



STUDY ON IMPACT OF DUST PARTICLES TOWARDS
PLANETARY BALL MILLING MACHINE'S MAINTENANCE
RELIABILITY AND PERFORMANCE USING DOE

DR. SHAHRUL KAMARUDDIN

UNIVERSITI SAINS MALAYSIA
KAMPUS KEJURUTERAAN
2008



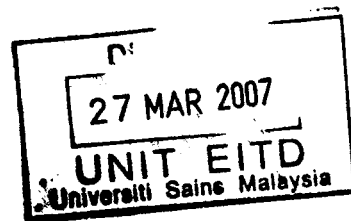
Laporan Akhir Projek Penyelidikan Jangka Pendek

Study on Impact of Dust Particles towards Planetary Ball Milling Machine's Maintenance, Reliability and Performance using DOE

by

Dr. Shahrul Kamaruddin

Assoc. Prof. Dr. Indra Putra Almanar



PEJABAT PENGURUSAN & KREATIVITI PENYELIDIKAN
RESEARCH CREATIVITY AND MANAGEMENT OFFICE [RCMO]

LAPORAN AKHIR PROJEK PENYELIDIKAN JANGKA PENDEK FINAL REPORT OF SHORT TERM RESEARCH PROJECTS

- 1) Nama Ketua Penyelidik :
Name of Research Leader :

Ketua Penyelidik Research Leader	PTJ School/Centre
DR. SHAHRUL B. KAMARUDDIN	PUSAT PENGAJIAN KEJURUTERAAN MEKANIK

- Nama Penyelidik Bersama
(Jika berkaitan) :
Name/s of Co-Researcher/s
(if applicable)

Penyelidik Bersama Co-Researcher	PTJ School/Centre
A.P. DR. INDRA PUTRA ALMANAR	PUSAT PENGAJIAN KEJURUTERAAN MEKANIK

- 2) Tajuk Projek : STUDY ON IMPACT OF DUST PARTICLES TOWARDS PLANETARY
Title of Project:
BALL MILLING MACHINE'S MAINTENANCE, RELIABILITY AND
PERFORMANCE USING DOE

3)

Abstrak untuk penyelidikan anda

(Perlu disediakan di antara 100 – 200 perkataan di dalam Bahasa Malaysia dan Bahasa Inggeris. Ini kemudiannya akan dimuatkan ke dalam Laporan Tahunan Bahagian Penyelidikan & Inovasi sebagai satu cara untuk menyampaikan dapatan projek tuan/puan kepada pihak Universiti & luar).

Abstract of Research

(Must be prepared in 100 – 200 words in Bahasa Malaysia as well as in English. This abstract will later be included in the Annual Report of the Research and Innovation Section as a means of presenting the project findings of the researcher/s to the university and the outside community)

English Version

In manufacturing industries, the capability to fulfil the customer's satisfaction in term of time delivery and quality products are the main objective of the manufacturers. One of the criteria for achieving this objective is to ensure the production machines are operating in high efficiency without or less breakdown. However, machines breakdown due to unplanned maintenance becomes a common hindrance for the company to achieve the objective as well as to reach the maximum profit. Economically, this problem reflects the high production lost (product reject) and increases the maintenance cost.

Preventive Maintenance (PM) is one of the strategies that can be applied to reduce the machine breakdown problem due to unplanned maintenance. However, the application of PM in term of when is the best time to carry out the PM is an important issue. The answer to this question should be based on an adequate maintenance analysis. The existing study in determining the PM time is not based on an adequate maintenance analysis, where there are not considered the external factor (covariate) and without understanding the failure mechanism (physical failure). Therefore, the determination of PM time is not accurate enough and reduced the PM benefits.

In this research, a decision model of maintenance analysis by considering the external factor (covariate) and physical failure has been developed in order to determine the more accurate time of PM. Therefore, the PM strategy that applied can maximise the benefits of PM. In order to validate this model, a case study was carried out on a processing industry in Malaysia. The case study only focused on non-repairable components in a machine.

The results from this physical failure analysis have identified the possible external factors (covariates) that influence to the component failure and have classified the censored and uncensored data. This information is being used for the next analysis (covariate analysis) in the decision model. The result shows that some identified covariates have significant effects to the component failure. Thus, the parameter of covariates effects is used to determine more accurate time of PM. The result of PM time determination shows that there has a significant difference of PM time with and without considering the external factor. Therefore, this result implies that more accurate time of PM should be determined by considering the external factor (covariate).

Versi Bahasa

Di industri pengeluaran, keupayaan untuk memenuhi kehendak pelanggan dari segi masa penghantaran dan kualiti produk merupakan objektif utama bagi setiap pengeluar. Salah satu kriteria untuk mencapai objektif ini ialah dengan memastikan mesin-mesin untuk proses pengeluaran beroperasi dengan lancar tanpa atau kurang berlakunya kerosakan secara tiba-tiba (sudden failure). Walau bagaimanapun, kegagalan mesin beroperasi yang disebabkan kerosakan tiba-tiba merupakan masalah yang sering berlaku dan ia merupakan halangan utama dari mencapai objektif tersebut. Dari segi ekonominya, masalah ini juga akan mengakibatkan kadar kerosakan pada produk (product defect) yang tinggi dan meningkatkan kos penyelenggaraan mesin.

Penyelenggaraan pencegahan (Preventive Maintenance – PM) merupakan salah satu strategi yang digunakan untuk mengurangkan masalah kerosakan mesin yang berlaku secara tiba-tiba. Walaupun begitu, persoalan bilakah masa yang terbaik untuk menjalankan aktiviti PM merupakan isu terpenting dalam pengaplikasian strategi ini. Jawapan untuk persoalan tersebut ialah dengan berdasarkan analisis penyelenggaraan (maintenance analysis). Penyelidikan sedia ada mengenai penentuan masa untuk menjalankan PM kebanyakannya tidak berdasarkan analisis penyelenggaraan yang mencukupi yang mana ia tidak mengambilkira faktor luaran yang mengakibatkan kerosakan mesin dan tidak memahami bagaimana proses kerosakan mesin tersebut berlaku (analisis kerosakan fizikal). Oleh sebab itu, penentuan masa terbaik untuk menjalankan PM tidak cukup tepat dan ia akan mengurangkan faedah daripada strategi PM.

Dalam penyelidikan ini, satu model pembuat keputusan berdasarkan analisis penyelenggaraan dengan mengambilkira faktor luaran dan analisis kerosakan fizikal telah dibangunkan untuk menentukan dengan lebih tepat masa yang terbaik untuk menjalankan PM. Oleh itu, faedah daripada strategi PM ini dapat dimaksimumkan. Bagi penilaian model ini, satu kajian kes telah dijalankan di industri pemprosesan di Malaysia. Kajian kes ini memberi tumpuan pada kerosakan komponen mesin yang tidak boleh diperbaiki (non-repairable component).

Keputusan daripada analisis kerosakan fizikal telah mengenalpasti beberapa maklumat penting iaitu faktor luaran yang mengakibatkan kerosakan komponen mesin dan pengkelasan data-data “censored” dan “uncensored”. Maklumat-maklumat ini merupakan input yang penting untuk analisis faktor luaran (covariate analysis) dalam model pembuat keputusan ini. Keputusan daripada analisis faktor luaran menunjukkan beberapa faktor luaran (covariates) yang dikenalpasti daripada analisis kerosakan fizikal memberi kesan yang serius kepada kerosakan komponen mesin. Oleh itu, nilai parameter daripada kesan tersebut digunakan atau diambilkira dalam pengiraan bagi menentukan masa untuk menjalankan PM dengan lebih tepat. Keputusan daripada pengiraan ini menunjukkan terdapat perbezaan masa PM yang ketara apabila pengiraan yang mengambilkira faktor luaran dan pengiraan yang tidak mengambilkira faktor luaran. Pada kesimpulannya, penentuan masa untuk menjalankan PM akan lebih tepat sekiranya faktor luaran diambilkira dalam pengiraan tersebut.

- 4) Sila sediakan Laporan teknikal lengkap yang menerangkan keseluruhan projek ini.
[Sila gunakan kertas berasingan]
Kindly prepare a comprehensive technical report explaining the project
(Prepare report separately as attachment)

Technical Report Attached as Appendix 1

Senaraikan Kata Kunci yang boleh menggambarkan penyelidikan anda :
List a glossary that explains or reflects your research:

<u>Bahasa Malaysia</u>	<u>Bahasa Inggeris</u>
Penyelenggaraan Producttif Menyeluruh	Total Productive Maintenance (TPM)
Maintenance	Penyelenggaraan
Industri Proses	Processing Industries

- 5) **Output Dan Faedah Projek**
Output and Benefits of Project

- (a) * Penerbitan (termasuk laporan/kertas seminar)
Publications (including reports/seminar papers)
(Sila nyatakan jenis, tajuk, pengarang, tahun terbitan dan di mana telah diterbitkan/dibentangkan).
(Kindly state each type, title, author/editor, publication year and journal/s containing publication)

The output of this research is the development of the decision model for the maintenance analysis in order to analyse the failure data of non-repairable component by considering the external factors.

This model can be used as a decision making tool to determine more accurate time for carrying out the Preventive Maintenance (PM). Therefore, the benefits from PM strategy can be maximised.

Publications

1. Implementation of dust control system using management and planning tools (MPT) – A case study, (2006), Management of Environmental Quality: An International Journal, Vol. 17, No. 4, pp. 390-408.
2. An investigation on the impact of dust particles on machine's component failure, (2006), Six Mechanical Engineering Research Colloquium, School of Mechanical Engineering, 11&12 July.
3. The characteristics of dust particles emitted from the processing industries and their physical impact on machine components: A review, (2005), International Conference on Recent Advances in Mechanical & Materials Engineering (ICRAMME, 05), Kuala Lumpur, 30&31 May.
4. Development of a framework for the relationship of machine's performance and the impact of dust pollution, (2005), International Conference on Recent Advances in Mechanical & Materials Engineering (ICRAMME, 05), Kuala Lumpur, 30&31 May.
5. The impact of dust particles on machine's reliability and preventive maintenance time, (2005), International Advanced Technology Congress (ATCi), Conference on Computer Integrated System, Putrajaya, 6-8 Dec.
6. The effect of repair and replacement time for the machine's component exposed to dust particles, (2005), International Advanced Technology Congress (ATCi), Conference on Computer Integrated System, Putrajaya, 6-8 Dec.

7. Analysis of failure data from machines production line – Case study in automotive industry, (2006), International Conference on Science & Technology: Application in Industry & Education (ICSTIE, 06), Universiti Teknologi MARA Pulau Pinang, 8&9 Dec.
8. Maximum machines availability via inspection policy - Case study in automotive industry, (2006), International Conference on Science & Technology: Application in Industry & Education (ICSTIE, 06), Universiti Teknologi MARA Pulau Pinang, 8&9 Dec.

(b) **Faedah-Faedah Lain Seperti Perkembangan Produk, Prospek Komersialisasi Dan Pendaftaran Paten atau impak kepada dasar dan masyarakat.**
Other benefits such as product development, product commercialisation/patent registration or impact on source and society

A research collaboration between School of Mechanical Engineering and Nibong Tebal Paper Mill (NTPM), Nibong Tebal, Pulau Pinang was initiated.

This collaboration has benefit both USM and NTPM Sdn. Bhd. itself, where all the verification and validation of the developed algorithm was carried out at the company. This eventually provide a real case study data which is useful for reference and publication either nationally or internationally. This collaboration has given more opportunity to the researchers to explore more research area and also has resulted in joint application of E-science grant from MOSTI.

- * Sila berikan salinan
- * Kindly provide copies

(c) **Latihan Gunatenaga Manusia**
Training in Human Resources

- i) Pelajar Siswazah :
Postgraduate students:
(perincikan nama, ijazah dan status)
(Provide names, degrees and status)

Rosmaini Bin Ahmad, MSc Research, Waiting for Viva

Title: Development of Decision Model on Maintenance Analysis on Non-Repairable Components by Considering External Factors.

- ii) Pelajar Prasiswazah :
Undergraduate students:
(Nyatakan bilangan)
(Provide number)

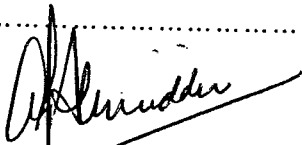
1. Tan Kok Siong, Understanding and Analysing The Impact Of Inspection Policy In Term Of Preventive Maintenance Using Simulation
2. Mimi Suliana Bt Endut, World Class Maintenance; Development of a Framework for Total Productive Maintenance (TPM) Based on Human Factor
3. Mohd Faizal World Class Maintenance: Understanding The Human Variability And Development Of A Framework For Total Productive Maintenance (TPM) Relating To Human Factor

None

None

KOMEN JAWATANKUASA PENYELIDIKAN PUSAT PENGAJIAN
Comments of the Research Committees of Schools/Centres

The project completed in the topic
concern with industrial collaboration is
commendable to the research team.



TAMBATANGAN PENERUSI
JAWATANKUASA PENYELIDIKAN PUSAT PENGAJIAN
Signature of Chairman
[Research Committee of School/Centre]

22/3/07

TARIKH
Date

Attachment 1: Technical Report

TECHNICAL REPORT

Objective

The general objective of this research is to apply the Preventive Maintenance (PM) strategy for solving machine breakdown problems. The specific objectives of this research are as below;

1. Develop a decision model for the maintenance analysis to analyse the failure data of non-repairable component by considering the external factors.
2. Identify the critical component (non-repairable component) that causes major machine breakdown using Pareto Analysis (PA).
3. Identify, classify and clarify the physical failure of non-repairable component using Failure Mode Effect and Criticality Analysis (FMECA) techniques.
4. Codify and measure the effects of the external factor (covariate) on component failure time by carrying out the Covariate Analysis (CA) based on Proportional Hazard Model (PHM).
5. Determine the accurate time of Preventive Replacement (PR) using maintenance optimisation model based on results from previous objective.

Methodology

Decision model development

The structure of the decision model consists of four phase analyses (see Figure 1). First phase is Pareto Analysis (PA) that used to identify the critical component that cause high machine breakdown. Second phase is Physical Failure Analysis (PFA) by using Failure Mode Effect and Criticality Analysis (FMECA) technique, which is applied to identify the physical characteristics (failure mechanism) of the component failure such as failure mode, failure cause, failure effect and criticality index of failure mode. Third phase is Covariate Analysis (CA), which for estimate the effects of external factor (covariate) that influencing on the component failure. Fourth phase is Preventive Maintenance (PM) modelling by using PM optimisation model in order to determine the PM time based on the result of the second and third phases.

PA is the first phase of the decision model which is applied in order to identify the highest machines breakdown due to the unplanned maintenance (component failure) in the production line. It follows by identification of the critical component that causes the highest machine breakdown. Then, this critical component is used as the analysis subject for next analysis of the decision model. Second phase of the decision model is Physical Failure Analysis (PFA) by using Failure Mode Effect and Criticality Analysis (FMECA) technique. The application of FMECA is focused on failure mode identification, failure causes (external factor or covariate) identification and the calculation of the criticality index of each failure mode. CA is the third phase analysis of the decision model. CA is performed using Proportional hazard model (PHM), which is a regression type model. The output of the CA is the value of covariates parameters that effects on the based line hazard rate function. The PM modelling is the last phase of the decision model. The main objective of PM modelling is to determine the PM time using PM optimisation model based on previous analysis. PM modelling consists of failure time process tests, fitting the failure time distribution and the calculation of PM time.

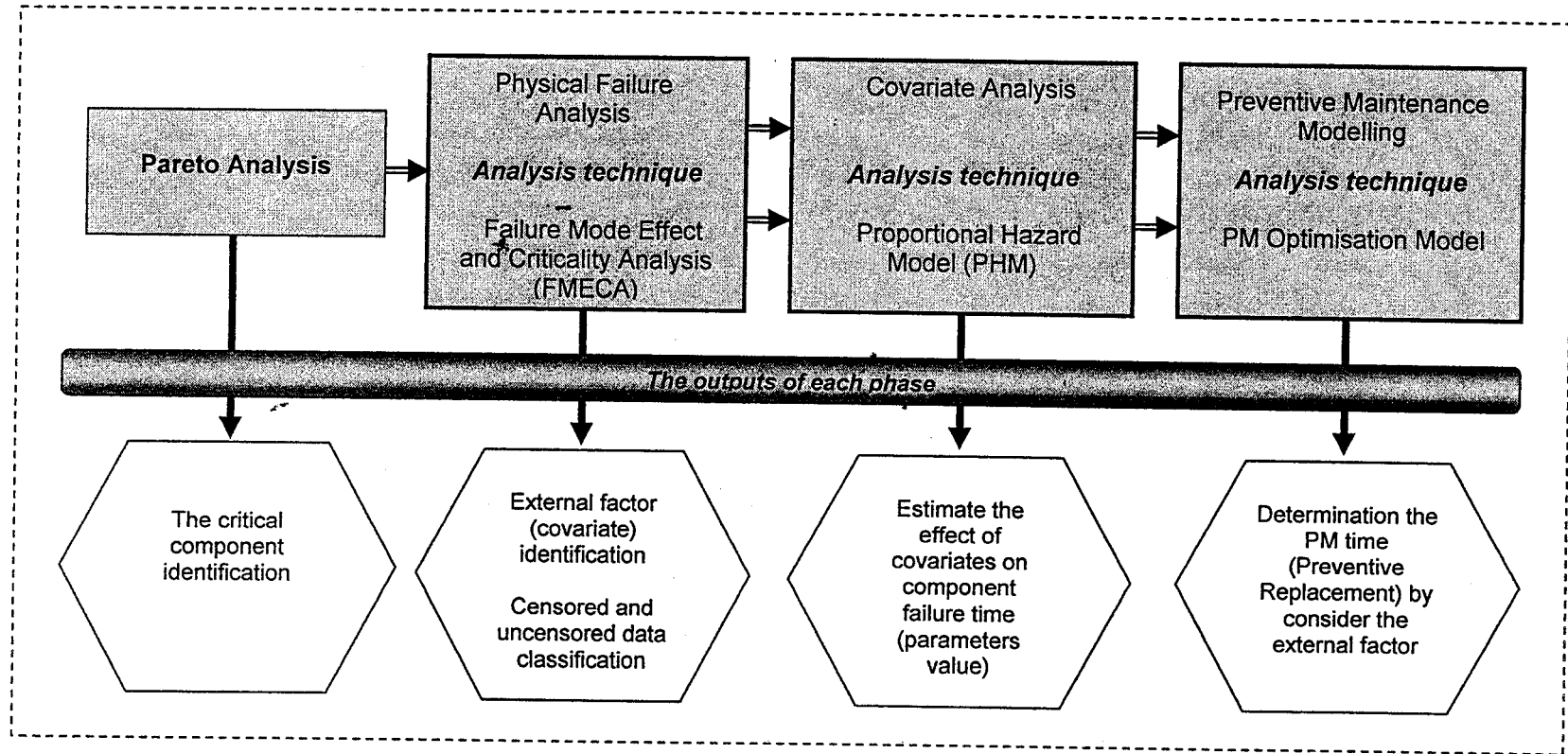


Figure 1: The general structure of the decision model

Result and Analysis

Decision model validation

PA is the first analysis of the decision model. The highest rate of machine breakdown is recorded on machine Log saw 5. The result indicates that 91% of the breakdown rate of this machine is due to the cutting blade and transmission belt failure. The second analysis of the decision model is PFA by using FMECA technique. From PFA, the censored & uncensored data based on criticality index calculation and external factor (covariate) were classified and identified. CA is the third analysis of the decision model. It is estimated the covariates parameters influencing to components failure (cutting blade and transmission belt). The final analysis of the decision model is PM modelling. From PM modelling, the PM time based on PR strategy was determined. The optimal PR time with and without covariates effects were compared. The result shows the PR time is more accurate when the covariates are considered in the PR time calculation.

