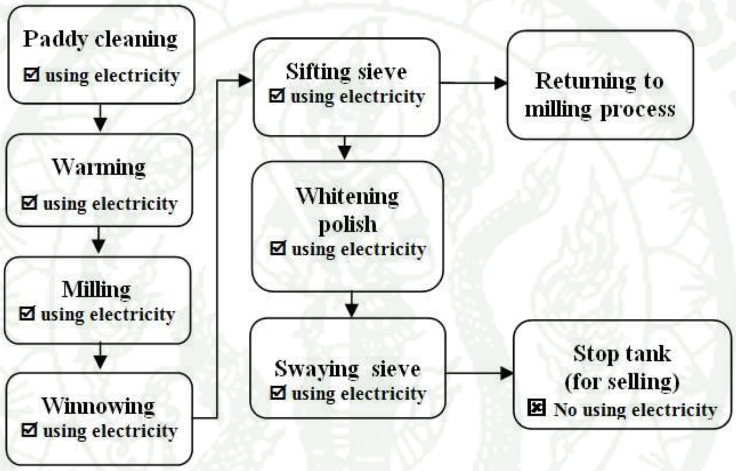


Figure 22 System boundary

Step 3 System Description and Functional Block Diagram

a) Rice Milling Process

Normally, paddies have moisture 13-14 %, so they need to be decreased humidity. They have been cleaned by separating mixed material like straw and soil. Then, their husks are removed and separated respectively. Paddy which removed husk is brown rice. Next, brown rice is polished in order to remove bran layer to be white rice. Finally, sifting process will separate white rice for stock for selling purposes. Rice milling process is shown in Figure 23.

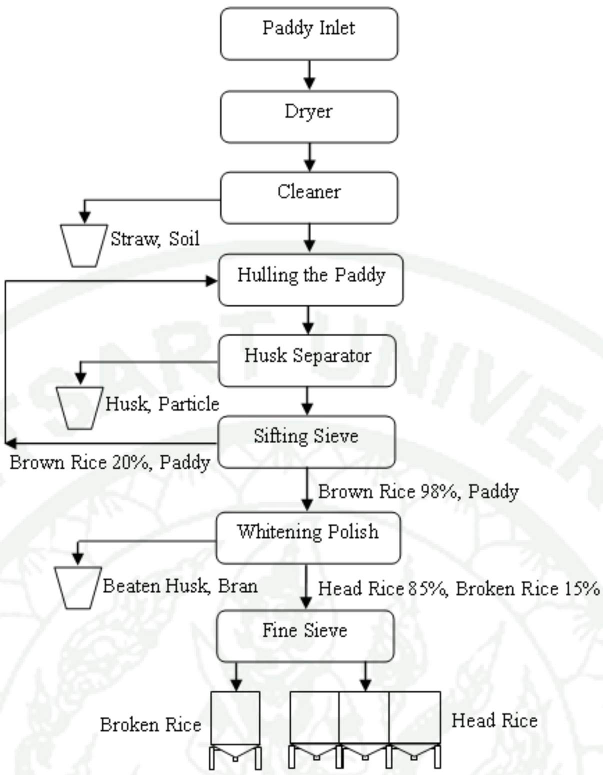


Figure 23 Rice milling process

b) Electrical System

The study plant receives 22 kV voltage level from Provincial Electricity Authority' Si Prachan district office (PEA) in Suphanburi province. The 800 kVA distribution transformer is installed to reduce voltage level from 22 kV to 400/230 V and Main Distribution Board (MDB) is installed to contain circuit breakers and capacitor bank for improving power factor. Circuit breakers control feeders for office (LP01), drying (LP02), sifting (LP03), lighting (LP04), Pressure Pump (LP05), conveyer (LP06) and 8 motors (80HP) for whitening and polishing (LP07) all shown in Figure 24.

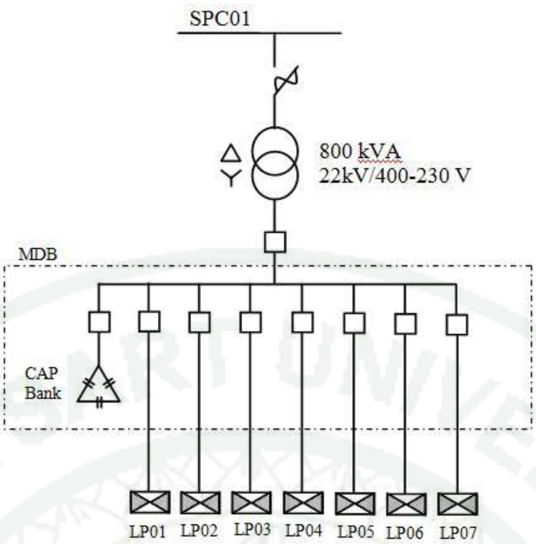


Figure 24 Single line diagram of study plant

Step 4 System Functions and Functional Failures

System functions and functional failures of electrical system and rice milling process are shown in table 1.

Table 30 System failure mode

System	Failure Mode
Electrical system	D/F blowing, conductor insulation failure, bus bar connector loosing, capacitor and CB failure
Rice milling process	Polishing bearing is breaking, hot and noise, conveyer failure, rubber roller failure

Step 5 Failure Modes and Effects Analysis
We consider the likelihood and severity of the failure effects to find the critical of failure mode effects as shown in table 2.

Table 31 Criticality of failure modes and effects analysis

Severity	Frequency	Critical Value
High	High	Very High
	Medium	High
	Low	Medium
	None (Non-Dominant)	N/A
Medium	High	High
	Medium	Medium
	Low	Low
	None (Non-Dominant)	N/A
Low	High	Medium
	Medium	Low
	Low	Non-Critical
	None (Non-Dominant)	N/A
None	High	Non-Critical
	Medium	Non-Critical
	Low	Non-Critical
	None (Non-Dominant)	N/A

Frequency of failure mode H; High is more than 20 times, M; Medium between 11-20 times and L; Low less than 10 times

Step 6 Logic (Decision) Tree Analysis
Decision tree analysis can help to determine the maintenance cost for choosing appropriate maintenance activities as shown in Figure 25. Safety problem in A refers to personal death, personal injury or may be equipment damage. Outage problem in B means focusing on plant outage or loss of productivity and economic problem in C refers to insignificant plant outage or loss.