Financial Statement

DR SHAHRUL KAMARUDDIN

304.PMEKANIK.6035138

JABATAN BENDAHARI
UNIT KUMPULAN WANG AMANAH
UNIVERSITI SAINS MALAYSIA
KAMPUS KEJURUTERAAN
SERI AMPANGAN
PENYATA KUMPULAN WANG

TEMPOH BERAKHIR 21/03/2007

STUDY ON THE IMPACT OF DUST PARTICLES TOWARD PLANETARY BALL MILLING MACHINE

JUMLAH GERAN :-

NO PROJEK :-

PANEL :- J/PENDEK

PENAJA :-

Tempoh Projek:15/03/2005 - 14/03/2007

<u>Vot</u>	Peruntukan (a)	Perbelanjaan sehingga 31/12/2006 (b)	Tanggungan semasa 2006 (c)	perbelanjaan Semasa 2007 (d)	Jumlah Perbelanjaan 2007 (c + d)	Jumlah perbelanjaan Terkumpul (b+c+d)	Baki Peruntukan Semasa (a-(b+c+d))
11000 GAJI KAKITANGAN AWAM	7,552.70	13,507.17	0.00	0.00	0.00	13,507.17	(5,954.47)
21000 PERBELANJAAN PERJALANAN DAN SARA	2,900.00	2,483.00	264.00	0.00	264.00	2,747.00	153.00
22000 PENGANGKUTAN BARANG	400.00	0.00	0.00	0.00	0.00	0.00	400.00
23000 PERHUBUNGAN DAN UTILITI	700.00	125.35	0.00	0.00	0.00	125.35	574.65
24000 SEWAAN	800.00	0.00	0.00	0.00	0.00	0.00	800.00
26000 BAHAN MENTAH & BAHAN UNTUK PENYEL	3,400.00	0.00	0.00	0.00	0.00	0.00	3,400.00
27000 BEKALAN DAN ALAT PAKAI HABIS	1,486.65	120.00	0.00	347.00	347.00	467.00	1,019.65
28000 PENYELENGGARAAN & PEMBAIKAN KECIL	277.30	0.00	0.00	0.00	0.00	0.00	277.30
29000 PERKHIDMATAN IKTISAS & HOSPITALITI	2,200.00	2,827.60	0.00	0.00	0.00	2,827.60	(627.60)
	19,716.65	19,063.12	264.00	347.00	611.00	19,674.12	42.53
Jumlah Besar	19,716.65	19,063.12	264.00	347.00	611.00	19,674.12	42.53

List of Publications



Implementation of dust control system using management and planning tools (MPT)

A case study

Rosmaini Ahmad and Shahrul Kamaruddin

School of Mechanical Engineering, Universiti Sains Malaysia, Pulau Pinang, Malaysia

Zahid A. Khan

Faculty of Engineering and Technology, Department of Mechanical Engineering, New Delhi, India, and

Mohzani Mokhtar and Indra Putra Almanar

School of Mechanical Engineering, Universiti Sains Malaysia, Pulau Pinang, Malaysia

Abstract

Purpose – To introduce a research carried out in a real world for implementing a dust control system (DCS) for controlling the indoor air quality (IAP) on the production floor of one of the major electronics company in Malaysia.

Design/methodology/approach – The paper is arranged as follows, a brief description of the significant of DCS in electronic industry and brief introduction to the electronic company as a case study company for introducing the DCS. The discussion on the characteristics management and planning tools (MPTs) that have been adopted as the analysing tools for assisting in the decision-making process in identifying the problems and improvement strategies. It follows by the detail analysis phase regarding the implementation process that it as backbone for introducing the DCS. Finally a discussion about the result obtained from the MPT analysis on the techniques for identifying the root causes of the dust pollution problem as well as the best improvement strategies that can be adopted by the case study company.

Findings – Three analysis techniques from MPT have been used; there are relation diagram, tree diagram and prioritization matrices analyses. These techniques are very powerful for analysing the specific problem using verbal data. The outputs (results) from these techniques have been used as the solutions to the dust pollution problem. As a result, the implementations of DCS successfully reduce the dust level and stabilise the dust distribution on the production floor.

Practical implications – This paper offer a systematic way in identifying and controlling the IAP in industry.

Originality/value – This paper introduces very useful methods in decision making for identifying the solutions for environmental problem and implementation of DCS in a real world environment.

Keywords Air pollution, Environmental management, Control systems, Shopfloor, Electronics industry, Malaysia

Paper type Case study



Introduction

Indoor air pollution (IAP) is defined as an indication of how air satisfies the thermal comfort, normal concentration of respiratory gases and acceptable limits of air pollutants (Woods, 1986). This is an issue that has been discussed for decades. Focusing on the industrial sector, IAP is becoming increasingly important issue for various reasons (Wypych *et al.*, 2005) such as:

- deterioration of performance of processing equipments;
- increase of the maintenance and clean-up cost;
- increase the respiration diseases cases; and
- societies are becoming more environmentally conscious.

The main contributor of IAP can be identified on the basis of the following five factors:

- (1) poor ventilation system;
- (2) workers activities;
- (3) people personalities (cloth, shoes and hair);
- (4) product (powder and fibre); and
- (5) processing methods (heating, grinding, sawing, and crushing).

The processing industries such as cement, wood, metal, agricultural-based and ceramic processing are the examples of industries that need to deal with severe IAP problems (Junker *et al.*, 2000). Their physical products (powder and fibre) and processing methods (grinding, crushing and milling) are the main factors that contribute to the IAP. In addition, outdoor air pollution is also contributing to the IAP (Maroni *et al.*, 1995). Poor ventilation system and workers activities become the medium of transferring the contaminant into the work place (production floor).

In order to reduce the impact of IAP in the workplace, researchers have identified and proposed various solutions and techniques. Bapat (2001) presented the application of electrostatic precipitators (ESP) for gas cleaning in cement industry for controlling the cement dust. Hindy (1997) also concluded that the application of ESP technique is very effective to control the cement dust. Nowadays, it has been the predominant choice in the cement industry for controlling the point-of-source emissions. Wypych *et al.* (2005) presented their results of quantifying and modelling of dust generation and air entrainment mechanisms that occur during free-falling streams of material in the material processing industries. Emphasis is placed on the effects of drop height and product temperature, where the results obtained from their investigation are imperative for the efficient design and operation of dust control systems (DCS). Lee (1999) carried out research on controlling the emission stemming from the hot air solder levelling process. Diffusion type fibre bed filters are the main equipment for controlling emission process which was found to be the optimal choice for the removal of oil mist (emission). A case study of an aluminium extrusion factory was carried out by Lyu *et al.* (1996) and their results showed how analysis of covariance (ANACOVA) model can be used by managers to identify pollution sources effectively. Wills and Jones (1996) in their paper discussed the pollution control design in continuous improvement. They explained the concept of the best practicable environmental option and the best available techniques that do not involve excessive cost. They also

discussed the way in which the regime attempts to control pollution in terms of the authorisation and variation process and through their enforcement.

As far as electronic industries are concerned, there are limited researches that have been carried out focusing on the IAP problems. There is a need to analyse the effectiveness of DCS used in electronic industries focusing on IAP. In this paper a case study is carried out where a DCS is used in one of the leading electronics industry in Penang, Malaysia. The powerful management and planning tools (MPTs) have been adopted as the analysing tools for assisting in the decision-making process in identifying the problems and suggesting the best improvement strategies.

The significance of DCS in an electronic industry

DCS is essential for controlling the IAP in the electronics industries on the basis of three main reasons:

- (1) controlling the quality of products (i.e. electronic components);
- (2) maintaining the performances of machines; and
- (3) avoid the effects on worker's health.

In term of products, dust pollution can affect their performances (reliability) and quality. Electronic products (components) such as integrated circuit (IC), capacitors, transistor, resistor and voltage regulator are sensitive with uncontrolled dust environment. Oyebisi (2000) reported that the dust and particulates (spore and fungus) can have an affect on the performances of these electronic components. He reported that when a ceramic capacitor was enclosed in a fungous environment, the percentage change in the capacitance value was up to 167.75. Sandroff and Burnett (1992) investigated the impact of hygroscopic dust on circuit boards reliability. Hygroscopic dust is believed to increase the risk of electrical overstress and the formation of leakage or "sneak" current paths. They reported that hygroscopic dust consisting of fine particulates with an average diameter of $0.5\mu\text{m}$ cannot be effectively removed by conventional filtration techniques.

In relation to machines, various machines are used to produce the electronic products or components. The machines themselves consist of many sophisticated components or parts that are sensitive to the dust particles. As an example, surface mount technology (SMT) machines such as chip placer, multi function mounter and high speed chip shooter are sensitive to dust pollution. Consequently, it reduces the performances of the machines for producing a quality product and also results in the increase of cost for maintaining the machines. The investigation by Hata *et al.* (2000) represented the functional relations among mechanical components and evaluated a possibility to apply it for failure analysis. Their results showed that the dust particles affected the function (performance) of the components such as roller, ball bearing and sensor.

The workers also have the risk from the air pollution, particularly when they are working continuously in uncontrolled dust pollution environment. They will be exposed to the critical diseases such as skin or lung cancer, asthma and eye problems (cataracts and pterygia) (Bascom *et al.*, 1995). As a result from these ailments, productivity of the workers will be reduced and treatment cost will escalate (Niemela *et al.*, 2002).

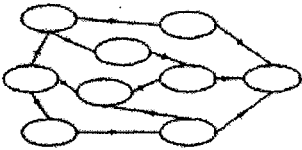
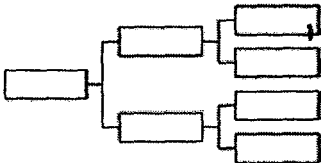
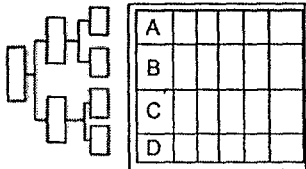
Therefore, there is a need to have an effective and efficient DCS for controlling the IAP especially on the production floor.

The management and planning tools

The MPTs are used to analyse the verbal data (Mizuno, 1988). These tools consist of affinity diagram, arrow diagram, relations diagram, tree diagram, matrix diagram, matrix data-analysis (prioritization matrices) and process decision program chart. However, in this paper relation diagram, tree diagram and prioritization matrices have been selected as MPTs for carrying out the analysis and providing a decision-making process for introducing the DCS in the case study of a company considered. The above three techniques are shown in Figure 1.

The purpose of applying MPTs is to convert apparent chaos into a workable, implement able action plan (Stockley, 1995). The tools thus provide a systematic approach to mainstream managers requiring the conversion of raw creativity into real change. MPTs can become very powerful by combining them into a cycle of activity in which the output of one technique becomes an input into the next technique (Ronald, 1995).

The primary purpose of the relation diagram technique is the identification of the complex causal interrelationships that may exist in a given situation (Mizuno, 1988). This technique presumes that there are many possible causes and effects surrounding a given "problem". In this case study, relation diagram is the starting technique that focuses for identifying the main sources/causes of dust pollution on

Management and Planning Tools Design	Description
	Relationship diagram: This tool takes complex, multivariable problems or desired outcomes and explores and displays all the interrelated factors involved. It graphically shows the logical relationships between factors
	Tree diagram: This tool systematically maps out in increasing detail the full range of paths and tasks that need to be accomplished in order to achieve a primary goal and every related sub-goal. Graphically, it resembles an organization chart or family tree
	Prioritization matrices: These tools take tasks, issues or possible actions and prioritize them based on known, weighted criteria. They utilize a combination of tree and matrix techniques, thus narrowing down options to those that are the most desirable or effective result

Source: Brassard (1999)

Figure 1.
MPTs design and their
description

the production floor. The objective is to elicit the possible causes of the problem from those who are familiar with it. Accordingly, the output (result) of this analysis can identify the main sources/causes that contribute to the dust pollution.

Tree diagram is the second technique used for identifying the best strategies in reducing the dust pollution problem. The tree diagram is designed to sequence the cause-effect relationships, or to identify means-end relationships. The result (output) from previous analysis (relation diagram) becomes the input (starting point) of this technique. The objective outcome in both of these techniques is to arrive at detailed, actionable items (Reynolds and Gutman, 1988). In the tree diagram there are two diagrams that can be used for analysis which are problem-focused diagrams where ideas are organized linearly based upon the causal relationships between the items (e.g. *b* causes *a*, and *c* causes *b*) and objective-focused diagrams where actions are linearly organized from the overall objective on the left side of the page, to the smallest actionable details on the right (e.g. *b* is the means to achieve *a*, and *c* is the means to achieve *b*, etc.). In the present case study considered, objective-focused diagram is used.

The final technique used is the prioritization matrices. Prioritization matrices (also known as weighted matrix) is the tool that prioritises options, information, ideas or tasks based on weighted criteria. It utilises a combination of tree diagram and matrix techniques, thus narrowing down options to those that are the most desirable or effective result (Brassard, 1989). In the case study considered, detailed information (improvement strategies) that is obtained from the tree diagram will be the important parameters for determining which options are responsible for implementing the improvement strategies.

Case study

A case study of one of the electronics industries in Penang, Malaysia is considered for the analysis. It is a multinational company employing around 600 workers in various positions from human resource to production. The company produces electronic components for the lighting products that are mostly used by original equipment manufacturer sector such as automotive, communication and computer industries. The production floor is the main area where major activities and processes are carried out by workers and machines. The production of the electronic components in the company involve different stages of processing such as wafer processing, board printing, components assembly and testing. Various sophisticated machines are used in producing the electronic components, e.g. wafer sawing machine, wafer recognition wire bonder machine, SMT machine, multi-function moulder and reflow oven checker in order to achieve the quality and volume demanded by customers.

Production layout

The company consists of nine sub-area of production floor that is marked as D1, D2, D3, D4, D5, D6, D7, D8 and D9 as shown in Figure 2. This figure also shows the arrangement of the machines and operators for each sub-area. The production floor of the company can be divided into two types: open and close area. The sub-area D1, D2, D3, D4, D5 and D6 are identified as open area and D7, D8 and D9 are identified as the close area.

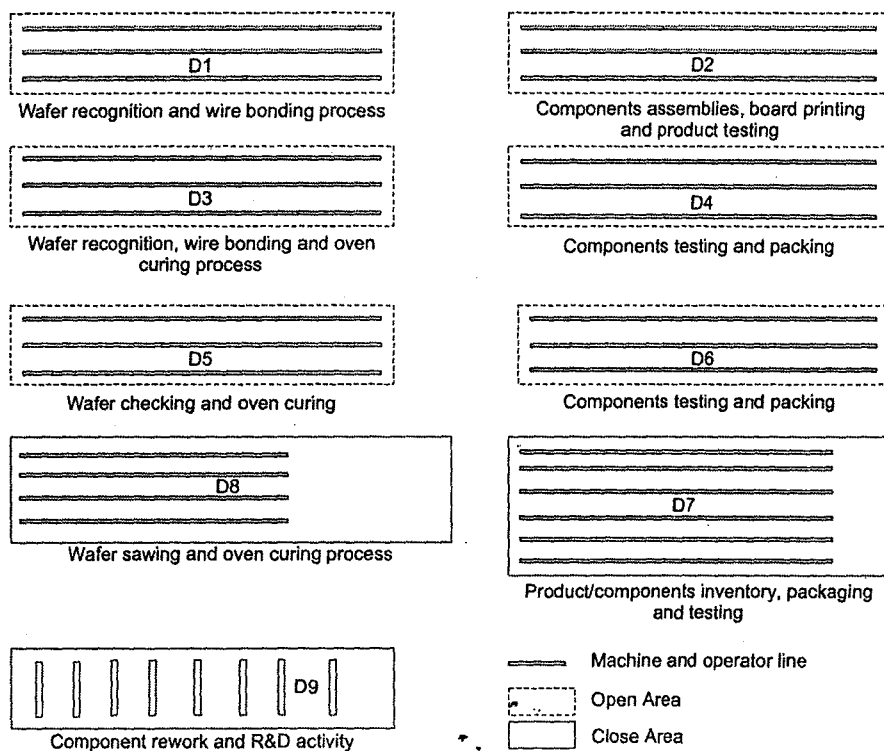


Figure 2.
Sub-areas in the
production floor

Each sub-area is separated according to the stages of the production processes. Referring to Figure 2, processes such as wafer sawing, oven curing, component reworking, R&D activity, product/components inventory, packaging and testing are located in close area (D7, D8 and D9) mainly due to safety reasons. Other processes are operating at open area because of the high volume of products produced which required vast material handling and workers movement as shown in Figure 2.

Company's dust control system

In relation to the IAP, the company currently is facing a problem with the dust pollution that occurs on the production floor. The dust measurement data recorded by the company personnel has shown that the dust distribution on production floor is unstable and the level of dust pollution is also inconsistent. Most of the areas on the production floor have recorded a dust level more than 30,000 ppm with the maximum reading as 96,200 ppm. The recorded data shows that the dust pollution on production floor is very high. As discussed earlier the dust particles can affect the quality of the product, performances of the machines and worker's health. Effects on product and machines' performance will be the serious problem to the company because it will involve the big amount of rework/reject and an increase in the maintenance cost. In order to reduce the impact of the dust pollution, effective DCS on the production floor is seen as the best strategy for controlling the dust pollution by the company management.

The DCS that is introduced on the production floor is based on the analysis method that is designed and developed by the authors and engineers from the company. The analysis method consists of three phases. The initial phase is primarily focussed on identifying the dust problem on production floor. It identifies the level and distribution of dust particles. The second phase is the detailed analysis of dust particle problem on production floor by using MPTs. In this phase, the possible sources and causes of dust pollution are identified. As a result the best and effective solution can be determined. The final phase is the evaluation analysis that is focussed on evaluating the effectiveness of the solutions that are determined in the second phase. Figure 3 shows the three phases introduced in the DCS for the case study of the company considered. The details of the phases implemented in the DCS are now discussed below:

Phase 1

Phase 1 is a starting point before a DCS can be introduced. The main objective for this phase is focussed on finding out the severity of the dust pollution problem on the production floor. The initial analysis based on data collection is started by determining the dust counting point for each sub-area on the production floor. This is accomplished by having the information regarding the level and distribution of dust particles for each sub-area on the production floor. Counting point for each sub-area need to be identified before any dust reading can be taken and collected. The collected data (dust reading) is analysed using statistical methods as discussed below to understand the severity of dust level and distribution of dust particles for each sub-area.

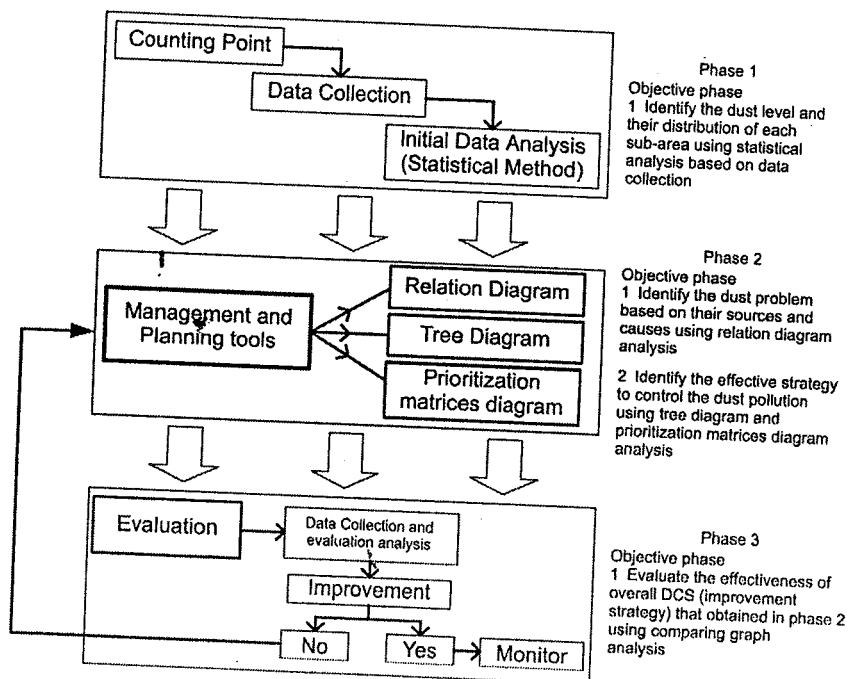


Figure 3.
Phases for introducing the
DCS in the case study
company

Identifying the dust counting point

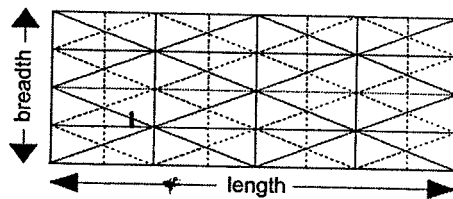
The analysis method will start by identifying the dust counting point for each sub-area on the production floor. The main objective at this stage is to identify the best reading of dust level depending on the space and number of workers of each sub-area. It is determined by using the following equation:

$$C_p^o = \frac{(S)}{S_T + S} P_T \frac{1}{O_p} \quad (1)$$

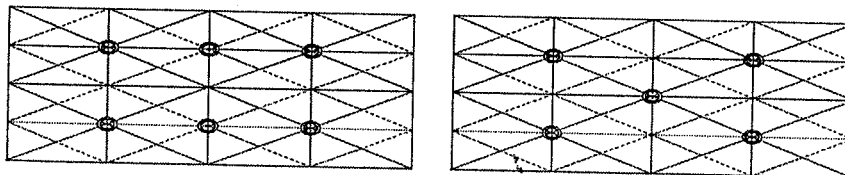
$$C_p^c = \frac{S}{O_p} \quad (2)$$

Where C_p^o , Counting point for open sub-area; C_p^c , Counting point for close sub-area; S , Sub-area spacious (m^2); S_T , Total sub-area spacious (m^2), for close sub-area; P_T , Production floor spacious (m^2); O_p , Total number of workers (normal situation), $O_p > 1$.