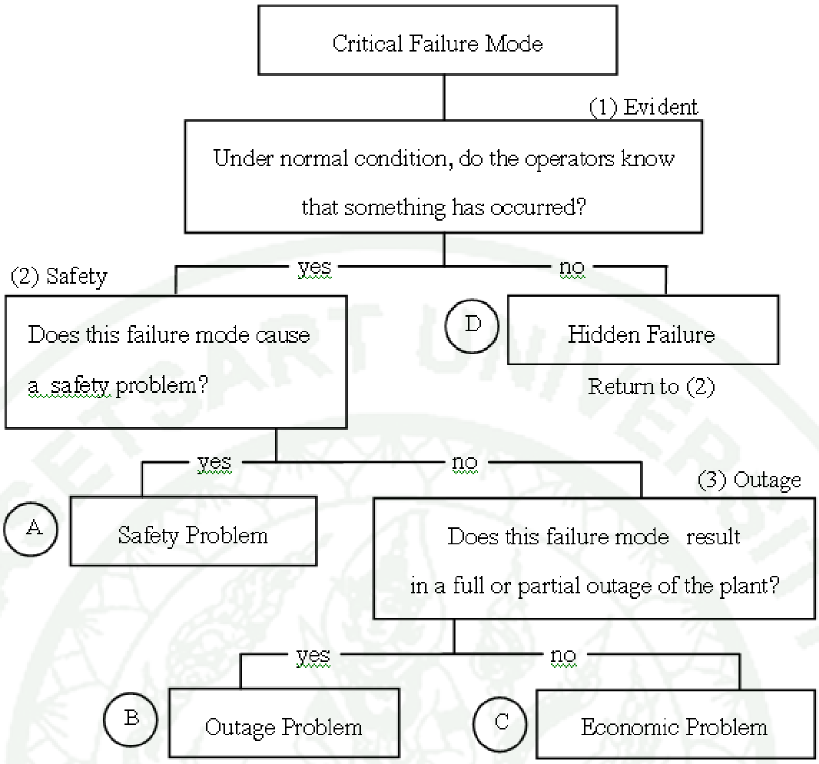


Figure 25 Decision tree diagram

<u>Step 7</u> Task Selection Process

After activities selection, they will be prioritized with benefit cost ratio. Preventive maintenance (PM) will be firstly selected and improvement maintenance (IM) will be chosen, respectively. Preventive and improvement maintenance activities are shown in Table 32.

Table 32 Preventive and improve maintenance activities

Activity	Failure Mode/	PM Task Description	PM Cost (Baht)	Outage Cost Saving (Baht/event)	Benefit Cost Ratio
A	Worn bearing	Visual inspection such as seeing or hearing (PM)	20	35,813	1791
B	Loose bus bar clamp	Fixing connector (PM)	20	17,907	895
C	Broken bearing	Greasing conveyer bearing (PM)	100	26,860	269
D	Transformer drop out fuse blowing	Installing bird guard (PM)	300	53,720	179
E	Transformer drop out fuse blowing	Installing snake guard (PM)	600	53,720	90
F	Broken bearing	Greasing whitening Bearing (PM)	400	35,813	90
G	Worn miller belt	Changing to high quality miller belt (IM)	180	5,968	33
H	Worn polishing belt	Changing to high quality polishing belt (IM)	360	8,953	25
I	Power factor correction failure	Measuring electric current every 6 month(PM)	2,000	35,813	18
J	Loose bus bar clamp	Thermal viewer (PM)	7,000	17,907	3

RCM is systematic process by starting with first step as selecting system and information collection that are the boundary and equipments to be improved with maintenance activities. Second step is to define the system boundary. Third step is to describe about data and detail of rice milling process and electrical system as shown by diagram. Fourth step is to list all electrical system and rice milling process functions by careful discussion and consideration. Then, fifth step is to considerate probability and severity of failure effects of the outage events. Sixth step is to make decision for critical failure mode about economical and safety aspects to select the activity by logic tree diagram. Final step is to make task selection process to highly select by evaluating of benefit cost ratio as shown in Figure 26 which shows the economical maintenance improvement.

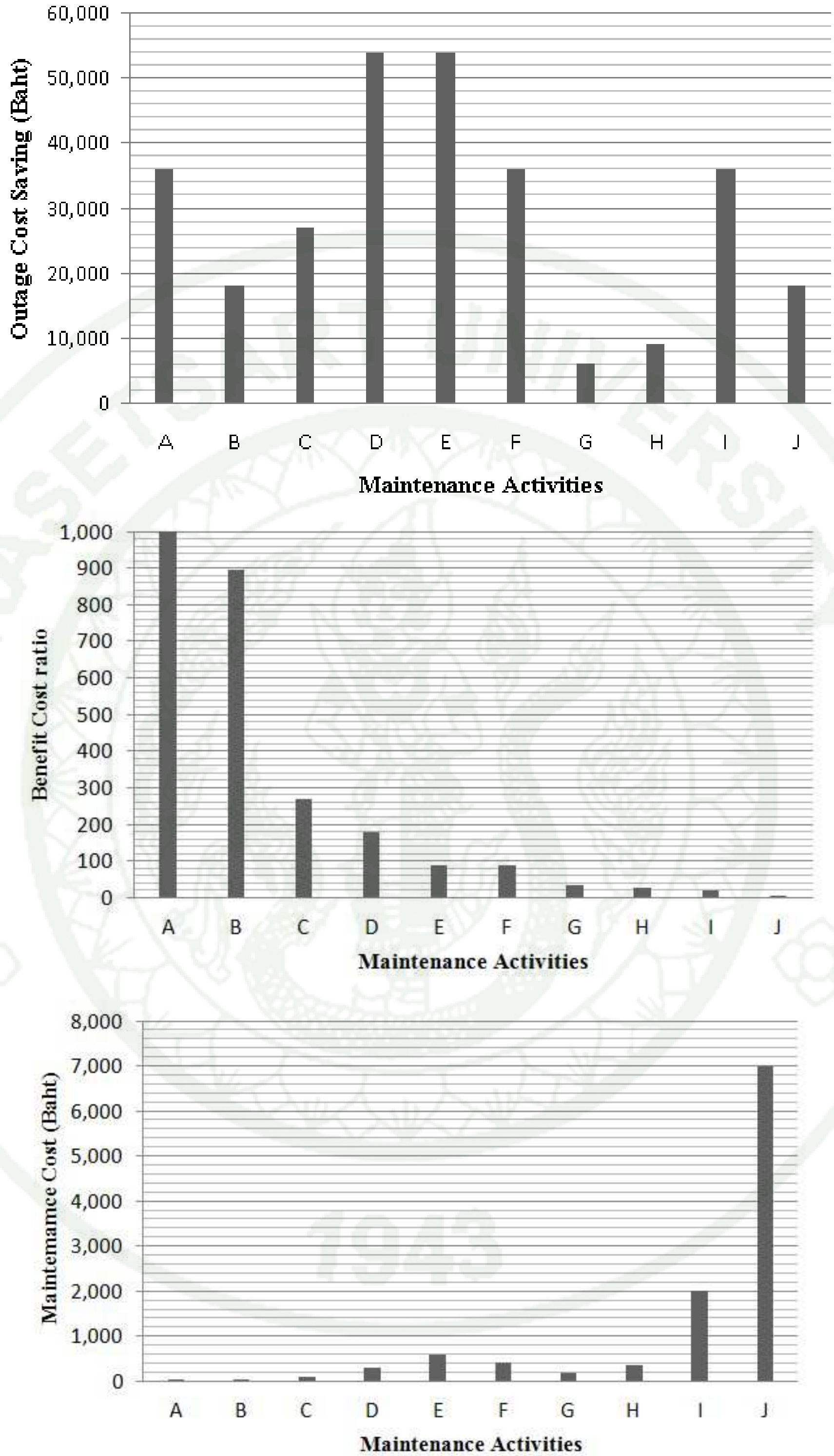


Figure 26 Prioritization of maintenance activities by B/C

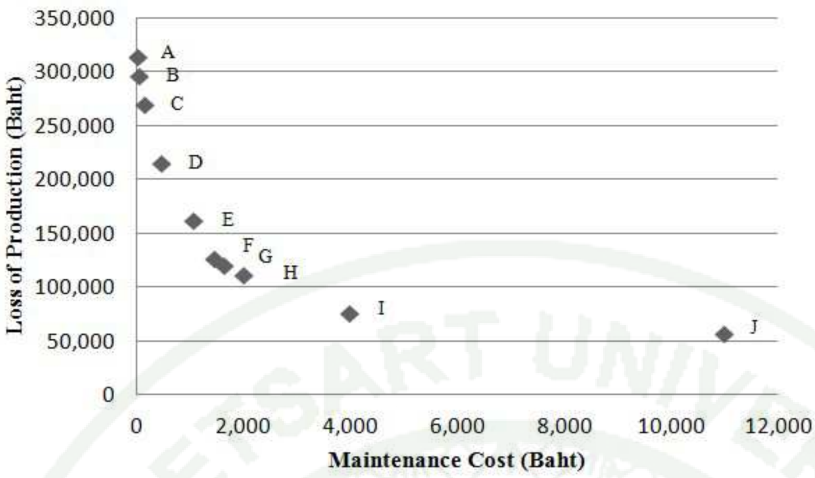


Figure 27 Economy of maintenance improvement

RCM is applied for rice mill maintenance planning to highly select the effective maintenance activities which are prioritized by B/C. This strategic methodology can help rice mill operator to contribute their daily, weekly, monthly and yearly maintenance plan. In Table 32, activity A is visual inspection (human senses like: seeing, hearing, touching and smelling) to observe the equipments which has no cost or very low cost. For activity we can use the thermo-scan infrared camera is used to inspect the loose connector for clearing hot spot. Consideration in Figure 25, if we do all activities which the amount of maintenance cost is not more than 12,000 Baht, the loss of production will decrease more than 200,000 Baht.