The counting points for each sub-area were identified using equations (1) and (2). For open sub-area (D1, D2, D3, D4, D5 and D6) five counting points are required and for close sub-area (D7, D8 and D9) six counting points are needed. The positions of the counting points are based on the gridlines design as shown in Figure 4a. The counting point is positioned at the cross line of the gridlines designed and it is based on the number of counting that has been determined. For example, the five and six counting positions for open sub-area (D1, D2, D3, D4, D5 and D6) and close sub-area (D7, D8 and D9) are shown in Figure 4b. Figure 5 shows the overall position of dust counting point in each sub-area (including open and close areas) on the production floor of the case study of the company considered.



(a) The gridline design for location of dust counting point

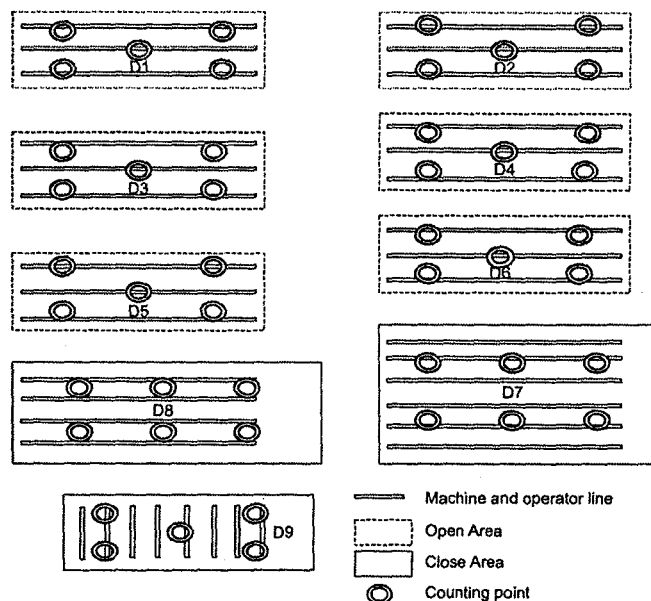


○ = Counting point

(b) Example of location for five and six counting point

Figure 4.

Figure 5.
The position of dust
counting point for overall
sub-area on production
floor of the case study
company



Initial data collection

Laser particles counter, model 227B is used in carrying out the dust counting processes. The objective of the initial data collection is to understand the dust pollution problems that occur on the production floor. The dust reading for a period of three months is collected in order to have a clear idea regarding the level and distribution of the dust pollution on each of the sub-area of the production floor. The size of dust particles considered is $0.5\mu\text{m}$ with an air flow in cfm (cubic feet per minute). Particulates of this size ($0.5\mu\text{m}$) usually cannot be effectively removed from the production area by conventional filtration techniques (Sinclair *et al.*, 1988).

In order to ensure the accuracy of the data collected, a proper procedure need to be put in place. This includes in identifying the best point in time for carrying out the dust counting process since the company of the case study is operating 24 h with three shifts and seven days a week. It has been fixed that for every particle reading process, it will start from one sub-area to other sub-area until all sub-areas are completed. Every dust reading process will be carried out consistently on the same day and time for every week for three months duration. It has been decided that particle reading process will be carried out once a week from 3 to 5 p.m. on every Thursday. This is due to the continuous working hour by operator as there will be no break in between the hour. In addition Thursday is selected because the production line has been operated for few days where the impact of dust particle starts to maximise.

The reading of dust particles will be taken for each counting points that have been determined in previous section. It means that, if a sub-area has six counting points then it will have six values and its mean (average) value can be easily calculated. The weekly mean (average) value can then be found out. One can then determine the mean monthly value. The calculation of weekly and monthly values can be determined as:

$$W_v = \frac{CP1 + CP2 + CP3 + CP4 + CP5}{5} \quad (\text{for five counting point}) \quad (3)$$

$$M_v = \frac{W_v1 + W_v2 + W_v3 + W_v4}{4} \quad (4)$$

Where CP, counting point; CPN, counting point ($N = 1, 2 \dots N$); W_v , weekly value; W_vN , weekly value ($N = 1, 2, 3, 4$); M_v , monthly value.

Data analysis

The data gathered and recorded for a period of three months is plotted in the form of a graph to observe the level and distribution of dust for each sub-area on the production floor. Figure 6 shows such a plot for the dust level and their distribution for different sub-areas for July, August and September.

It is evident from Figure 6 that the dust level and its distribution for most sub-areas is maximum for the month of September. Further, in this month the highest dust level is recorded at location D8 (59,060 ppm). For July, the dust level recorded is minimum and its maximum value is found to be at location D7 (33,885 ppm). In order to make a comparison during the evaluation phase, the overall range value (R_{ov}) is noted. The overall range for the initial data collection for Phase 1 is the difference between the maximum dust level (at D8) and the minimum dust level (at D4), which is 49,207 ppm.

The pattern of dust distribution in Figure 6 is also important to be examined. The dust distribution pattern for the close sub-areas (D7, D8 and D9) is different from that for open sub-areas (D1, D2, D3, D4, D5 and D6) for all the three months considered. The differences can be expressed by their range values. In the close sub-area, the maximum reading of dust level is at D8 (59,060 ppm, in the month of September) and its minimum is at D9 (26,678 ppm, in the month of July). Therefore, the range value, R_c for the close sub-areas is 32,382 ppm. For the open sub-area, the corresponding maximum and

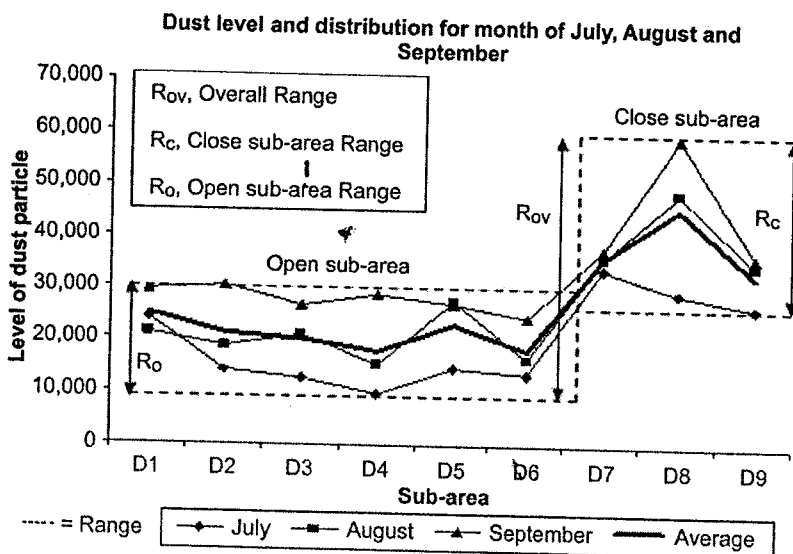


Figure 6.
Dust level and their
distribution in the month
of July, August and
September

minimum values are at D2 (30,504 ppm, in the month of September) and at D4 (9,853, in the month of July), respectively, and their range value, R_o is 20,651 ppm. The difference between the range values (variance) of both sub-areas (open and close), R_c is 11,731 ppm. This value will be used as a reference value in the evaluation phase (Phase 3).

From the analysis carried out on the basis of the data collected, it is observed that there are unbalanced distribution of dust particles between open and close sub-areas and high range of dust particles readings are found for overall sub-areas. It seems that the improvement actions must focus on the close sub-area because of the high level of dust particles. There are two problems that need to be solved; high level of dust pollution (shown by R_{ov} value) and unbalance of dust distribution (shown by R_{c-o} value). Therefore, the improvement strategies (actions) that need to be determined in Phase 2 must focus on these two problems.

Phase 2

The MPT are used to identify the root causes/sources of dust particles problems on the production floor. As a result, effective improvement strategies can be identified as a solution for reducing and controlling the dust problems. The improvement strategies are implemented for reducing the values R_{c-o} (difference of range for open and close sub-areas) and R_{ov} (overall range for sub-areas). Therefore, R_{c-o} and R_{ov} will be the important parameters for comparing the improvement achieved when the improvement strategies are implemented.

As mentioned earlier, the analysis techniques that are chosen for this phase are relation diagram, tree diagram and prioritization matrices. These techniques involve a group work activity to ensure that effective results are achieved. Generally, the analyses from these techniques are related to each other. It means that the output (result) from the first technique will be the input for the following technique. Each of these techniques as applied to the present case study is discussed in detail in the following section.

Relation diagram

The relation diagram is started by conducting brainstorming sessions to identify the sources/causes of the dust pollution problems on the production floor. A group consisting of five to six persons are involved in the sessions. During the brainstorming sessions, the group must come out with as many as possible sources/causes that contribute to the dust pollution problems on the production floor. The ideas are based on various main contributors to the IAP such as the air flow, worker activities, maintenance activities, machines and processes. These contributors are the starting point to find out the possible sources/causes of the problem. For example, unsystematic maintenance activities contribute to the air pollution through ventilation system. Sources/causes identified from the brainstorming activities are used to develop the relation diagram. The overall trend of relationship among the sources/causes of dust pollution is shown in Figure 7. In the relation diagram (Figure 7), if the arrow points from A to B it means that source/cause A contributes to the source/cause B. The result from this analysis is used to identify the most contributors of dust pollution with known sources/causes. The main contributors identified during the relation diagram are ventilation, activity, product, process and people as shown in Figure 7.

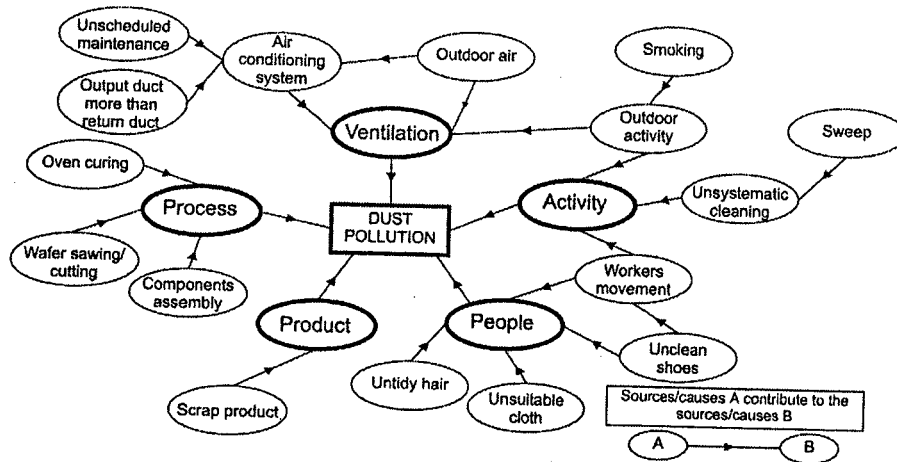


Figure 7.
The relation diagram
analysis of dust pollution
problem

However, to get a clearer picture of the trend and the relationship of the sources/causes, further analysis is required in order to measure the relationship rating among the sources/causes of dust pollution. The concept of this analysis is based on the number of relationship between one source/cause to other sources/causes. From this analysis, the percentage value of each contributor (ventilation system, activities, people, product and process) is evaluated.

For example, unscheduled maintenance, output duct and return duct, air conditioning system and outdoor air and outdoor activity are the main contributors of the ventilation. Therefore, the total relation value of ventilation is five. Each factor listed previously contributes one relation value that makes up to five. From the relationship values the percentage of each main contributor is evaluated. Table I shows the percentage of each main contributor that contributes to the dust pollution problem: ventilation (26.3 per cent), activity (31.6 per cent), people (21.1 per cent), product (5.3 per cent) and process (15.8 per cent).

The value gained from the above analysis will be significant information for finding out the solutions for the next analysis. In order to identify the best improvement strategies for reducing and stabilizing the level and distribution of dust pollution, decision is made to focus on those contributors that contribute 15 per cent and above only to the dust pollution. As a result, activity, ventilation, people and process are the main inputs for the next analysis, i.e. tree diagram.

Tree diagram

As mentioned earlier, the main objective of tree diagram analysis is to identify the efficient improvement strategies to reduce and stabilize the level and distribution of dust pollution. From the previous analysis of the relation diagram, four main contributors that contribute to the dust problem on the production floor were identified. These four contributors will be the starting point for the tree diagram analysis. On the basis of the contributor's factors that have been identified, group members are encouraged to give solution or improvement strategy that can be used to reduce or control the dust pollution problem. Objective-focused tree diagram is used for the

Table I.
The relationship analysis
extended from relation
diagram result

Ventilation	Relation value	Activity	Relation value	People	Relation value	Product	Relation value	Process	Relation value
Unscheduled maintenapce	1	Outdoor activity	1	Unclean shoes	1	Scrap product	1	Components assembly	1
Output duct and return duct	1	Smoking	1	Un-suitable cloth	1			Wafer sawing	1
Air conditioning system	1	Un-systematic cleaning	1	Untidy hair	1			Oven curing	1
Outdoor air	1	Workers movement	1	Workers movement	1				
Outdoor activity	1	Unclean shoes	1						
		Sweep activity	1						
Total value	5		6		4		1		3
Percentage	26.3		31.6		21.1		5.3		15.8

analysis where actions are linearly organized from the overall objective on the left side of the page, to the smallest actionable details on the right.

Figure 8 shows the details of the tree diagram analysis. It consists of four levels of objective (A, B, C and D), where objective A is the main objective and objectives B, C and D are detailed actions for achieving previous objectives. According to the analysis carried out the two main contributors, ventilation and activity have four main improvement strategies and eight detail actionable plans (objective D) as shown in Figure 8. For ventilation, the main improvement strategies are improving the maintenance of the air-conditioning system as well as its entrance system. In the case of activity the main improvement strategies are to use the cleaning system efficiently and reduce/limit the outdoor activities. Contributors such as people and process have one improvement strategy each and four detail actionable plans (objective D). For people, the improvement strategy identified includes the introduction of the personal protective equipment (PPE) whereas for process the improvement strategy is to confine the processing activity in close area.

On the basis of the tree diagram analysis (Figure 8), it can be summarised that six improvement strategies (objective C) and 12 detail improvement actions (objective D) have been identified as the solutions to reduce/control the dust pollution on the production floor for the case study under investigation. They are listed as under:

- Improve the maintenance system for the air conditioning system. It refers to the increase in the quality of maintenance activity and maintaining its systematic schedule.
- Improve the entrance system (door and window) where the entrance causes pollution to the production area. The best solutions are to up-grade the single entrance to the double entrance section and place a carpet at every entrance section, so that the workers can clean their shoes before entering the production area.

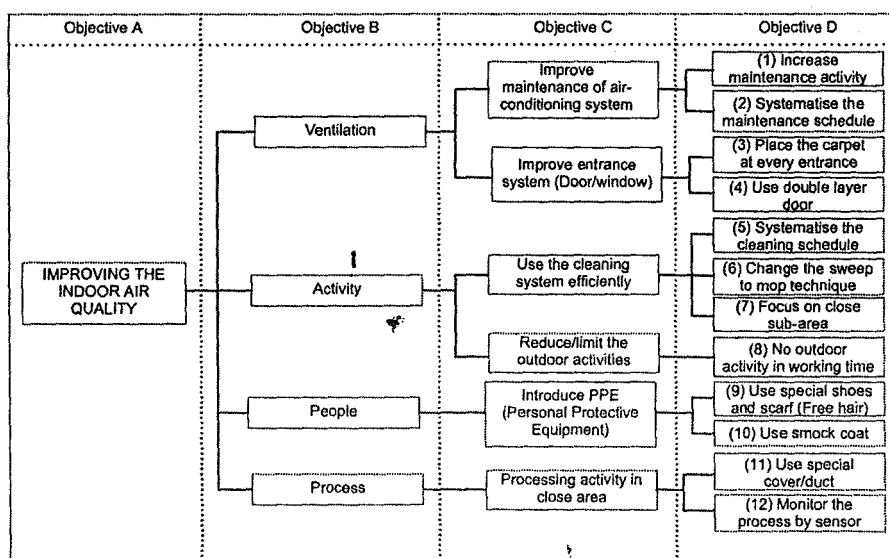


Figure 8. Tree diagram analysis to identify the detail improvement strategy to reduce or control the dust pollution

- Improve the available cleaning system to more efficient one with systematic cleaning schedule. The cleaning activity will be focussed on close sub-area (Figure 6). Change the sweeping using a broom to a mop in order to reduce the dust particle airborne into the air.
- Reduce/limit the outdoor activity during working hour by enforcing no outdoor activities during the working hour specially for the workers on production line.
- Introduce the PPE to the workers on the production line. The PPE consists of standard shoes, scarf and smock coat.
- Any processing method that contributes to the IAP must be operated in a close room.

However, before these improvement strategies are implemented the question that needs to be answered is "who are responsible for implementing the improvement strategies that have been identified?" Therefore, in order to identify the person responsible for implementing the improvement strategies, prioritization matrices are used, the details of which are given as under:

Prioritization matrices

Continuing from the tree diagram analysis, prioritization matrices are used to identify who are responsible to implement the improvement strategies that have been identified. As a starting point the person(s) who are capable of implementing the improvement strategies successfully and considered to be the first parameter (X-axis) are administration personnel, industrial engineer, safety engineer, maintenance engineer, maintenance technician and logistic supervisor.

The second parameter (Y-axis or vertical) is the six improvement strategies and 12 detailed actions derived from tree diagram analysis. Both parameters (X-axis and Y-axis) are correlated by weighting criteria. Three weighting criteria with different rating are used. The weighted criteria are first priority, second priority and keep inform with their ratings as nine, three and one. The relationship level between parameters X-axis and Y-axis is determined by the total number of weighted rating. The total number of weighted rating is then converted to the percentage value and this will be the reference for identifying the person or department that is responsible for the improvement actions. Figure 9 shows the detailed layout of prioritization matrices for the two parameters mentioned above.

The prioritization matrices as shown in Figure 9 shows that 23.1 per cent of improvement strategies responsibility goes to industrial engineer, 19.8 per cent goes to maintenance engineer and logistic supervisor, 14.9 per cent goes to safety engineer and maintenance technician and 7.4 per cent goes to administration personnel. Consequently, this result is the important information to manager for delegating the responsibility when implementing the improvement strategies on the production floor.

Phase 3

Phase 3 is the evaluation phase. The main task is to evaluate the effectiveness of overall improvement strategies implemented on the production floor for the case study of the company considered. Result from the data analysis in Phase 1 is compared with the results obtained at this phase in terms of the changes that occur on the level and distribution of dust particles for each sub-area.

Personnel Responsible		Administration Personnel	Industrial Engineer	Safety Engineer	Maintenance Engineer	Maintenance Technician	Logistic Supervisor
Improvement Plans							
Improve maintenance system	1				○	⊗	
	2				⊗		
Improve entrance system (Door/window)	3		⊗				○
	4		△				
Efficient the cleaning system	5		⊗				○
	6						⊗
Reduce/limit the outdoor activities	7						⊗
	8	⊗					
Introduce PPE (Personal Protective Equipment)	9			⊗			
	10			⊗			
Processing activity in close area	11		⊗		⊗		
	12				○	⊗	
Total ratings		9	28	18	24	18	24
Responsibility percentages		7.4%	23.1%	14.9%	19.8%	14.9%	19.8%
Typical Symbol	Ratings						
⊗ First Priority	9						
○ Second Priority	3						
△ Keep inform	1						

Figure 9.
Prioritization matrices for
the relationships between
improvement strategies
and responsibility ratings
of person or department

The evaluation of DCS

Once the improvement strategies and the responsible personnel have been identified, the strategies are implemented on the production floor of the case study of the company and the impact of the improvement strategies are discussed by comparing the level and distribution of dust pollution before and after implementing the improvement strategies. For this, the comparison is made between the value of R_{c-o} (difference of range value for close and open sub-area) and R_{ov} (overall range value for sub-areas) before and after the strategies are implemented. The evaluation process begins with data collection for a period of three months starting from October. Similar procedure as discussed for Phase 1 is followed for collecting and analysing the data. From the data collected a graph was plotted in order to determine the level and distribution of dust particles on the production floor. Figure 10 shows the overall trend of the dust level and distribution of dust particles at each sub-area on the production floor for October, November and December for the case study of the same company considered.

It is observed from Figure 10 that the maximum level of dust particles is 21,100 ppm in the close sub-area located at D8 from the data collected for December and its minimum value is 11,343 ppm found in the open sub-area and located at D3 from data collected for October. Focusing on the open sub-area the maximum reading is 19,046 ppm at location D5 corresponding to the data of December and the minimum reading is 11,343 ppm located at D3 for the month of October. As regards close sub-area, the maximum reading recorded is at location D8 (21,100 ppm) for December and the minimum reading is recorded at location D8 (13,100 ppm) for October. The overall range, R_{ov} of sub-area is 9,757 ppm (D8 (December) – D3 (October)). The value

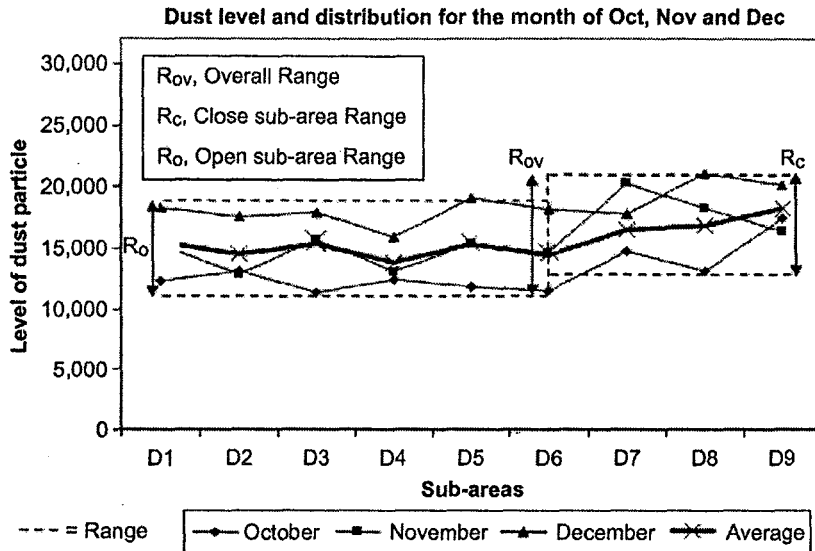


Figure 10.
Dust level and distribution
for the month of October,
November and December

for open sub-areas, R_o is 7,703 ppm (D5 (December) – D3 (October)) and for close sub-areas, R_c is 8,000 ppm (D8 (December) – D8 (October)). The difference (variance) of ranges of close and open sub-areas, R_{c-o} is 297 ppm.

Improvement achieved for the case study of the company by implementing the DCS

The evaluation of DCS is measured by comparing the value R_{c-o} (difference of range value for close and open sub-areas) and R_{ov} (overall range value for sub-areas) before and after the improvement strategies were implemented. Table II recapitulates the range values (R_{ov} and R_{c-o}) before and after the improvement strategies were implemented.

Referring to Table II, the variance before and after implementation of improvement strategies is 39,450 ppm (i.e. $R_{ov}^B - R_{ov}^A$). The variance of ranges before and after the improvement strategies were implemented ($R_{c-o}^B - R_{c-o}^A$) is 11,424 ppm. In percentage, the decreasing value of R_{ov} showed a significant improvement in terms of the dust level in all sub-areas of the production floor. The overall percentage improvement (reduced

Before and after implement Range values	Before (^B) Range value, R^B	After (^A) Range value, R^A	Improvement percentage
Overall sub-area (R_{ov})	R_{ov}^B 49,207	R_{ov}^A 9,757	80.2
Close sub-area (R_c)	R_c^B 32,382	R_c^A 8,000	75.3
Open sub-area (R_o)	R_o^B 20,651	R_o^A 7,703	62.7
Variance close and open sub-area (R_{c-o})	R_{c-o}^B 11,731	R_{c-o}^A 297	97.5

Table II.
The range between initial
stage (Phase 1) and
evaluation stage (Phase 3)

value) of the dust level is 80.2 per cent. The decrease in R_{c-o} value shows a significant improvement of dust distribution between open and close sub-areas. The percentage improvement in R_{c-o} is 97.5 per cent.

Conclusion

A detailed process of implementing the DCS on production floor of a case study company has been presented. Three analysis techniques known as relation diagram, tree diagram and prioritization matrices analyses from the powerful MPTs have been used in identifying and implementing the DCS. As a result the overall range level of dust particles for the whole sub-area, R_{ov} is reduced to 80.2 per cent compared to its value before the improvement strategies are implemented. In addition, the distribution of dust particles between close and open sub-areas also becomes more stable compared to its initial distribution as shown by the variance, R_{c-o} which is reduced to 97.5 per cent. However, continuous monitoring is needed to ensure that the level and the distribution of indoor air quality are maintained at a minimum level. Controlling the sources/causes of dust pollution is the best preventive actions. The cooperation among team members also becomes an important factor in order to successfully implement the proposed DCS.

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AN INVESTIGATION ON THE IMPACT OF DUST PARTICLES ON MACHINE'S COMPONENT FAILURE

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Abstract

Processing industries such as cement, ceramic, metal, agricultural-based and wood generate dust pollution in huge quantities during their machining process. The exposure of dust particles will not only unhealthy to human but also have adverse effects on machines component due to failure. In this paper, an investigation on the impact of dust particles on machine's component failure is presented. The emphasis of this paper is to present the component failure analysis, dust sources identification and proposed a methodology for evaluating the effect of component failure exposed to dust.

Keywords: Failure Mode and Effect Analysis (FMEA), Proportional Hazard Model (PHM), Preventive Maintenance (PR) Strategy.

Introduction

In traditional failure analysis, the failure time of the component/system is always assumed to be time-dependent. It means the failure time of the component/system depends only on the factor of time. Various time-dependent failure (reliability) models were introduced to model the component/system failure. The popular models are weibull, exponential, normal, log-normal distributions, etc. In practice, the assumption of time-dependent for the failure time analysis is always incorrect (Kalbfleisch and Prentice, 1980). The external factors (covariates) such as environmental, human and maintenance strategies influences the failure time of the component. Martorell et al, 1999 reported that some components in nuclear power plant are place in very hard environment such as under high temperatures and doses of radiation. Therefore, it is very useful to dispose of time-dependent failure (reliability) model that consider the time factor.

Many researchers have study the effects of covariates in failure time analysis and the popular models used for failure time modelling is Proportional Hazard Model (PHM), Accelerated Failure Time Model (AFTM) and Exponential-Weibull regression models. For instance, Ghodrati and Kumar, (2005) applied the PHM in failure (reliability) modelling of hydraulic jack with consider the covariates variable such as human, oil quality, temperature and dust. Liu and Makis, (1996) presented the reliability assessment of cutting-tool using AFTM with consider the covariates variable such as tool geometry, contact angle, tool and work-piece materials etc.

In this paper, an investigation on the impact of dust particles on machine's component failure is presented. The emphasis of this paper is to present a part of this investigation, which focusing on the component failure analysis, dust sources identification and proposed a methodology for evaluating the effect of component failure exposed to dust. The objective of the component failure analysis is to identify

the failures of machine's component (failure mechanism) that influence by dust. The Failure Mode and Effect Analysis (FMEA) is used in the component failure analysis. The proposed methodology will focus on data collection and classification as well as analysis technique for evaluating the impact of component failure exposed to dust.

Research Layout

This research will be carried out base on four main phases and it is illustrated in Figure 1. From Figure 1, first phase is identifying a case study in the processing company that suffer with dust pollution in their production area. Second phase will focus on the identification of the critical machine that exposed to dust. This phase can be divided by component failure analysis and dust sources identification. Following phase is referring to the research methodology for evaluating the effect of the component failure time exposed to dust. The methodology will focus on data collection and classification as well as data analysis technique. Final phase of this research is applying the Preventive Replacement (PR) strategy by considering the effects of dust to component failure.

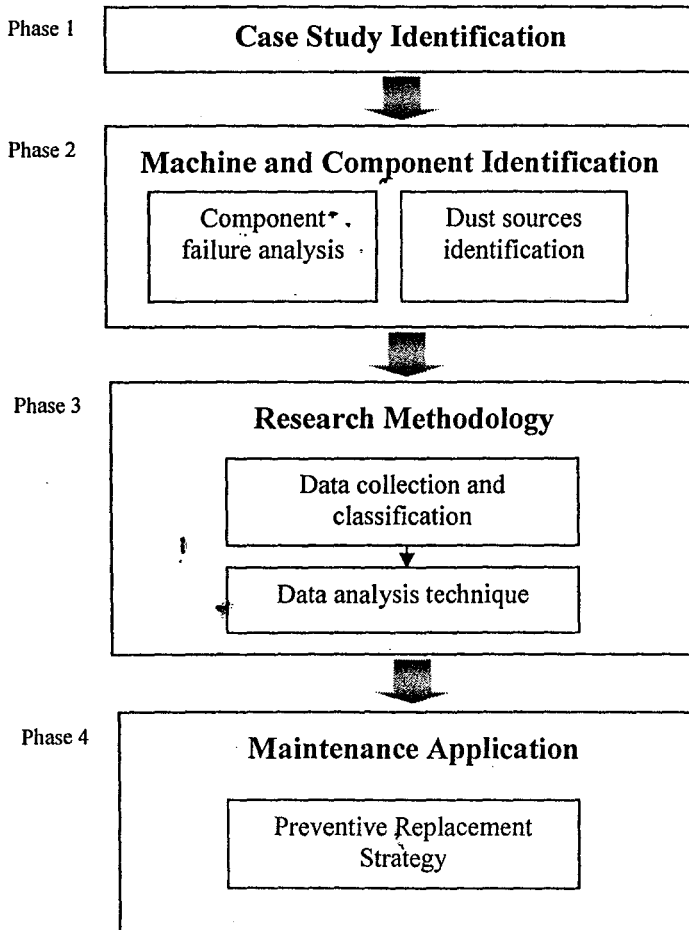


Figure 1: Research layout

The emphasis of this paper is to present the finding of the phase 1 and phase 2 as well discussed the proposed the methodology in phase 3.

Case Study Identification

A processing company (wood based industry) was identified for a case study in this investigation. The production area of this company suffers tremendous dust pollution that affects the machine's component due to failure. Figure 2 shows the effects of dust on machine's component during the machining process.

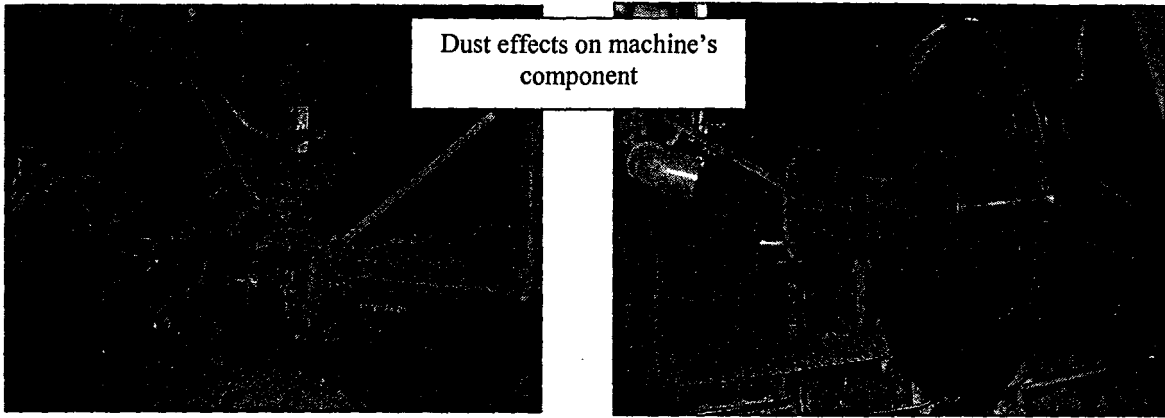


Figure 2: The effects of dust exposed on machine's component

From reliability and maintainability point of view, dust is believed to have an affect to the lifetime (failure time) of some mechanical component, resulting their actual lifetime (failure time) to be shorter than their design lifetime. This situation can be classified as time-independent failure, which means the failure time of the component depends on covariate variable (dust). Therefore, there is an important to carry out a research to evaluate the effect of dust on component failure from the reliability and maintainability perspectives. The benefit of this research will be developing a better maintenance strategy such as preventive replacement and spare parts can be forecast more accurately.

Machine Identification

Two types of machines are identified as the most critical machines that exposed to dust during the machining process. These machines are sawing machine and rewinding machine. Therefore, the component failure analysis will focus on the sawing machine and rewinding machine.

Component Failure Analysis

The objective of the component failure analysis is to identify the failures of machine's component (failure mechanism) that influence by dust. This analysis is carried out by using Failure Mode and Effect Analysis (FMEA). FMEA is the analysis technique that widely used in failure analysis. The main objective of FMEA is to classify and clarify the failure possibility (causes) and failure effects depend on the failure modes (Palumbo, 1994).

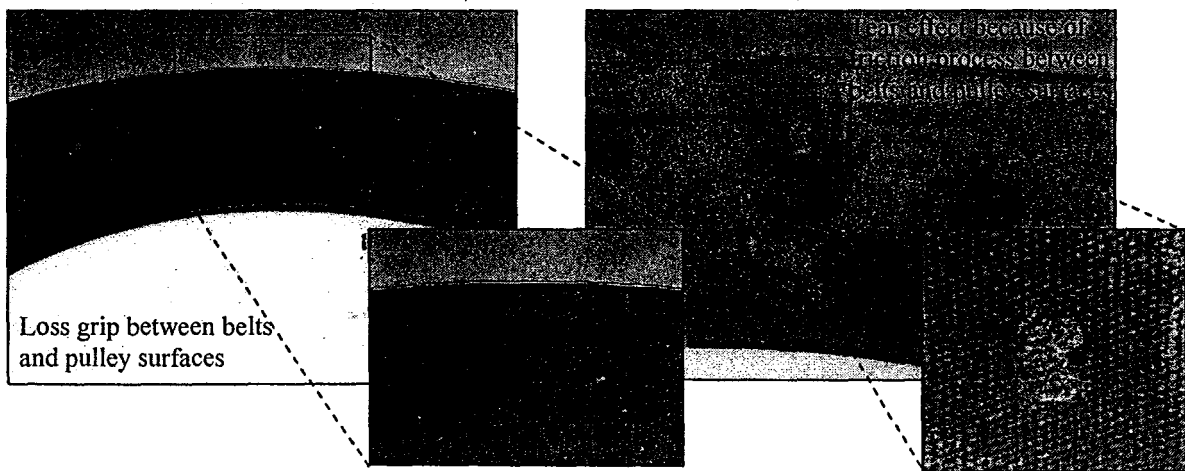
From the failure records and experience of the maintenance personal, belt and bearing are the most mechanical components that their failures are influence by the dust. Therefore, FMEA is applied to analyse the failure belt and bearing and the results of FMEA are summarised in Table 1. Table 1 show the most cases of belts failure (failure mode) is lost grip between belts surface and pulley. However, some

cases of belts failure (failure mode) is break. The failure mode of the bearing such as jammed, abnormal sound and vibration are recorded. The failure possibility of the failure modes for both of belts and bearing are identified influences by aging, contamination, dust, friction and wear, fatigue and abnormal stress. The effects of belt and bearing failure will cause the production shutdown.

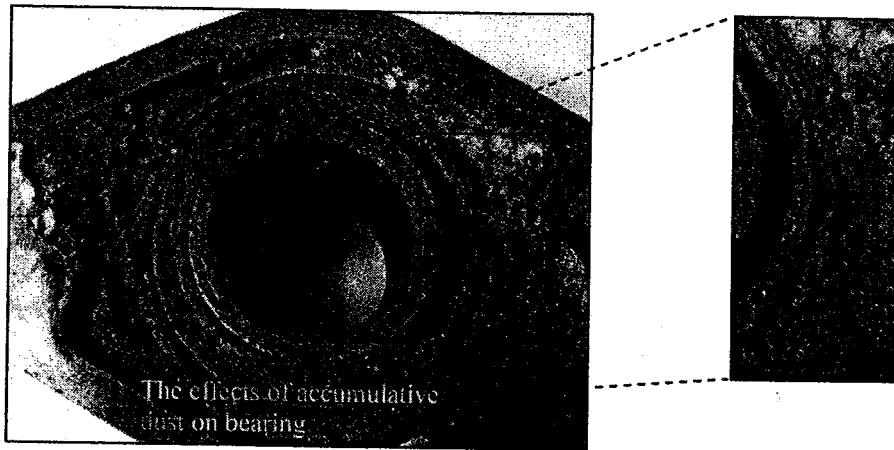
Component	Failure modes	Failure possibility (causes)	Failure effects
Belts	Lost of grip	Aging, dust, friction and wear, fatigue	Shutdown of production line
	Break	Aging, dust, abnormal stress	
Bearing	Jammed, abnormal sound and vibration	Aging, friction, accumulative wear, dust	Shutdown of production line

Table 1: The summary of FMEA for belts and bearing failure on sawing machine

Based on FMEA, the failure of belt and bearing are seriously influence by the extreme environmental factor (dust). This hypothesis can be supported based on the failure diagram of belts and bearing as show in Figure 3. Figure 3 shows the diagram of failure modes of the transmission belts and bearing. It shows the normal failure modes that usually occurred on belt and bearing.



(a) Transmission belts



(b) Bearing

Figure 3: The failure modes of the belts and bearing

Dust Sources Identification

The main sources of dust are identified coming from the products and it is generated during the machining process such as rewinding and cutting. Figure 4 shows the graphical views of the main source of dust that emitted in sawing machine. It shows that dust will randomly emit during the cutting process at sawing machine. The other source of dust in sawing machine is coming from grinding stone that generated for sharpening the cutting blade.

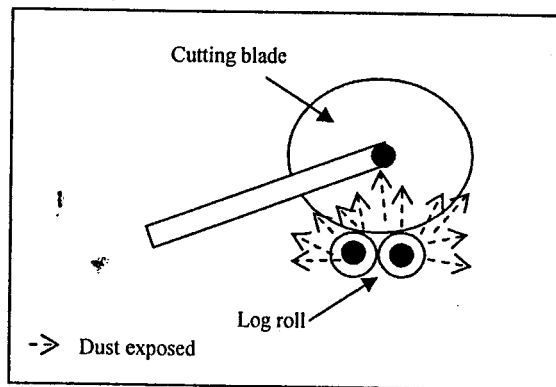


Figure 4: The main sources of dust in sawing machine

The quantity of dust emitted during the cutting process depends on the types of products it produce. The type of products is referring to the size of product that will be cut. Shorter products to be produced will results more dust in cutting process.

Research Methodology

In order to evaluate the effect of component failure time that influence by dust, a methodology of data collection, data classification and analysis technique is proposed (Figure 5). Two types of data are considered for data collection, there are component failure times and covariate data (dust). Proportional Hazard Model (PHM) is the analysis technique for evaluating the effect of component failure that influence by dust.

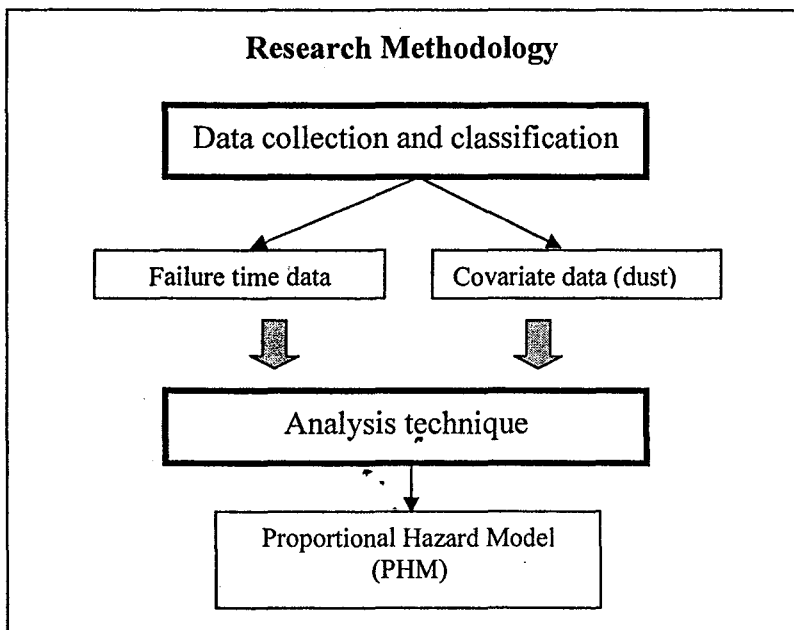


Figure 5: The methodology of the research

Data Collection and Classification

In the analysis of failure time that influence with the covariate variable (dust), the types of data collection must be classified and defined clearly (Tsang, et al, 2006). Therefore, two types of data are identified for collection; there are component (belt and bearing) failure time data and covariate data which refer to the quantity of dust exposed during machining process.

Failure Time Data

Failure time is referred to Time Between Failure (TBF) of the component. TBF is measure by the length of operating time of the component. Figure 3 shows the TBF for interval (t_1, t_2) . The sign of x_i , shows the length of operating time and i , is the number of failure time (number of data) at interval (t_1, t_2) , which the value of x is random.

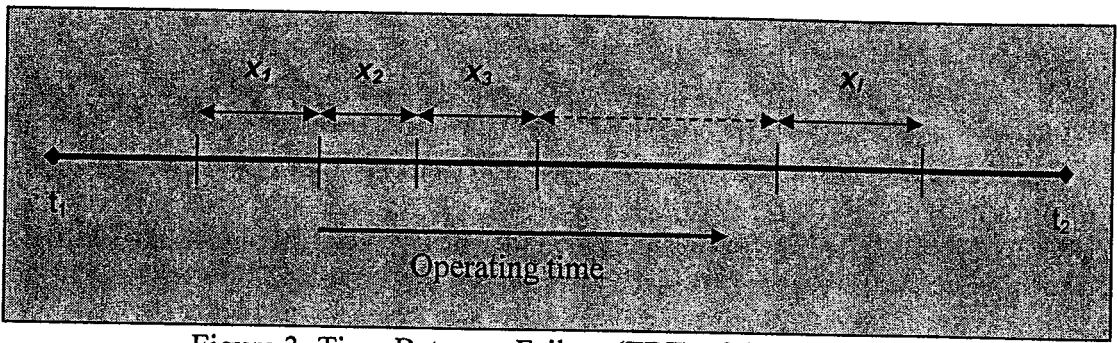


Figure 3; Time Between Failure (TBF) of the component

Covariate Variable

The covariate variable is the second data that consider in data collection process. In this case study, covariate variable is defined as the quantity of dust that exposed during machining process (cutting process). The quantity of dust is measured in the unit of weight and it depends on the product types (product sizes).