Discussion

From the results as feeder customer outage cost that can help for prioritization feeder services maintenance. The selection of outage cost model will be useful for outage cost assessment of all industry in the country that we know the type of industry and production rate or any related input variables. Outage cost would be reduced by suitable maintenance activities as preventive maintenance or improvement maintenance. The results of reducing outage cost would support high performance of distribution system which keep reliability of electrical system and contentment of their customers.

CONCLUSION AND RECOMMENDATION

Conclusion

The practical outage cost evaluation is proposed in this thesis. Customer data surveys of industrial customers are used to collect the data by questionnaires. The survey questionnaire is developed from on-site interviews to find the appropriate process of simple data collection forms. The survey information is considered to establish the Customer Damage Function (CDF) which is composed of both duration outage cost and initial outage cost. The CDF can be used to calculate the outage cost of each customer by substitution of outage duration. For prioritization of power distribution feeders, the outage cost of a feeder can be resulted from evaluation of CDFs of all feeder customers. This may look straightforward, but in fact it is very difficult to survey all feeder customers in order to develop their CDFs.

This research also proposes the assessment method of customer outage cost using available and easy-to-find information based on Fuzzy regression and conventional linear regression techniques. Outage cost modeling can be achieved using both techniques. The customer outage cost models are helpful to assess the outage cost of the unsurveyed customers. In addition, the selection criteria of the appropriate outage cost model between both techniques is presented using mean absolute percentage error (MAPE) and hypothesis testing by Analysis of Variance (ANOVA). In more details, the proposed modeling is done with customers of each Thai Standard Industrial Classification (TSIC) group individually. This has considerably helped improve the accuracy of outage cost assessment because production processes and losses due to interruptions vary from industry to industry. Finally, the outage costs resulted from the proposed method are compared with the actual outage costs for effectiveness evaluation. The results obtained from outage cost assessment can be very supportive to power utilities to prioritize their distribution feeders or areas for reliability improvement projects.

Recommendation

The assessment accuracy can be further improved by applying the modeling method to customers of each sub-TSIC group individually. It is because industrial customers in the same TSIC group are often found dissimilar in terms of multiplicity of production processes. On the other hand, other techniques possible for outage cost modeling may be taken into account such as artificial neural networks or other nonlinear regression techniques.

LITERATURE CITED

Allan, R.N. and M.G. Da Silva. 1995. Evaluation of reliability indices and outage costs in distribution systems. **IEEE Transactions on Power Systems** 10(1) : 413 – 419.

Alvarado, F., Y. Hu, D. Ray, R. Stevenson and E. Cashman. 1991. Engineering foundations for the determination of security costs. **IEEE Transactions on Power Systems** 6(3): 1175 – 1182.

Azadeh, A., Khakestani, M. and Saberi, M. 2009. A flexible fuzzy regression algorithm for forecasting oil consumption. **Energy Policy** 37: 5567-5579.

Billinton, R. and Allan., R. N. 1994. **Reliability Evaluation of Power Systems**. 2nd ed. Plenum, New York.

Billinton, R. and W. Li. 1994. **Reliability Assessment of Electric Power Systems Using Monte Carlo Methods**. Plenum, New York.

Billinton, R. and S. Jonnavithula. 1996. Optimal switching device placement in radial distribution systems. **IEEE Transactions on Power Delivery** 11(3) : 1646 – 1651.

Billinton, R. and W. Wangdee. 2005. Approximate methods for event-based customer interruption cost evaluation. **IEEE Transactions on Power Systems** 20(2): 1103 – 1110.