Analysis Technique

The evaluation on the effects of component failure time exposed to dust can be analysed (model) using Proportional Hazard Model (PHM). Historically, PHM was introduced by Cox (1972), which is a regression type model. PHM is considered as an analysis technique that widely used in failure time (reliability) analysis that influences by the covariate variables.

The basic assumption of PHM is that the hazard rate of a system or component is the product of a based line (time-dependent) hazard rate $\lambda_0(t)$ and a positive (time-independent) functional term $\exp(z\alpha)$, basically independent of time, incorporating the effects of a number of covariates as shown in equation below;

$$\lambda(t) = \lambda(t, z) = \lambda_0(t) \exp(z\alpha)$$

Where z , is a row vector consisting of the covariates and α is a column vector consisting of the regression parameters.

In this study, covariate variable is defined as the amount of dust that exposed. The based line of hazard rate $\lambda_0(t)$ follows the weibull distribution, where;

$$\lambda_0(t) = \beta/\theta (t/\theta)^{\beta-1}$$

Where, β and θ is shape and scale parameters, respectively. The assumption of weibull distribution is a most versatile model for characterizing the life of mechanical component Ghodrati and Kumar (2005). The integrating the effect of covariates with regard to PHM, we have;

$$\lambda(t) = \beta/\theta (t/\theta)^{\beta-1} \exp(z\alpha)$$

The advantage of the PHM is that it is distribution-free and no additional assumptions are necessary about the failure time Jardine et al, (1999). Moreover, PHM is quite

flexible. In this case study, the PHM will be analysed using SYSTAT or/and SPSS software with the input of the mean time to failure of component (belt and bearing) and the influencing covariates (dust quantity).

Discussion

According to the FMEA results, the factor of dust is influenced to the failures of belts and bearings. This hypothesis is based on the failure modes of these components and it showed in Figure 3. Therefore, the belt and bearing become the target component in evaluating the effects of their failure time exposed to dust. In this evaluation, two types of data are considered for collection; there are failure time for belt and bearing and the quantity of dust (covariate variable). The PHM is proposed as the analysis technique for this evaluation and the results will be applied for Preventive Maintenance (PR) strategy. The advantage of applying the PR according this evaluation results is the PR time can be determined accurately.

Conclusion

This paper presented the component failure analysis, dust sources identification and proposed a methodology in the study on the impact of dust pollution on component failure. The results of the component failure analysis showed the failures of mechanical component such as belts and bearings are influence by dust. The main sources of dust exposure are generated during machining process such as cutting process and the quantity of dust depends on the size of product. The methodology that proposed in this paper discussed the data collection and classification as well as analysis technique for evaluating the effects of failure time exposed to dust. The failure time and quantity of dust (covariate variable) are considered for data collection. The Proportional Hazard Model (PHM) is proposed as analysis technique to evaluate the effects component (belt and bearing) failure time exposed to dust.

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DEVELOPMENT OF A FRAMEWORK FOR THE RELATIONSHIP OF MACHINE'S PERFORMANCE AND THE IMPACT OF DUST POLLUTION

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ABSTRACT

Processing industries generate huge amount of varieties of pollutants, including dust particles. The pollutants, in general and the dust particles, in particular adversely affect the performance, availability, reliability, and capability of machine components as well as the processing machines. Keeping this in view, an attempt has been made in this paper to develop a framework to show the relationship between machine's performance and the impact of dust pollution. In the framework, a measurement method to determine the overall machine performance based on dust particle impact is introduced.

Keywords: Dust particle, Machine performance, Availability, Reliability and capability

INTRODUCTION

Processing industries such as cement, wood, metal, agricultural-based and ceramic processing contribute huge amount of dust particles as the waste products. Processing methods from these industries are identified as the main sources of dust pollution [1]. Processing methods such as grinding, drilling, sawing, polishing, milling and melting generate various types of dust pollution. The characteristics of emitted dust pollution depend on the raw material being processed and it can be in the form of gases, chemicals and airborne particles (such as dust particle). Uncontrolled dust pollution in the processing industries can have adverse effects on the workers and also on the machines. In relation to the workers, the effect of dust pollution may result in low productivity [2] and high risk of getting critical diseases such as lung or skin cancer, asthma, eye problems including cataracts and pterygia (growths on the eye) [3]. On the other hand, performance of machines might deteriorate due to failure of the machine components and it may lead to major breakdown of the machines. This may result in high maintenance cost and eventually may also increase the operating cost.

Physical impact of dust pollution on the machine components is the main reason for the deteriorating performance of the machines. Examples of physical impacts that are caused by the dust can be characterised as friction, wear and short circuit. This paper begins with the discussion on the sources of dust pollution that is emitted from five main processing industries such as cement, wood, metal, agriculture-based and ceramics. It is followed by a brief introduction to machine performance parameters such as availability,

reliability and capability. The main objective of this paper is to propose a measurement method for determining the performance value of machine components as well as overall machine performance. This measurement procedure is developed and proposed by adopting the availability, reliability and capability parameters and determining the relationship between these parameters and the effect of dust pollution on the overall machine performance.

THE SOURCES OF DUST PARTICLE

As discussed in the previous section, the processing methods used in the processing industries are the main sources of dust pollution. Processing methods are used to process raw material and also to process semi-finished or finished products. Crushing, melting, mixing and burning are examples of raw materials processing methods. Examples of semi-finished or finished products processing include crushing, grinding, drilling, polishing, sawing/cutting, shaping, sintering and coating. Dust pollution generated by both processing activities can be differentiated according to the sizes, forms and contents of dust pollution. Generally, size of dust pollution generated from semi-finished or finished products processing is larger compared to the raw material processing ($>100\mu\text{m}$) [4]. The particle can exist in the form of powder and chips and the contents are based on the materials that have been processed. In the raw materials processing, the dust particles are very small until $0.5\mu\text{m}$ and it is in the form of fume, gases and moisture. The dust pollution emitted during the raw material processing contains various complex compositions such as ammonia, sulfur and arsenic. The overviews of types of dust pollution in terms of their contents that are generated by various processing methods used by the processing industries (i.e. cement, wood, metal, agricultural-based and ceramic) are presented briefly in the following section.

Cement is a mixture of compounds and is made by burning limestone and clay together at very high temperatures ranging from 1400 to 1600°C . Table 1 shows the processing methods such as crushing, mixing, milling, and packing and the pollutants that are generated from cement industries. It can be seen from this table that the dust pollution emitted during these processes contains various types of toxic trace metals such as aluminum, mercury, zinc, chromium, arsenic, vanadium and thallium [5].

Wood is the most important raw material to produce varieties of products such as furniture, building components, papers, tissue and carton box. The processing methods used for wood also generate high volume of dust pollution. For example, in the furniture making industries, the processes used in producing furniture involves several processing methods such as sawing / cutting, shaping, polishing and routing (Table 1). These processing methods produce pollution in the form of wood chips and wood dust (Table 1). Generally the content of wood dusts is mainly the combination of cellulose, polyoses and lignin. Besides, some insects can also be found in the wood dust.

Metal processing also generates huge amount of dust pollution during processing of different types of metals. Raw materials processing such as melting, burning and sintering emit several types of pollution such as gases, oil particle and fume. On the other hand, processing methods for processing the semi finished or finished products such as polishing and shaping generates dust pollution in the form of powder and chips. Table 1 shows the processing methods for metals processing industries and the contents of the emitted dust.

Agricultural-based processing produces two types of dust i.e. organic and inorganic dust. For example in rice processing, before the paddy grain becomes a finished product, generally, it goes through three stages of processing. The first stage is the cleaning of the paddy grain, where the main objective is to remove unwanted impurities such as insects and soil. Milling is the second stage for processing the paddy grain, where paddy grain shell is removed. This phenomenon is also known as husking. The final stage is the polishing where rice with better appearance, quality and storability is produced. Table 1 shows the processing methods for rice processing and the content of dust emitted during its processing.

Ceramics are compounds of inorganic and nonmetallic solids that are subjected to high temperature in manufacture and/or use [6]. The composition of the most common ceramic material is oxides, carbides, and nitrides. Ceramic processing is similar to the metal processing but due to the differences in types of bonding, there are differences in the roles being played by various processing methods. Usually, processing of ceramics involves various stages such as consolidation of ceramic powders, drying and green machining, sintering and finally hot compaction. Table 1 also shows the processing methods used for ceramics along with

the contents of dust pollution generated during processing.

Table1: Summary of dust particle sources and the dust contents emitted by the processing industries

Processing Industries	Processing Methods	Dust Pollution Contents
Cement	Crushing Milling Packing Mixing	Lead Mercury Copper Chromium Arsenic Zinc Vanadium Thallium
Wood	Sawing / Cutting Sanding Shaping Routing	Wood chips <i>Main composition; cellulose, polyoses and lignin</i> Insects
Metal	Melting Sintering Burning Coating Polishing Shaping	Toxic gases (ammonium and sulfur) Cadmium Lead Arsenic Limestone Rubber Plastic Metal scraps
Agricultural-based	Cleaning Polishing Milling Packing	Silica Quartz Coal Asbestos Molds Spores Grain
Ceramic	Grinding Mixing Sintering Leaching Cutting	Gases Zinc Aluminum Tungsten Thallium Cadmium Silica Glass

THE CONCEPT OF MACHINE PERFORMANCE

Machine consists of many components and each one of them is assembled together to structure a complete machine. The integration between the machine components can be translated into various groups of element, and each element corresponds to each other for the purpose of controlling and operating the machine. The integration of each component for building up the machine is depicted in Figure 1. Machine performance depends on the performances of its components, where

performance can be defined as the ability of components or unit to perform its intended functions. The ability of each component to perform in turn, determines the overall machine performance. Overall machine performance can be measured based on three parameters; availability, reliability and capability. In the following section, the concept of these parameters is discussed briefly.

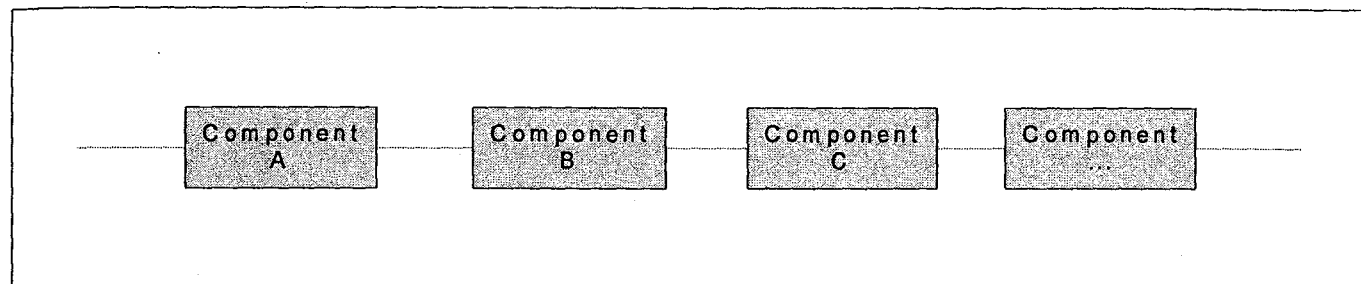


Figure 1: The integration of each component for building up a machine

AVAILABILITY

Availability is the ability of components to perform their required functions at a given point or over a stated period of time. Availability gives information about how long the components or the machine can be used and it is expressed as the availability ratio or probability. Generally, availability deals with the duration of up-time for operations and is a measure of how often the system for operations and is a measure of how often the system is working and running. Up-time and downtime refer to dichotomized conditions [7] where up-time refers to the capability to perform the task and downtime refers to not being able to perform the task. Availability is often expressed as equation (1) [8];

$$\text{Availability} = \frac{(\text{up-time})}{(\text{up-time} + \text{downtime})} \quad (1)$$

Several factors must be considered to determine the value of availability. In determining the value of availability, it has to deal with at least three main factors [9], which are;

1. Increasing time to failure
2. Decreasing downtime due to repairs or scheduled maintenance
3. Accomplishing items 1 and 2 in a cost effective manner.

RELIABILITY

Reliability can be defined as the ability of a product or equipment to perform, without failure, a specified function, under a given condition and for a given period of time [9,10]. Reliability deals with reducing the

frequency of failures over a time interval and is a measure of the probability of failure-free operation during a given interval. In other words, it is a measure of success for a failure free operation. Barringer [7] stated that the following two parameters are commonly used to determine reliability:

- i. Mean Time Between Failure (MTBF) and
- ii. Mean Time to Failure (MTTF).

i. Mean Time Between Failure (MTBF)

MTBF is the average time between successive failures of the equipment or components. Relationship between the reliability of system and mean time between failures is given in Eqn. (2) [11].

$$R(t) = \exp(-t/m) = \exp(-\lambda t) \quad (2)$$

Where, R = System reliability

t = Specified period of failure – free operation

λ = Failure rate (constant failure rate)

m = MTBF

ii. Mean Time To Failure (MTTF)

Oyebisi [12] stated that mean time to failure (MTTF) is used to measure the reliability of components or items that are not repairable such as capacitors, resistors, fuses, filament lamps and others. The value of mean time to failure (MTTF) can be calculated using Eqn. (3):

$$\text{MTTF} = \frac{\text{Length of test times}}{\text{Number of failures}} \quad (3)$$

CAPABILITY

Capability deals with productive output compared to inherent productive output. It is a measure of how well a system is performing its functions, compared to the datum. Capability of a system can be measured by adopting the statistical process control techniques [13]. For example, capability for variables data can be described in terms of the distance of the process average from the specification limits in standard deviation units, Y_{min} = minimum of YUCL (upper control limit) or YLCL (lower control limit). The Y-index helps to predict the Yield if normal data distribution are applied. Capability may also be measured with machine tool capability (C_p) and process capability (C_{pk}) index. It relates to the scaled distance between the process mean and the closest specification limit to half the process spread that is the range of a process variation [14]. In addition, capability studies can estimate future process performance only when such performance is consistent over time (stable process). A stable process may be predictable. In terms of the industrial application, capability analysis is used to determine the processes for producing products whether it is within the tolerance limits and engineering values [15].

PROPOSED FRAMEWORK FOR THE RELATIONSHIP OF MACHINE'S PERFORMANCE AND THE IMPACT OF DUST POLLUTION

As mentioned in the previous section, machine performance depends on the performances of its components in terms of availability, reliability and capability. The understanding of the concept of machine is significant in order to have a clear picture of the relationship between machine and its performance. Machine can be described as any mechanical or electrical device that transmits or modifies energy to perform or assist in the performance of human tasks. Modern machines have mechanical, electrical and electronic components. Figure 2 shows the relationship between these components and their performance parameters i.e. availability, reliability, and capability and it also depicts how the machine performance is related to the performance parameters of the components.

The overall machine performance can be measured on the basis of;

- i. the existence of machine components and
- ii. performance parameters of each component
- iii. the existence of machine components and
- iv. performance parameters of each component

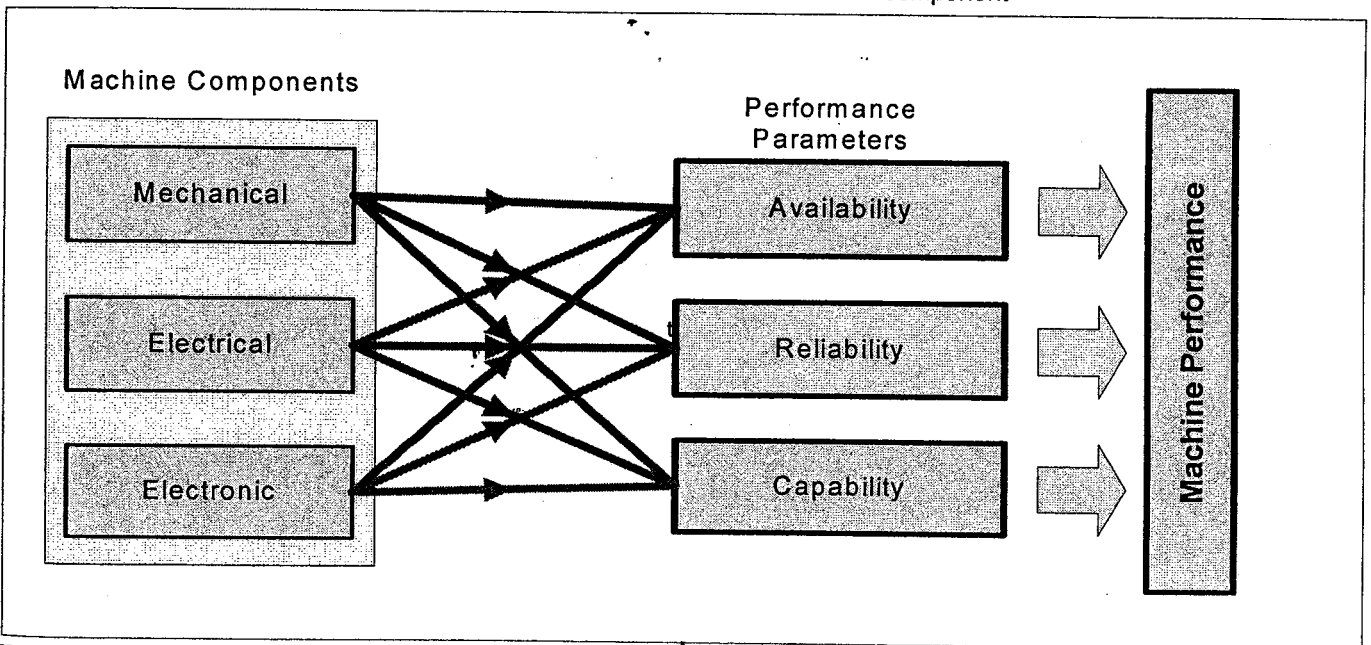
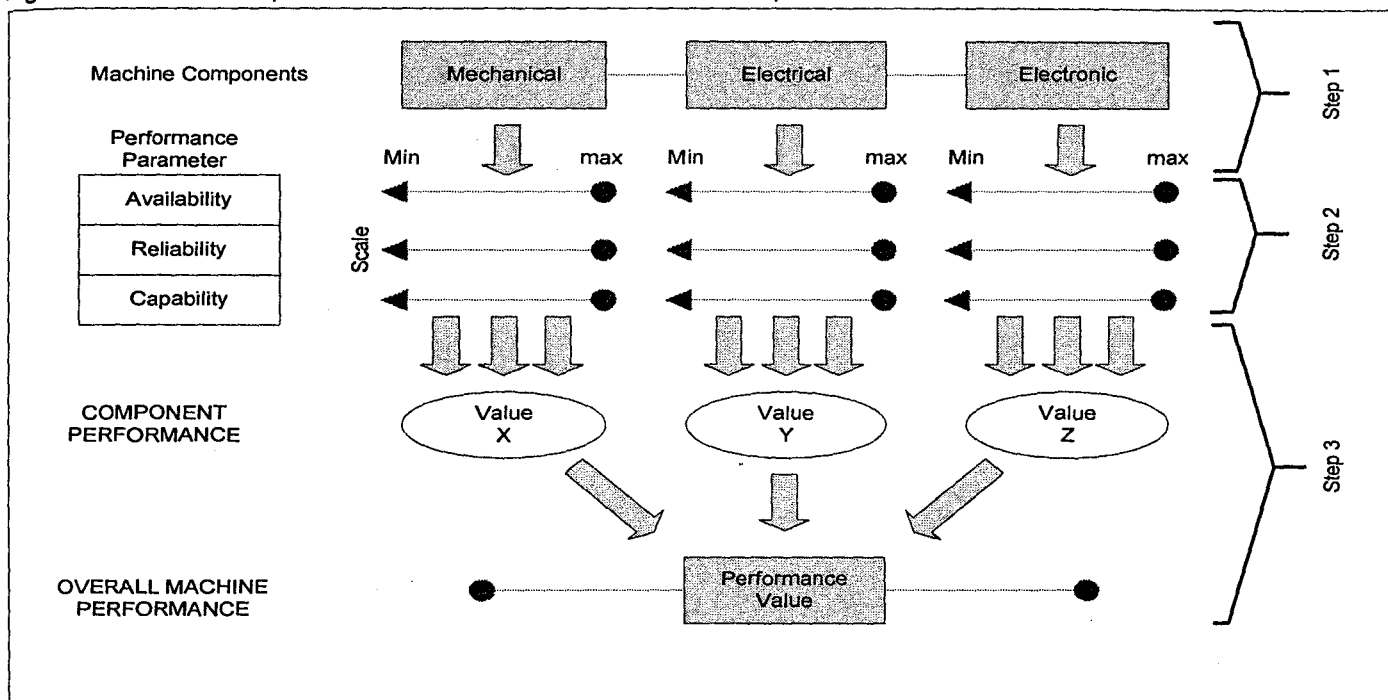


Figure 2: The relationship of machine components and performance parameters towards the overall machine performance.

Figure 3 illustrates the procedure of measuring the performance of machine due to the impact of dust

pollution. Details of the procedure are discussed in the following steps:

Figure 3: Measurement procedure to determine the overall machine performance



Step 1: Identifying Machine's Components and Scale for Performance Parameters

As mentioned before, most machine components can be divided into three types; mechanical, electrical and electronic. The overall performance of the machine gets affected when these components are exposed to the dust pollution. Therefore, the first objective is to identify the components (it can be mechanical, electrical and electronic) that are sensitive to the dust pollution. Once these components are identified, the second objective is to determine the value of availability, reliability and capability (ARC) performance of each component. This is achieved by using the performance parameters concepts that have been discussed in the previous section.

Usually, the value determined is the top performance of machine components because it has not been exposed to the dust particle so far and it is at maximum in the scale. For example, a good condition 3-phase electric motor will have a life span of 10,000 hours operating in a normal condition (free from dust pollution). The 10,000 hours will be an indication of the maximum value for the scale of availability in the framework. Furthermore, since it is in good condition and operating in a clean environment, the value for both reliability and capability is at 100.

Step 2: Experiment and Data Collection

Once all the information for the first step is available, experiments need to be conducted in order to collect data. The experiments can be carried out either in the laboratory on a similar machine in a simulated environment or directly on the source machine. The objective of the experiment or data collection is to measure the value of changes in components' availability (A), reliability (R) and capability (C) due to change in dust pollution volume (V) with respect to time (t). In addition, the contents (refer Table 1) also have effects on the performance parameters due to the characteristic of the dust pollution. Therefore, it is important to take into consideration the impact of various content of dust pollution when measuring the changes of the performance parameters. The important aspects that need to be considered during the experiment or data collection are:

- volume of dust pollution (V)
- content of dust pollution
- time of exposure (t)
- performance parameters; availability (A), reliability (R) and capability (C)

Step 3: IDENTIFYING THE OVERALL MACHINE PERFORMANCE

Step 3, is a stage where all the values of availability (A), reliability (R) and capability (C) for each component are added up for determining the overall machine performance. Referring to Figure 3, the performance value for each component is identified as value X (mechanical), value Y (electrical) and value Z (electronic). The overall machine performance value is the combination of X, Y and Z values. In other words, the overall machine performance depends on the combined value of each component performance.

CONCLUSION

This paper has reviewed the impact of dust pollution on machine performance especially in the processing industries such as cement, wood, metal, agriculture-based and ceramic. The theory of machine performance in terms of availability, reliability and capability is discussed. A framework has been proposed to provide a mechanism for understanding of overall machine performance from machine components perspective. In the framework measurement procedure is proposed for determining the overall machine performance based on relationship of machine components (mechanical, electrical and electronic) and performance parameters when exposed to dust pollution. Therefore, from the framework overall machine performance can be determined which is, indeed, a combination of availability, reliability and capability values of various machine's components. Furthermore, the framework allows a detail collection of information regarding the impact of dust pollution and as a result improvement and prevention towards dust pollution can be developed.

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THE CHARACTERISTICS OF DUST PARTICLES EMITTED FROM THE PROCESSING INDUSTRIES AND THEIR PHYSICAL IMPACT ON MACHINE COMPONENTS: A REVIEW

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ABSTRACT

Dust pollution has largely been ignored for years but is now being recognised as a serious problem in industries. It has been observed that more dust pollution is generated by the processing industries such as cement, ceramic, metal, agricultural-based and wood. These processing industries generate various types of dust particles which are not only unhealthy for human but also have adverse effects on machines. Ways to reduce the impact of dust pollution include constant monitoring and understanding of the impact of dust on the environment especially the working environment. This paper presents a review on the type of dust pollution generated by cement, ceramic, metal, agricultural-based and wood processing industries. Furthermore, the characteristics of each dust pollution emitted by these industries in terms of its contents and substances are also discussed. Finally, the paper describes the physical impact (i.e. friction, wear and short circuit) of the dust pollution on machine components.

Keywords: Dust pollution, Dust characteristics, Machine Components

INTRODUCTION

Processing industries are involved in the physical or chemical transformation of raw materials, semi finished materials or components into new products, either by manual or automated method. They cover a wide range of activities i.e. from large timber mills to metal manufacturers. Given such characterisation, they make a major contribution to the economy of a country especially in Malaysia. Generally, the above mentioned industries operate on a medium/large scale with high utilisation of machines. The effluents discharged by these industries lead to serious environmental pollution. The presence of dust pollution, in the presence of environmental variables such as temperature and humidity, makes the work environment even worse and causes health related problems as well as reduction in functional values of the machines. As a result, these industries are experiencing severe deterioration of machine performance due to the effect of dust pollution. It has been observed that the dust pollution prevention and control mechanisms among these industries are inadequate. Therefore, there is a need for an approach to introduce successful dust pollution management

strategies either through effective effluent treatment and better dissipating of knowledge or through replacement of the existing production processes with the cleaner production technologies. The purpose of this paper is to discuss the impact of dust particles on machine components from the processing industries point of view. This paper focuses on five processing industries which include, wood, metal, steel, agricultural and ceramic. It begins with an overview of the relationship between the dust particles and their physical impact on machine components. It also presents a discussion on the detail characteristics of dust particles that have an impact on the machine components. Furthermore, the physical impacts of these dust particles which are, indeed, significant factors for machine operations are discussed in detail.

RELATIONSHIP BETWEEN PROCESSING INDUSTRIES, MACHINE COMPONENTS AND THE PHYSICAL IMPACT OF DUST PARTICLES

Processing industries such as cement, ceramic, metal, agricultural-based and wood generate huge amount of dust pollution during their processing. In the metal and wood industries for example, processing methods such as melting, sintering, coating and burning emit various dust particles. In addition, machines that are used for operations such as grinding, milling, sawing, drilling, polishing and crushing are also the main sources of dust particles especially when producing ceramic, metal and wood products.

Dust pollution contains several elements of toxic gases, metals, organic and inorganic materials. For example, dust from cement contains elements from various metals. Similarly, dust from wood consists of cellulose, polyoses and lignin elements. These elements determine the characteristics of the dust pollution. The characteristics of dust pollution can be classified according to their physical, chemical, biological and electrical features. The strength, hardness, ability of electric conductivity and capability to react with environmental factors (temperature and moisture) are the examples of the dust pollution characteristics.

The working environment consists of five elements which are workers, machines, materials, methods and environment (temperature, moisture and dust). Each of these elements has a strong relationship with each other. For example, the relationship between workers and environment can be seen from the effect of the dust

pollution. If the workers are exposed to the working environment that contains toxic dust, in a long term, the health of the workers will deteriorate and productivity will be reduced. Similar impact can be seen on machines. The machines that are involved directly in materials processing may break down due to exposure to the dust pollution. The impact of dust pollution in working environment is the most significant and interesting issue to discuss. In addition, the characteristics of dust pollution play an important role in creating its physical impact on machine components. Figure 1, shows the relationship between the processing industries in terms of the components of machine and problems caused by reaction of dust pollution. In addition, it also shows the type of problems such as friction, wear and short circuit that will result from direct impact when the machine components are exposed to the dust particle. Detail information regarding the dust characteristic and physical impact are discussed in following section.

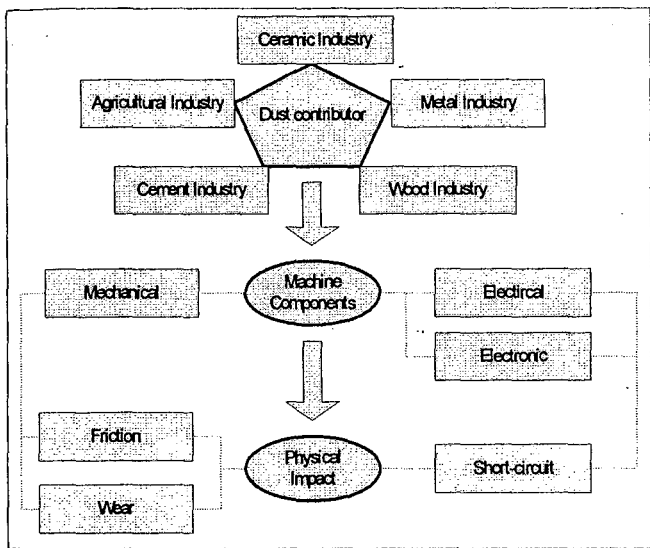


Figure 1: Relationship between processing industries and physical impact on machine component

CHARACTERISTICS OF THE DUST POLLUTION EMITTED FROM PROCESSING INDUSTRIES

The characteristics of dust pollution emitted from processing industries described in previous section are discussed as follow:

Cement industry

Cement is made by burning a mixture of limestone and clay at a very high temperature between 1400°C to 1600°C. Before it reaches to this stage, it requires several operations such as quarrying, crushing and mixing. During these stages various machines and processing methods are involved. For example a ball milling machine is used for crushing the limestone. Quarrying and crushing are the main processes that contribute to the large amount of dust pollution in the cement industries. Most of the dust particles emitted are

hazardous and harmful to the human and also to the machines [1]. In general, cement is an alkaline inorganic composite containing surface hydroxyl [2]. The dust particles of cements contain several elements such as toxic metals, radioactive, chemical reactive and minerals. The example of toxic trace metals are aluminum, mercury, zinc, chromium, arsenic, vanadium and thallium [3]. Table 1 shows the percentages of dust particle and the chemical elements that are generated during the processing of cement.

Table 1: Percentage of dust particle and chemical elements based on cement processing (Al-Harthy, 2004; Pehanich, 2004)

Chemical elements of dust	Dust particles (%)	Oxide equivalent weight (%)
SiO ₂	21.95	20.7
Al ₂ O ₃	4.95	4.2
Fe ₂ O ₃	3.74	2.3
CaO	62.33	63.7
MgO	2.08	3.7
SO ₃	2.22	3.1
K ₂ O	0.56	0.57
Na ₂ O	0.32	-
TiO ₂	0.17	-
Mn ₂ O ₃	0.05	-
Cl	0.01	-

Wood industry

In terms of the wood industry classification, it includes the processing of wood, wood products and furniture, paper and paper products. Saw mills are the main activities in wood processing for producing sawn timber. Manufacturing plants produce various types of fiberboard, woodchips for particle board manufacture, paneling, low pressure laminates and particle board in fully integrated operations. When the wood is processed, such as when it is turned, drilled, chipped or sanded then a large amount of wood dust particles of different sizes and characteristics are generated. Wood dust contains various substances and its composition is based on species of tree, such as rubber wood, holly oak, strawberry tree, ash, poplar and oak. Chemical composition of wood dust mainly consists of cellulose, polyoses and lignin, with a large and variable number of substances with lower relative molecular mass. The lower molecular mass substances significantly affect the properties of wood and it consists of substances extracted from non-polar organic solvents, polar organic solvents and water soluble substances. Table 2 shows the three main constituents of chemical composition of wood dust. It also shows the constituents with relatively lower molecular mass that are present in the wood dust.

Table 2: Chemical composition and substance of relative molecular mass of dust particle.

Chemical composition of wood dust		
Cellulose	Polyoses	Lignin
Substances of relatively lower molecular mass		
Non-Polar organic extractive	Polar organic Extractive	Water-soluble extraction
Fatty acids Resin acids Waxes Alcohols Terpenes Sterols Steryl esters Glycerols	Tannins Flavonoids Guinones Lignans	Carbohydrates Alkaloids Proteins Inorganic material

Metal industry

Metal industry is the most important and diverse sector of processing industry. It can be classified as basic metal products, fabricated metal products, transport equipment, other machinery and equipment based industries. The primary metal industries such as manufacturing of steel, aluminum, zinc, copper and lead are the basis of the metal processing industries for producing products from metal ore and / or scrap metal. These industries utilise both ferrous and non-ferrous metals to produce pure metal products or alloys in the form of end products or stocks for use by other industries. Processing of metals in these industries involves various stages. At each stage huge amount of dust particles is emitted. In general, the primary metal production industry concentrates on the mining site, prior to reaching the metal processing plant. The primary processes include crushing, roasting and floating. Dust pollution emitted from primary metal processing often contains cadmium, lead and other compounds, depending on the inputs. Secondary processing such as melting, sweating, mixing, separation, reduction and distillation are done after primary processes. Sweating and melting are the main contributors of dust particles. The dust pollution emitted includes metal fumes, volatile metals, flux fumes and smoke, rubber, plastics and metal scrap. Table 3 shows the substances that are emitted during primary and secondary stage of metal processing.

Table 3: The dust particles emitted during metal processing

Stages of processing of metal	Processing methods	Dust particles emitted
Primary	Crushing Roasting Flotation	Cadmium, lead, mercury, chromium, arsenic, vanadium, thallium and sulfur dioxide. (Depending on material inputs)
Secondary	Melting Mixing Reduction Distillation	Zinc fumes, volatile metals, flux fumes and smoke, rubber, plastics and metal scrap.

Agricultural-based industry

Agricultural-based processing industries are one of the biggest sectors in the Malaysia, e.g. the palm oil sector. Other industries that can be classified under the agriculture-based industries include rice, corn, oil-seeds and rubber processing. Generally, during the processing of this agriculture based materials, various types of waste and pollution such as chemical waste and dust are generated. For example in oil-seeds and nuts processing, dust pollution is produced during mechanical process such as cleaning, crushing and conditioning [4]. Dust pollution from agricultural industries can be divided into two; organic and inorganic [5]. In terms of organic dust it consists of non-grain plant matter, molds and spores, humid grain, bacteria and their biochemical components and excretions and insects. Soil on the farm area is the main source of inorganic dust. The soil contains substances like silica, quartz, coal, asbestos and beryllium. However, inorganic fraction of soils from very arid locations may be dominated by calcium carbonate and more soluble salts rather than by silicates. Table 4 summarizes the overall dust matter in organic and inorganic dust emitted from the agricultural-based processing industries.

Table 4: Organic and Inorganic Dust emitted from Agricultural-Based Industries

Organic Dust		Inorganic Dust	
Main dust matter	Other dust substance	Main dust matter	Other dust substance / examples
Silica Quartz Coal Asbestos Beryllium	microorganisms mycotoxins allergens decomposition gases pesticides	Non-grain plant	Hay Paper Fuel
		Molds and spores	Aspergillus Cladosporium
		Humid grain	Thermophilic Actinomycete Mycotoxins Ochratoxin T2 toxin
		Bacteria and their biochemical components and excretions	Endotoxins peptidoglycans Proteolytic enzymes
		Insects	Grain weevil Parts of insects Rodents

Ceramic Industry

Ceramic can be classified as inorganic and nonmetallic solids. Ceramics are used in the manufacturing of numerous consumer products and they are gaining popularity in the industrial applications. This is due to the capability of ceramics to maintain its strength and to withstand high temperature. Ceramic products are mostly clay-based and are made from either single clay or mixture of minerals such as quartz and feldspar. Ball clay and kaolin are usually used in a commercial purposed product. The ceramic materials are generally oxides, carbides and nitrides of metals. Other materials such as silicide, boride, phosphide, telluride, and selenide are also used for producing ceramic products. Generally, production of a ceramic product involves operations such as beneficiation, mixing, forming, green machining, drying, pre-sinter thermal processing, lazing, firing, final processing, and packaging [6]. The pollution that is generated during the processing is difficult to avoid. For example, in the raw material beneficiation process, such as crushing and grinding, dust pollution with dust particle matter of the size of 10µm in aerodynamic diameter is generated [7]. The other sources of dust pollution come from various processing stages such as leaching, heat treating, polishing, surface coating and glazing preparation such as mixing and grinding. Table 5 shows the varieties of dust pollution that consists of metals, gases, acid and volatile organic compounds emitted during processing of the ceramics.

Table 5: Particle emission in ceramic processing

Ceramic processing	Particle Emission
Calcining	Nitrogen Oxides (NOx) Sulfur Oxides (SOx) Carbon Monoxides (CO) Carbon Dioxide (CO ₂) Volatile Organic Compounds (VOC)
Leaching	Hydrochloric acid (HCL)
Glaze preparation such as (Mixing and grinding)	Zinc Mercury Aluminum Tungsten Thallium Cadmium Vanadium Silica Glass
Green machining (Grinding and cutting)	Volatile Organic Compounds (VOC) Mineral oxides

THE PHYSICAL IMPACT OF DUST POLLUTION ON MACHINE COMPONENTS

Machine can be described as any mechanical or electrical device that transmits or modifies energy to perform or assist in the performance of human tasks [8]. Machines generally consist of three types of components i.e. mechanical, electrical and electronic. Mechanical components are made by combining different types of mechanisms. The mechanism is used to transfer energy into motion, or move materials in a controlled way. Electrical components refer to the item or equipment which is used to change electrical energy into another form of energy for performing a task. This energy can be mechanical (motive), magnetic, thermal (heat) or chemical. Electronic components are devices that are used for controlling the voltages and/or current in different signal. Electronic components can be grouped into either being passive or active devices. Active devices are components that are capable of controlling voltages or currents. It can create a switching action in the circuit. Passive devices are components that contribute no power gain (amplification) to a circuit or system. In other words, this device has no control action and does not require any input other than a signal to perform its function. Table 6 shows the classification of machine components on the basis of mechanism used for transformation of energy.

Table 6: Classification of machine components

Machine Component	Type of machine component		
Mechanical	Chain Sprockets Gears Shaft Pawls Bearings		
	Types of energy changing		
Electrical	Mechanical	Magnetic	Thermal
	Motor Switch	Alternator Coil	Lighter
Electronic	Passive device		Active device
	Resistor Capacitors Inductors	Diodes LED Transistor Integrated Circuits Microprocessors	

Generally, the above listed components are common in the machines that are used by the processing industries. As discussed in the previous section, various types of dust particles with different characteristics are generated from the processing industries. These dust elements have capability to react with other elements. Hence, it can cause a physical impact on the machine components and consequently performance of the machine will deteriorate. For example, in terms of mechanical components, dust particle from processing industries can cause physical impacts such as friction and wear. The physical impact on machine components caused by the exposure of dust pollution is detailed in the following section.

The impact on friction and wear of mechanical components

Friction is defined as the resistance to relative motion between two bodies in contact under a normal load [9]. In processing industries, friction plays an important role due to the relative motion and force that are always present on tools, dies, work pieces and moving machines' components such as gear, motor and pulley. Uncontrolled friction for certain period can cause wear between contact surfaces. Kalpakjian et. al. [9] have defined wear as the progressive loss or removal of material from a surface. Wear has great technological and economical significance because it modifies the shape of machine components.

Dust particles that are generated by processing industries have high potential to give an impact on friction and wear of machine components. The characteristics of dust particles play an important role in understanding the pattern of friction and wear process. Dust pollution that comes from metal and ceramic processing contains various types of toxic gases, metal and mineral elements.

Generally, lubricants such as greases, waxes, soaps, oils and emulsions are used to reduce the friction between two materials surface. The impact of dust particles on mechanical components can reduce the lubricant function and this will cause wear and tear of the components. Figure 2 illustrates the effect of exposure of materials surface to dust particles. The impact can increase the friction rate and can cause significant wear and tear of the components.

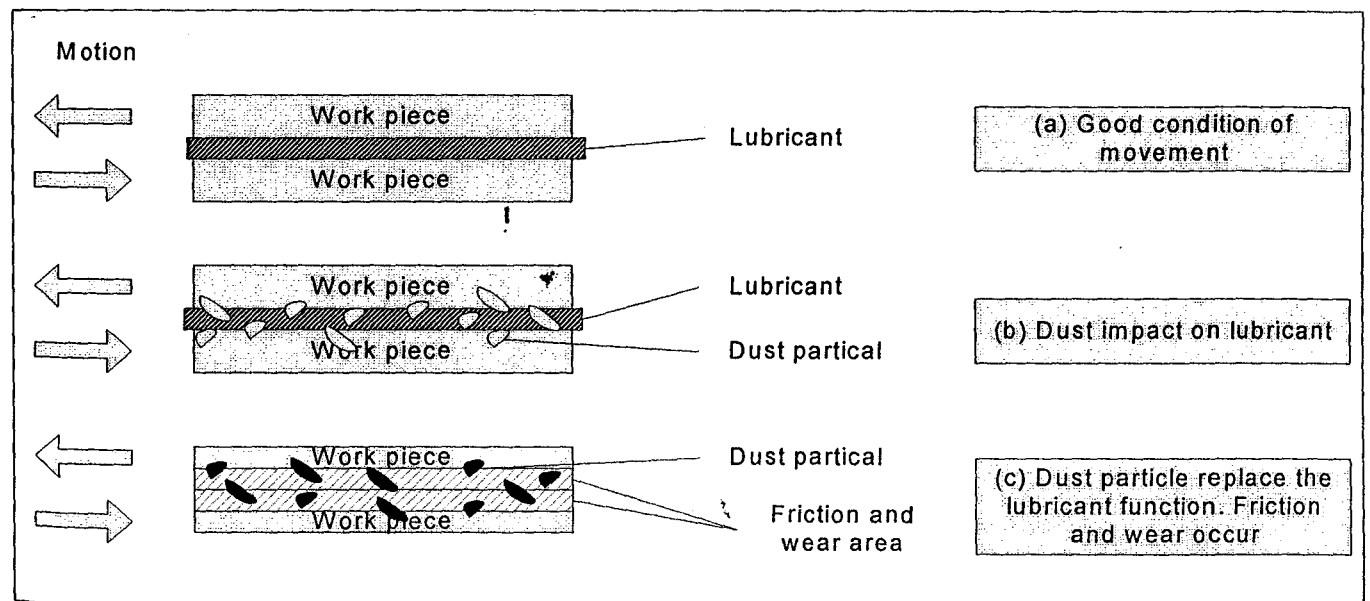


Figure 2: The impact on dust particle between materials surface. (a) Good condition, (b) Exposure of lubricant to dust. (c) Dust particles replaced the lubricant function.