Billinton, R., E. Chan and G. Wacker. 1994. Probability distribution approach to describe customer costs due to electric supply interruptions. **Transmission and Distribution Generation**, IEE Proceedings.

Brown, R.E. 2002. **Electric Power Distribution Reliability**. Marcel Dekker, Inc, USA.

Burns, S. and G. Gross. Value of service reliability. **IEEE Transactions on Power Systems** 5(3): 825 – 834.

Bertling, L. and M. Lehtonen. 2007. **Maintenance management in power system.** Ph.D. course, TRITA-EE 2007:043, KTH, Stockholm, 007. Available Source: http://www.ee.kth.se/php/modules/publications/reports /2007/TRITA-EE_2007_043.pdf.

Brillinger,D.(2002), John W. Tukey: His Life and Professional Contributions, **The Annals of Statistics** 30: 1535-1575.

Chatterjee, S. and B. Price. 1991. **Regression Analysis by Example**. USA: Wiley-Intersceince.

Dom, R. M., S. A Kareem, I. A. Rasak and B. Abidin. 2008. A learning system prediction method using fuzzy regression. *In* **Proceedings of the International MultiConference of Engineers and Computer Scientists**. 19-21 March 2008, Hongkong, PR China.

Datla, S.V. and M.D. Pandey. 2005. Estimation of life expectancy of wood poles in electrical distribution networks. **Structural Safety**.

Energy Research Institute. 2001. **Electricity Outage Cost Study**. Chulalongkorn University, Thailand.

Elvers, G. C. 2013. Using SPSS for one way analysis of variance. University of dayton. Available Source: http://academic.udayton.edu/ gregelvers/psy216/spss/1wayanova.htm

Eua-arporn, B. 2005. Fuzzy interrupted energy assessment rate based on actual system performance. **IEEE Transactions on Power Systems** 20(1): 156 – 163.

Goel, L. 2007. Well-Being Reliability worth indices due to difference customer outage cost functions. *In* **Proceeding of IEEE IPEC**. Singapore.

George, D. and P. Mallery. 1999. **SPSS for Windows step by step**. Allyn and Bacon.

Hokierti, J. 2006. **Reliability and Power Distribution System Maintenance**, Faculty of E ngineering, Kasetsart University. (in Thai)

IEEE Committee Report. 1997. **Report in Reliability Survey of Industrial Plants, Part II: Cost of Power Outages, Plant Restart Time, Critical Service Loss Duration Time, and Type of Loads Lost Versus Time of Power Outages**. IEEE Std 493-1997.

Ip, K.W., Kwong, C.K. and Wong, Y.W. 2003. Fuzzy regression approach to modeling transfer moulding for microchip encapsulation. **Journal of Materials Processing Technology** 140: 147 – 151.

Kariuki, K.K. and R.N Allan. 1996. Applications of customer outage costs in system planning, design and operation. **Generation Transmission and Distribution, IEE Proceedings** 143(4): 305 – 312.

______. 1996. Assessment of customer outage costs due to electric service interruptions: residential sector. **Generation Transmission and Distribution, IEE Proceedings.**

Kariuki, K.K. and R.N Allan. 1996. Evaluation of reliability worth and value of lost load. **Generation Transmission and Distribution**, **IEE Proceedings.** 143(2): 171 – 180.

Kirsch, L.D., R.L. Sullivan, T.A. Flaim, J.J. Hipius and M.G. Krantz. 1988. Developing Marginal Costs for Real-Time Pricing. **IEEE Transactions on Power Systems** 3(3): 1133 – 1138.

Kjolle, G., L. Rolfseng and E. Dahl. The economic aspect of reliability in distribution system planning. **IEEE Transactions on Power Delivery**. 5(2): 1153 – 1157.

Kim, K. J., H. Moskowitz and Koksalan, M. (1996), Fuzzy versus statistical linear regression, **European Journal of Operational Research** 92: 417 – 434.