Types of wear

Burwell [10] from his survey listed four types of wear i.e. adhesive wear, abrasive wear, erosive wear and surface fatigue. Adhesive wear, abrasive wear and erosive wear are mostly related to the dust pollution. Abrasive wear occurs when dust particles are grounded between two components surface and it causes a material removal process [11, 12]. Abrasive wear is caused by hard and rough surface or a surface containing hard and protruding particles (such as dust) that slides across a surface. Under the conditions of high velocity or high pressure or both, small particles can impinge on the component surface; this phenomenon is known as erosive wear. In this case, particles can be much smaller than the components clearances but can cause extensive damage due to the velocities and pressures involved [13]. Particles generated during erosive wear also add to the overall contamination of the components and further increase machine wear. Erosive wear most commonly occurs in hydraulic systems that contain devices such as servo and proportional valves. Adhesive wear takes place under the conditions of excessive load, low speed, or reduced fluid viscosity, occurring when the fluid-film thickness is reduced to the point where metal-to-metal contact occurs [14]. When "high spots" or asperities from the opposing surfaces come into contact, they are cold-welded together. As the components surfaces separate, the welded asperities are sheared off and become wear particles in the lubricant. Due to the cold-welding process, these adhesive wear particles are harder than their parent metal surfaces. Further cold-working, as they are broken into smaller particles, makes them even harder.

The impact of short circuit on electrical and electronic components

The impact of dust pollution on electric and electronic components usually is a factor for short circuit. Generally, short circuit can occur due to various reasons such as short on the load, a mistake during the connection of the wires between the device and the load (i.e. L6203 driving a motor) and also an accidental short between the wires. Polykrati et al [15] stated that short circuits initially appear as asymmetric and afterwards as symmetrical. In terms of short-circuit current asymmetric part includes both the alternate current (A.C.) and direct current (D.C.) components and symmetrical part includes the steady-state short-circuit current. As discussed in the previous section, the characteristic of dust such as electric conductivity, corrosive, thermal absorption, thermal conductivity and capability to produce microorganism are the basis for disturbing the electrical function and causing short circuit. Dust particles from metal, ceramic and cement processing contain various metal elements such as aluminum, zinc, copper and silver (Refer Table 1, 3 and 5). These metal elements possess the conductivity characteristic. It can develop a connection in the electrical and electronic

circuit and short circuit can occur. In addition, as discussed in previous section dust pollution from agricultural-based and wood industries contain various organic and inorganic elements such as carbohydrates, alkaloids, proteins, organic and (hay, paper and fuel). All these elements have the ability to react with other environmental parameters such as temperature and humidity to produce microorganism. Fungus, bacteria and spores are some microorganism that will have affect on the electronic components and result in malfunction of the machine. Oyebisi [16] reported that fungi and spores gave an impact on capacitance value of some types of capacitor. In long term the performance of capacitor will be reduced and current load will be unstable. Hence, it contributes to the short circuit on electric and electronic components.

5.0 CONCLUSION

This paper has reviewed the generation of dust pollution generated from various processing industries such as cement, ceramic, metal, agricultural-based and wood. The characteristics of dust pollution emitting from these industries are presented. It has been found that the dust generated by processing industries contains various toxic gases, metals, organic and inorganic materials. Furthermore, the paper has also discussed the capability of the dust pollution to react with environmental parameters (temperature and moisture). It has been observed that the dust particles have adverse physical impacts on the machine components. In addition, the paper has also discussed in detail the effects of physical impacts on the machine components. As for future work, further investigations will be carried out to focus on more detail parameters such as time of exposure and the effects on machine performance due to the impact of dust particles.

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THE EFFECT OF REPAIR AND REPLACEMENT TIME FOR THE MACHINE'S COMPONENT EXPOSED TO DUST PARTICLES

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Abstract

Dust pollution is a serious problem faced by many processing industries. It has been observed that the processing industries such as cement, ceramic, metal, agricultural-based and wood generate dust pollution in large quantities. Various types of dust particles are generated based on their materials processing which are not only unhealthy for human but also have adverse effects on machines. Machines used in the processing industries have a combination of mechanical, electrical, and electronic components. The performance of these components and the machine as a whole can be adversely affected by the dust pollution. Moreover, the impact of dust particles on the machine may give rise to higher risk of machine breakdown. Replacing a failed component and implementing the repairable analysis observed to be an effective method to reduce the failure rate and improve the machine reliability. In this paper, the effects of repairable and replacement time for the machine components failed that cause by dust particles is described. A framework has been proposed to analyze the impact of dust particles on repairable and replacement time of the machine's component.

Introduction

Maintenance can be defined as all activities performed on a component to retain it in or restore it to a specified state. Preventive Maintenance (PM) and Corrective maintenance (CM) are the important elements in maintenance system. PM is referring to restore or keep the component to function at the stated condition. CM is focusing on bringing the failed component to state in which it can again perform the required function. CM, also known as repair or replacement of a fail component; which is repair refers to the repairable components such as mechanical parts and replacement refers to the non-repairable component such as electric and electronic parts. However, the replacement time for repairable component will be carried out base on their lifetime or component aging [1]. It means after i th number of identical component has been repaired, it will be replaced by new one at time T . Time, T also refer as preventive replacement. Machine breakdown that contribute by component failure is a problem on the shop-floor. Component failure can be divided in two situations; firstly the component totally failed (out of function) and secondly the degradation (reliability reduction) of the component. These types of failure usually refer to the minimum failure and major failure or catastrophic failure [2, 3]. Lam and Zhang [4] has reported that the deterioration of a component is due to an internal cause such as aging and accumulated wear of the system. Whereas, an external cause such as an environmental factor such as temperature, humidity and dust is another reason for the component

deterioration to failure. In this paper, the impact of dust particles on repairable and replacement time on machine's component will be discussed. First part of this paper will discuss the repairable and replacement under different approaches for PM and CM. Second part will focus on the concept of minimal repair and optimum time of replacement for repairable component. Next part will discuss an impact of dust particles on repairable and replacement time. The framework to analyze the impact of dust particles on repairable and replacement time of the machine's component is proposed and it will be discussed in the final section.

Repairable and Replacement System - PM Vs CM Approaches

Repairable and replacement (RR) can be classified into two groups, which is RR for Preventive Maintenance (PM) and Corrective Maintenance (CM). RR for PM and CM can be differentiated on how the RR will be implemented. RR for PM will be carried out when the function of machine's component is under reliability requirement. Whereas, RR for CM will be carried out after the component failed. Wang [5], has reviewed in detail the maintenance system regarding the repairable and replacement between the PM and CM approaches. His paper includes a comparison of various repairable and replacement policy such as 'age replacement policy, random age replacement policy, block replacement policy, repair cost limit policy, repair time limit policy and repair number counting point policy. According to the repairable component (CM approach) such as mechanical component, the repair process will be carried out continuously. Repair process can be divided by two situations either the renewal or minimal repair processes. Renewal process is consistent with the notion that the component is restored to its original condition, or "as good as new" [6]. Whereas, minimal repair process will leave the component in approximately the same state (age) it was in just prior to the failure and the component reliability will improve but not as a new component.

The Concept of Minimal Repair and Optimum Time of Replacement

Minimal repair means that a failed component will function, after repair, with the same rate of failure and the same effective age as at the epoch the last failure [7]. Therefore, as a result of minimal repair, the Time Between Failure (TBF) of the component will be shortened and the component may continue to deteriorate over time. A useful and somewhat natural way to model this situation is to treat as a stochastic point process. To model this point process, an intensity function, $\rho(t)$ defined as the rate of change of the expected number of failures with respect to time and a common form for the intensity function is in equation (1) [6]. Intensity function also referred to as the renewal rate, failure intensity, peril rate, or the rate of occurrence of failure. Intensity function is an absolute rate of failure for repairable component.

$$\rho(t) = abt^{b-1} \quad \text{Where } a, b > 0 \quad (1)$$

Which a , and b is the parameters of intensity function. If $b < 1$, the component is improving over time and if $b > 1$, the component is deteriorating over time, as might be observed under minimal system repair. The expected number of failures in the interval (t_1, t_2) can be computed from equation (2),

$$m(t_1, t_2) = E[N(t_2) - N(t_1)] = \int_{t_1}^{t_2} \rho(t) dt \quad (2)$$

Machine consists of many components that refer as a system. If the system is under minimal repair process, the repair time of the overall component that composing a system can be compute an average (mean) from knowledge of the mean component repair time. The system Mean Time To Repair (MTTR_s) is

$$MTTR_s = \frac{\sum_{i=1}^n q_i f_i MTTR_i}{\sum_{i=1}^n q_i f_i} \quad (3)$$

Where

MTTR_s = The system mean time to repair

MTTR_i = The mean time to repair of the *i*th unique component

q_i = The number of identical component of type *i*

f_i = The expected number of failures of the *i*th unique component

The expected number of failures of the *i*th component can be computed from

$$f_i = \left\{ \int_0^{t_{oi}} \rho_i(t) dt \right\}, \text{ for minimal repair}$$

Where, *t_{oi}* is the total umber of operating hours of the *i*th component over the system design life.

A failed component will be repaired until *n*th number of repair and it will be replaced with a new component when it reach maximum number of repair (cost consideration) or their age of design life at time, *T* (preventive replacement). This concept also known as age replacement policy that introduced by Barlow and Hunter [8] and has extended by many researchers. For instance, Pham and Wang [9] extended this concept to Corrective Maintenance (CM) after a component failed and Preventive Maintenance (PM) at age, *T*. The CM or PM can be minimal, imperfect or perfect repair. In this paper, we focus on minimal repair at failed component and replace (perfect repair for PM) a new component at age, *T* or *n*th number of repair. The replacement time can be express by equation (4), which is *a* and *b* is the parameters from intensity function.

$$t^* = \left[\frac{C_u}{C_f a(b-1)} \right]^{1/b} \quad (4)$$

Where,

C_u = unit cost

C_f = cost of a failure (repair cost)

*t** = replacement time

The Impact of Dust Particles on the Repairable and Replacement Time

Dust pollution is an environmental problem that occurs in most processing industries such as cement, ceramic, metal, agricultural-based and wood processing. Dust particles can be in different form such as powder, chips, fibre or smoke and also have different characteristics [10]. Dust particles affects are not only unhealthy for human but also have adverse effects on machines in term of their reliability and maintainability. In the processing industries, the main sources of dust particles that give an impact on machine's component is generated by product (raw materials) it self during machine processing such as grinding, sawing, polishing, rewinding and drilling. The impact of the dust particles will deteriorate the function of machine's components and it is the contributor to component failures. The examples of component deteriorating before it totally fail are loss of motor power frequently, less sensitivity of sensor and friction on bearing or shaft. The types of component failures that cause by dust particles can be occurred in different modes of failure. For the mechanical component, their failure modes are friction, wear and tear. Whereas, the electric and electronic components are short circuit, less sensitivity and power intermittent.

The component failure that cause by dust particles will affects to their repairable and replacement time. The Mean Time To Repair (MTTR) (for repairable component) will be shorted by increasing the amount of dust particles expose. Then, the replacement time (repairable component) of the component also will be shorted compare their actual design life time. Therefore, the amount of dust particles expose on machine's component is the important parameter to cause the component failures. Hence, it's important to identify the amount of dust particles that can give an impact on component failure. Thus, the number of next failure (number of repair) and optimum time of replacement of the machine's component can be predicting base on the amount of dust particles expose. The next section will discuss the framework to analyze the impact of dust particles on repairable and replacement time of the machine's component.

The Framework of Repairable and Replacement Analysis

The main objective of the framework is to identify the impact of dust particles on machine's components failure and the effects to their repairable and replacement time. Figure 2 shows the framework for the machine's components that being exposed to extreme dust particles and the analysis of an effect on their repairable and replacement time. The source of dust particles is assumed to be generated from raw material during machine processing. The framework consists of four stages; the first stage will focus on the identification of the components failure that cause by the dust particles using Failure Mode and Effect Analysis (FMEA). Second stage will focus on data collection. Next stage will focus on the data analysis and the final stage will focus on the analysis repairable and replacement. Detail processes of each stage will be discussed in the next section.

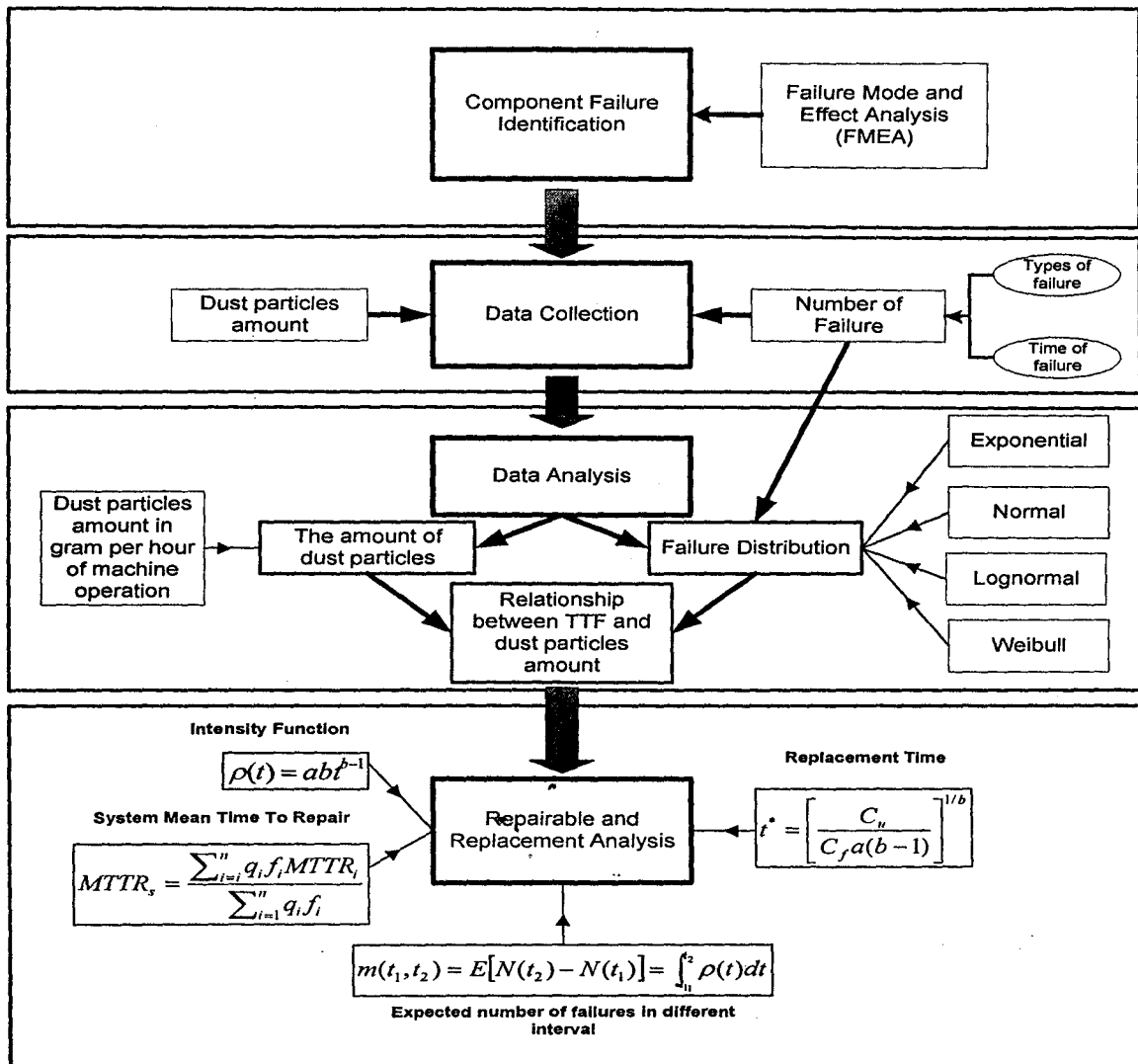


Figure 2: The Framework of Repairable and Replacement Analysis for Machine's Component Exposed to Dust Particles

Component Failures Identification

The main objective of this stage is to identify the machine's component failures that cause by the dust particles. Historical failure records are needed to identify the component failure that frequently occurred. Failure Mode and Effect Analysis (FMEA) will be used to identify the components failure in term of their failure modes and failure causes. FMEA is a method to analyze the characteristic of the component failure for getting primary document for obtaining diagnosability information. Diagnosability information is used for predictive analysis such as reliability and maintainability [11]. The basic steps used in performing FMEA are as follows;

1. Define the component failure, its associated component function and their mechanism process
2. Identify and list down the failure modes of the component
3. Identify and list down all possible causes of failure modes
4. List effect or effects of each failure modes on overall machine process
5. Review each critical failure modes and initiate appropriate measure

In this framework, FMEA will be performed in different approach to reach the objective in this stage. Different approach is referring to identify the component that their failure modes are cause by dust particles. First step of FMEA will focus to identify the components subject to failure. It includes the understanding of the components function and their mechanism process such as their input and output. Second step is focusing on the identification the failure modes of the components. Examples include fractures, short, ruptures, breaking and loss of output. Step three is identification the possible causes of failure modes. The main objective at this step is to identify the failure modes of the component that cause by dust particles. All possible causes of failure modes will be listed and it will be discussed among the experts such as maintenance, mechanical and electrical engineer. The result of this analysis will focus on the component that failed cause by dust particles and this component will be the target components at the next analysis stage.

Data Collection

In data collection stage, two types of data will be collected. It includes the number of component failure at interval (t_1, t_2) and the amount of dust particles that expose on the components. The numbers of components failure at interval (t_1, t_2) include the information such as Time To Failure (TTF), time to repair (minimal repair) and total machine downtime. This data can be collected from historical record and current data. Regarding the amount of dust particles, the main sources of dust particles are considered from raw materials that processed by the machine. Therefore, the amount of dust particles that expose on the component at certain time can be predicted when the quantity of raw materials is known with assumption there is repeated process and the machine speed is constant. The amount of dust particles that generate by m , quantity of raw material in one hour of machine operation will be identified. The quantity of raw material can be measured in pieces (pcs), kilogram (kg) or ton (T) and the amount of dust particles expose will be measured in gram per hour (ghr) using a standard dust collection technique. A hand-held dust collector is use for the dust collection with specification of airflow is $33\text{m}^3\text{h}$ or 19.4 cfm. The amount of dust particles (ghr) that generate in one hour by m , quantity of raw material will be recorded. The six to eight reading is needed to compute their average amount of dust particles that expose on the component in one hour of machine operation. Hence, the average amount of dust particles generates by m , quantity of raw material in one hour operating time will be used to estimate the TTF of identical component at next interval.

Data Analysis

The main objective at this stage is to identify the failure trend of the component and the relationship between Time To Failure (TTF) of the component and the amount of dust particles expose. The failure trend is referring to the failure distribution of the component at interval (t_1, t_2) , whereas, it can be exponential, normal, lognormal or weibull distribution. The relationship between TTF and the amount of dust particles expose is referring to the identification the amount of dust particles that generate by raw material that cause to the component failure. On the other words, if each hour of machine operation has generated d gram of dust particles, component will fail when

the amount of dust particles reach at di gram, where i refer to the total hour of machine operation.

The fit distribution test (goodness-of fit test) is the method use to identify the distribution of failure data at interval (t_1, t_2) . The objective of this test is to fit a theoretical distribution to a random sample of failure or repair data. By fit it mean to perform a statistical test in order to accept or reject the hypothesis that the observed times come from a specified distribution [6]. This method consists of exponential distribution, normal distribution, lognormal distribution and weibull distribution test.

Repairable and Replacement Analysis

In order of repairable and replacement analysis, minimal repair process will be carried out after the component failed. The number of repair (minimal repair) is depending on the number of the component failure at interval (t_1, t_2) and this process will generate the fail-repair-fail-repair cycle until the component reach to the replacement time. To determine the expected number of component failures at the next interval, the intensity function, $\rho(t)$ [equation (1) and (2)] will be used to model the minimal repair process. The Time To Failure (TTF) of the component can be estimated base on the amount of dust particles expose during machine operation.