Leblanc, W.J. 1988. Customer attitudes regarding electric outage costs and back-up generation. **IEEE Transactions on Power Systems** 3(4): 1823 – 1826.

Li, Wenyuan and R. Billinton. 1993. A minimum cost assessment method for composite generation and transmission system expansion planning. **IEEE Transactions on Power Systems** 8(2):628 – 635.

Lin, W.M., C.D Yang and M.T Tsay. 2000. Distribution system planning with evolutionary programming and a reliability cost model. **Generation Transmission and Distribution**. **IEE Proceedings.** 147(6): 336 – 341.

Lawton, L., M. Sullivan, K.V. Liere, A. Katz and J. Eto. 2003. **A Famework and review of customer outage costs: Integration and analysis of electric utility outage cost surveys.** Population Research Systems, LLC and Lawrence Berkeley National Laboratory, LBNL-54365, Nov. 2003.

Lassila, J., S. Honkapuro and J. Partanen. 2005. Economic analysis of outage costs parameters and their implications on investment decisions, pp.1-8. *In* **Proceedings of IEEE 2005**.

Makinen, A., J. Partanen and E. Lakervi. A practical approach for estimating future outage costs in power distribution networks. **IEEE Transactions on Power Delivery** 5(1): 311 – 316.

Montgomery, D. 2001. **Design and Analysis of Experiment**. fifth edition, John Wiley & Sons.

Nam, K.Y., S.B. Choi, H.S. Jeong, J.D. Lee and D.K. Kim. 2006. A Survey on interruption costs of Korean industrial customers, pp. 1-7. *In* **Proceedings of IEEE 2006**.

Nasiri, M., Shanbeh, M. and Tavanai, H. 2005. Comparison of statistic regression, fuzzy regression and artificial Neural Network Modeling Methodologies in Polyester Dyeing. *In* **Proceedings of the International Conference on Computational Intelligence for Modelling,Control and Automation, and International Conference.** 28-30 November, Vienna, Austria.

Neter, J., W. Wasserman and M. H. Kutner. 1989. **Applied Linear Regression Models.** USA: IRWIN.

Nazarko, J. and W. Zalewski. 1996. The fuzzy regression approach to peak load estimatation in power distribution systems, **IEEE Transaction on Power System** 14(3): 809-814.

Population Research Systems. 2003. **A Framework and Review of Customer Outage Costs: Integration and Analysis of Electric Utility Outage Cost Surveys**. Prepared for Office of Electric Transmission and Distribution, U.S.

Department of Energy, LLC and Lawrence Berkeley National Laboratory, University of California Berkely, CA, USA.

Rerkpreedapong, D. 2008. **Reliability Target Setting Project final Report**, Faculty of Engineering, Kasetsart University.

Satish, J. and R. Billinton. 1995. Minimum cost analysis of station configurations. **IEEE Transactions on Power Delivery** 10(4): 1799 – 1805.

Stephenson, W.M. and D.J. Barney. 1988. Economic of energy reliability. **IEEE Potentials** 7(2): 26 – 27.

Sullivan, M.J.,T. Vardell and M. Johnson. 1997. Power interruption costs to industrial and commercial consumers of electricity. **IEEE Transactions on Industry Applications** 33(6): 1448 – 1458.

Sullivan M. and D. Keane. 1995. **Outage cost estimation guidebook**. Electric Power Research Institute, TR-106082, Dec. 1995. Available Source: http://www.epriweb.com/public/TR-106082.pdf, July 9, 2008.

Smith, A. M. and G. R. Hinchcliffe. 2003. RCM-Gateway to **World Class Maintenance.** USA: Elsevier Butterworth-Heinemann.

Shapiro, A. F. 2005. **Fuzzy regression models**. Penn state University, Available Source: http://www.soa.org/library/research/actuarialresearch.../ arch06v40n1-ii.pdf

Tanaka, H., S. Uejima and K. Asai. 1982. Linear regression analysis with fuzzy model. **IEEE Transactions on System, Man and Cybernetics** 12(6): 903 – 907.

Teng, Jen-Hao and Chan-Nan Lu. 2002. Feeder-switch relocation for customer interruption cost minimization. **IEEE Transactions on Power Delivery** 17(1): 254 – 259.

Wacker, G. and R. Billinton. 1989. Customer cost of electric service interruptions. **IEE Proceedings** 77(6): 919 – 930.

Wijayatunga, P.D.C. and M.S. Jayalath. 2003. Assessment of economic impact of electricity supply. www.elsevier.com/locate/enconman. **Energy conservation & Management Journal.**

Wanichbancha, K., 2001. **Principle of Statistic**, Thailand: Chulalongkorn University, Bangkok

Zadeh, L. A. 1978. Fuzzy sets as a basic for a theory of possibility, **Fuzzy Sets and Systems** 1: 3 - 28.

CURRICULUM VITAE

NAME : Mr. Chaliew Ketkaew

BIRTH DATE : July 25, 1976

BIRTH PLACE : Bangkok, Thailand

EDUCATION :

YEAR	**INSTITUTE**	**DEGREE**
2000	MUT	B.Eng. (E.E.)
2003	KMUTT	M.Eng. (E.E.)

POSITION/TITLE : Lecturer

WORK PLACE : Faculty of Engineering and Architecture, RMUTSB

SCHOLARSHIP/AWARD : Rajamangala University of Technology Suvarnabhumi (RMUTSB) Scholarship 2006-2008

List of publications

- **Ketkaew, C.**, Yimpresert, Y., Sonklin, N., Khatsaeng,T, .Noohawm, O. and Rerkpreedapong, D. 2007. Outage Costs Analysis for Customer Oriented Maintenance. Proceeding of the international conference on Electrical Engineering.
- **Ketkaew, C.**, Yimpresert, Y., Sonklin, N., Noohawm, O. and Rerkpreedapong, D. 2008. Outage Cost Assessment of Industrial Customers for Maintenance Planning. Proceeding of the 8th Annual Electrical Power & Energy Conference.
- **Ketkaew, C.**, Yimpresert, Y., Noohawm, O. and Rerkpreedapong, D. 2008. Outage Cost Assessment of Industrial Customers for Maintenance Planning and Reliability Improvement. Proceeding of the 31st Electrical Engineering Conference, 423-426. (in Thai)

List of publications (Continued)

- **Ketkaew, C.**, Noohawm, O. and Rerkpreedapong, D. 2010. Outage Cost of Industrial Customers in Distribution and Subtransmission Systems for Reliability Improvement. Proceeding of the 45th International Universities' Power Engineering Conference.
- **Ketkaew, C.**, Noohawm, O. and Rerkpreedapong, D. 2011. Outage Costs Assessment of Industrial Customers in Distribution Systems. Proceeding of the 3rd of Electrical Engineering Network of Rajamangala University of Technology. (in Thai)
- **Ketkaew, C.**, Noohawm, O. and Rerkpreedapong, D. 2012. Outage Cost of Rice Mill Industry. Proceeding of the 4th of Electrical Engineering Network of Rajamangala University of Technology. (in Thai)
- **Ketkaew, C.**, Noohawm, O. and Rerkpreedapong, D. 2013. Rice mill industry maintenance planning using Reliability Centered Maintenance (RCM). Proceedings of the IASTED International Conference Power and Energy Systems, 462-467.
- **Ketkaew, C.**, Noohawm, O. and Rerkpreedapong, D. 2013. Outage Cost Modeling of High Energy Consumption Industries. Proceeding of the 8th GMSARN International Conference.
- **Ketkaew, C.**, Noohawm, O. and Rerkpreedapong, D. 2014. Outage Cost Modeling of High Energy Consumption Industries. GMSARN International Journal, 8(1).
- **Ketkaew, C.**, Noohawm, O., Rerkpreedapong, D. and Plueksawan, W. 2014. An Assessment Method of Customer Outage Cost of Rice Mill Industries. waiting for review of Engineering Journal Kasetsart University. (in Thai)