In the case that more than one components in a machine (consider a system) and fail at random time cause by dust particles, the average (mean) system repair time will compute as a weighted average of the overall components that compose the system MTTRs (system Mean Time To Repair). The weights are based on the relative number of failures at previous intervals. The MTTRs can be calculating using equation (3). Base on theory after i th number of repair occurred, the component will be replaced by new one at time T ; the optimum time of component replacement will be computed using equation (4). The variables to compute the optimum time of component replacement includes cost of new component C_u , cost of a failure (repair) C_f and parameters from intensity function.

Conclusion

Repairable and replacement of the component can be divided into two approaches, either preventive maintenance or corrective maintenance. The different between repairable and replacement for preventive and corrective approach is the time there are apply. In preventive, repair and replace will be carried out before the component fail, whereas in corrective approach it will conduct after the component failed. Minimal repair is the frequent process in repairable component. Replacement of the component will be carried out when the component reach n number of repair or at age T . Internal and external sources influence the number of failure (repair) and the time of replacement in interval (t_1, t_2) . Internal causes include the factors such as aging and accumulated wear, whereas an external cause is focus with environmental factors. Dust particles is one of the environmental factor that cause to the component failure. Hence, the repairable and replacement time of the component also have an effected. The number of component failure at interval (t_1, t_2) will increase when the amount of dust particles expose increase. A framework has been proposed to analyze the impact of dust particles on machine component on their repairable and replacement time. The

first stage is focus on the identification of the component failure that cause by the dust particles using Failure Mode and Effect Analysis (FMEA). FMEA is the practical method to identify the characteristic of the component failure. Second stage is focus on data collection; two types of data will be focused, first is number of components failure at interval (t_1, t_2) and second, is the amount of dust particles that being expose over operating time. Next stage is focus on the data analysis. The main objective is to identify the failure trend of the component and the relationship between Time To Failure (TTF) of the component and the amount of dust particles expose. The final stage is focus on the analysis repairable and replacement. At this stage, Mean Time To Repair (MTTR) of the machine's component will be determined, the expected number of the failure at next interval (t_m, t_n) will be predicted and optimum time of replacement will be determined.

Acknowledgement

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THE IMPACT OF DUST PARTICLES ON MACHINE'S RELIABILITY AND PREVENTIVE MAINTENANCE TIME

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Abstract

In processing industries, machining processes such as grinding, milling, sawing, drilling, polishing, rewinding and crushing is the major contributors of dust pollution. These processes generate huge amount of dust particles that not only have adverse effects on the workers health but also on machine's component function. The exposure of machine's component to the extreme dust particles will reduce the reliability of the certain component in a machine. As a result, the reliability of the component will deteriorate due to component failure and it will affect to overall machine operation. This paper describes the impact of dust particles on the machine's component in terms of their reliability and the effect to the Preventive Maintenance (PM) time. A framework has been proposed for investigating the impact of dust particles on machine's component reliability. The analysis procedure to determine the optimum time of PM to meet the reliability requirement also is proposed in this framework.

Introduction

The effective maintenance system is one of the important elements for the success of manufacturing operations. The purposed of maintenance is to return a failed or deteriorating of machine's component to a satisfactory operating state. Deterioration is a process where the condition of the component gradually worsens and the process will lead to component failure. The failure rate of the component is constantly increase by operating time and it usually cause by internal causes such as aging and accumulated wear. However, external causes such as dust particles will increase the failure rate of the component before reaching their design lifetime.

Processing industries such as cement, ceramic, metal, agricultural-based and wood generates huge amount of dust particles during their machining processes. The machining processes include grinding, sawing, milling, rewinding and crushing. The effect of dust particles on machine's component will reduce their reliability level and affect the overall machine operation [1]. Preventive Maintenance (PM) is one of the effective strategies to return the component to the level of reliability requirement. PM includes the activities such as periodically inspection or minimum repair/replace of the component before it fails [2]. In term of cost, PM activities reduce the overall maintenance cost compare to the Corrective Maintenance (CM) activities. PM is the systematic approach through the schedule activities to avoid the component failure during machine operation. This is because major repair or replace after component

failed (CM) will increase not only the maintenance cost but also the operation cost such as labour, production and reject cost. In this paper, the impact of dust particles on machine's component reliability and the effect to their PM time will be discussed. First section in this paper will focus on the reliability concept of machine's component. Second section will discuss the reliability of machine's components under Preventive Maintenance (PM) policy. Third section will discuss the theory of the impact of dust particles on machine's component in term of their reliability and the effect into the PM time. Final section in this paper a framework for investigating the impact of dust particles on machine's component reliability is proposed. This framework includes the procedure to determine the optimum time of PM to meet the reliability level of the component

Reliability Concept of Machine's Components

Reliability can be defined as a probability of a component that perform a required function for a given period of time when used under stated operating conditions. It is an important factor in component maintenance because lower component reliability means higher need for maintenance. Generally, the reliability of a component can be computed by using equations (1) and Mean Time To Failure (MTTF) is the basic measure of the component reliability [3];

$$R(t) = \exp\left[-\int_0^t \lambda(t) dt\right] = e^{-\lambda t} \quad (1)$$

$$MTTF = \int_0^{\infty} R(t) dt = \int_0^{\infty} e^{-\lambda t} dt \quad (2)$$

Where,

$R(t)$ = reliability at time t

$\lambda(t)$ = hazard rate or time-dependent failure rate

A machine consists of many components that refer to a system. A system consists of more than two components that it may be related to one another in two primary ways: in either a serial or a parallel configuration. Reliability of a system can compute base on their components configuration. In series, all components must function for the system to function. In a parallel or redundant, at least one component must function for the system to function [4]. Figure 1 show the reliability block diagram of serial and parallel configuration and their formula to compute the overall system reliability.

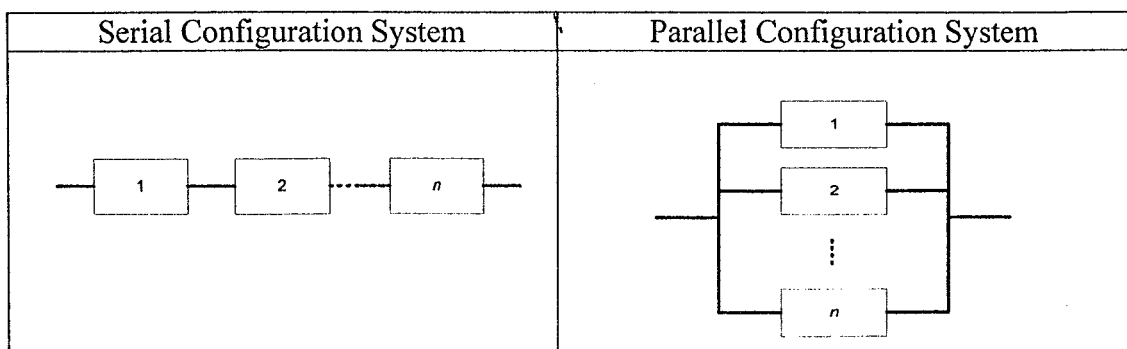


Figure 1: The block diagram of an n-unit/component series and parallel system

For independent and non-identical components, the reliability for the series and parallel system can be obtained using equations (3) and (4), respectively.

$$R_s(t) = \prod_{i=1}^n R_i(t) = \prod_{i=1}^n \exp(-\lambda_i t) = \exp(-\lambda_s t) \quad (3)$$

$$R_p(t) = 1 - \prod_{i=1}^n [1 - e^{-\lambda_i t}] \quad (4)$$

Where,

- R_s = Series system reliability
- n = Number of unit
- R_i = Reliability of unit or block i

Reliability of Machine's Component under Preventive Maintenance Policy

The improvement of reliability level for the machine's component can often be achieved through a maintenance policy. Preventive Maintenance (PM) is an effective program that can reduce the effect of aging or wear-out and have a significant impact on the life of the machine's component. Assume that when the reliability level of the machine's component is under requirement, it will be restored or minimal repair to its original condition following the PM time or cycle. Let $R_m(t)$ be the reliability function of the machine's component with PM [4]. Then,

$$R_m(t) = R(T)R(t - T) \text{ for } T \leq t < 2T \quad (5)$$

Where, $R(T)$ is the probability of survival until the first PM and $R(t - T)$ is the probability of surviving the additional time $t - T$ given that the machine's component was restored to its original condition at time T . The general equation can be expressed as,

$$R_m(t) = R(T)^n R(t - nT) \text{ for } nT \leq t < (n+1)T, \text{ where } n = 0, 1, 2, \dots \quad (6)$$

Where $R(t)^n$ is the probability of surviving n maintenance interval and $R(t - nT)$ is the probability of surviving $t - nt$ time components past the last PM. The MTTF under PM can be found using equation (7).

$$MTTF = \int_0^{\infty} R_m(t) dt = \frac{\int_0^T R(t) dt}{1 - R(T)} \quad (7)$$

The developments of PM policy to improve the reliability level of machine's component have been reported in many papers. For instance, Zhao, [5] developed a PM policy with a critical reliability level to meet the preference of field manager. Lin and Titmuss [6] developed a PM policy based on the lifetime of an individual component to improve their reliability level. However, most of the reliability study under PM policy assumed that the component undergoes relatively constant condition of environment during their operation and the component failure is caused by internal causes such as aging and accumulated wear [7]. In this paper, the impact of dust

particles (external causes) on the machine's component reliability and the effects to the PM time will be the focus of the study.

The Impact of Dust Particles on Machine's Component Reliability and PM Time

As mentioned previously, processing industries generates huge amount and various types of dust particles that are not only unhealthy for human but also have adverse effects on machines performance. Ahmad et al, [1] discussed in detail regarding the impact of dust particles on machine operation in term of their maintainability and reliability. They also addressed the types of physical impact of dust particles occurred on machine's components that affected on overall machine performance. Extreme condition of dust particles will reduce the reliability level of machine's component faster compare if the component operates under normal condition (without/less of dust particles). Therefore, the PM time or Time Between Preventive Maintenance (TBPM) at interval (t_a, t_b) also will be short. Figure 2 show the effect of PM time for reliability reduction of the machine's component that expose to different amount of dust particles.

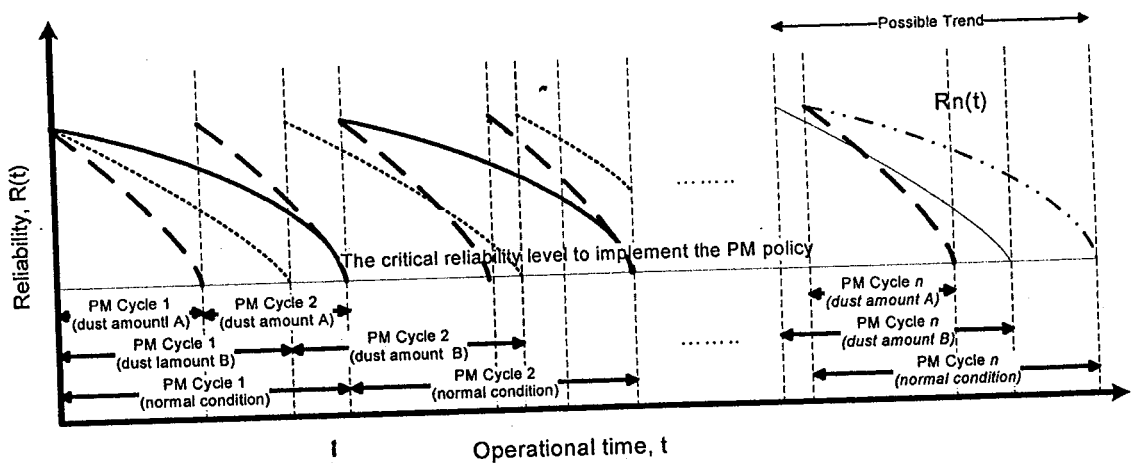


Figure 2: The PM time for reliability reduction of the machine's component that expose to differ amount of dust particles

Referring to figure 2, the number of PM (cycle) at interval (t_a, t_b) will increase when the amount of dust particle expose on machine's component increase. These hypotheses assume that the time of PM depends on the level of dust particles that expose on machine's component and their reliability level after PM will return to original condition.

In real situation, the main sources of dust particles come from raw materials used and also generated during machining processes. The amount of dust particles that emitted during machining process influence by various factors such as machine speed, types of processing and raw materials used. Hence, the amount of dust particles and the time that machine's component expose to dust particles are the important parameters that cause the component failure. A framework will be proposed in the next section to investigate the effect of both parameters to component reliability and determine the optimum time of PM to meet the reliability level of component.

The Framework of the Machine's Components Analysis

In this section, a framework is proposed to investigate the impact of dust particles on machine's component reliability and to identify the optimum time of Preventive Maintenance (PM) to meet the reliability requirement. This framework focus on machine's components that an expose to extreme dust particles during machining process. The source of dust particles is assumed to be generated from raw material that being processed by the machine. Figure 3 shows the schematic diagram of the framework. The framework consists of three phases; first phase will focus on identification the failure of the components that cause by dust particles using Failure Mode and Effect Analysis (FMEA). Second phase will focus on data collection that consists of two types of data. Third phase will focus on data analysis to determine the reliability level of machine's component and compute the optimum time of PM to meet the reliability requirement. Detail explanation of the each phase will be discussed in the following section.

Phase 1- Identification the Machine's Components Failure and Configurations

The main objective in this phase is to identify the failure of the machine's components that cause by dust particles and their configuration in a machine. The failure of the components and their configuration will be analyzed using Failure Mode and Effect Analysis (FMEA). FMEA is a useful method of failure analysis for obtaining diagnosability information and it is valuable input for predictive analysis such as reliability and maintainability [8]. FMEA use to identify the characteristics of the components failure in term of failure modes, the causes of the failure modes, assessing their probabilities of occurrence and their effects on the whole machine operation, and determining corrective or preventive measure [4].

In order to achieve the objective of phase 1, the first step of FMEA will focus on identification the machine's components that will be subject to failure and their configuration. It include the definition of components function and physical (hardware) description of the components. A functional analysis provides the initial description of the components without regard to how the components will operate and maintained. The physical description of the components is represented by an indenture diagram showing subassemblies, sub-component, and parts along with their hierarchical relationship. The second step will focus on identification the failure modes of the components that subject to failure. In other word, it identifies how the components failed. Examples, include fractures, short, ruptures and loss of output. Third step will focus on identification the failure modes causes. The main purpose in this step is to identify the failure modes of the component failed cause by the dust particles. All the possible failure modes that cause by the dust particles will be identified. As a result, the most possible failure of the components that cause by dust particles will be the focus of investigation the reliability and PM analysis.

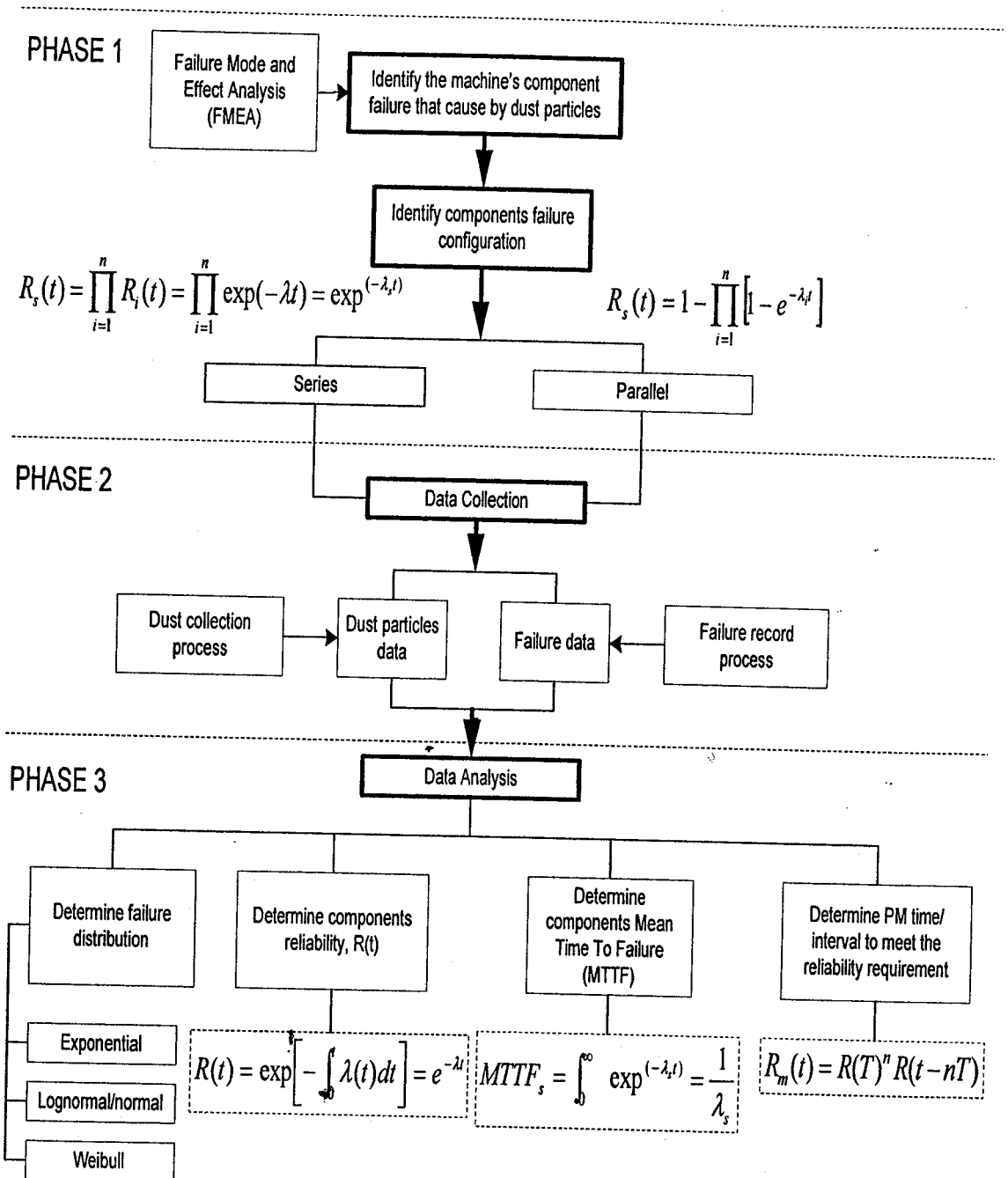


Figure 3: Framework of machine' component that expose to dust particles and the procedure to determine the optimum time of PM base on reliability requirement

Phase 2-Data Collection

The main objective of the second phase is to identify the number of components failure at interval (t_1, t_2) and the amount of dust particles expose during operating that cause the components failure. The number of components failure will be used to determine the components reliability and Time Between Failure (TBF) in interval (t_1, t_2) . The amount of dust particles that cause the components failure will be used to identify the next Time To Failure (TTF) of the components.

Data can be divided into two types; first data is regarding the number and the time (date or machine operating time) of components failure at interval (t_1, t_2) that identified at phase 1. The interval time can be determined base on mission time, a scheduled maintenance interval and/or component design life. Second data is the amount of dust particles that expose on the components during their operating time.

The amount of dust particles will be collected using a hand-held dust collector with specification of air flow is $33\text{m}^3/\text{h}$ or 19.4 cfm. The process of dust collection will be carried out in one hour (collecting time) during machine operation. This process will repeated six times to get the average amount of dust particles expose in one hour operating time with assumption that used similar raw material (product), identical machine and process, and the constant speed of the machine. Therefore, if the average amount of dust particles expose in one hour of machine operation is x , which is, x will be measured in gram per hour and if, i is the total time of machine operation; then the total amount of dust particles that expose in i hour operating time into the machine's component is xi gram hour.

Phase 3-Data Analysis

Final process of this framework is data analysis. The main objective in this phase is to determine the failure distribution, reliability of the components that subject to failure, Mean Time To Failure (MTTF) for the components and estimate the optimum time of Preventive Maintenance (PM) to meet the reliability requirement of the components. First step of data analysis is to determine the failure distribution. The fit distribution test (goodness-of fit test) is a method for identifying the distribution of failure data at interval (t_m, t_n) . The objective of this test is to fit a theoretical distribution to a random sample of failure or repair data. By fit it means to perform a statistical test in order to accept or reject the hypothesis that the observed times come from a specified distribution [4]. This method consists of exponential, normal, lognormal and weibull distribution test. After the failure distribution is obtained, the next analysis is to compute the MTTF and reliability of the components that subject to failure. Equation (1), (2), (3) and (4) will be used to compute MTTF and the reliability of the components. Finally, the analysis to determine the optimum time of Preventive Maintenance (PM) to meet the reliability requirement will be carried out. Equation (5) and (6) will be used to compute the optimum time of PM, where T is the maintenance interval.

Conclusion

This paper has discussed the impact of dust particles on machine's components reliability and the effect on Preventive Maintenance (PM) time to meet their reliability specification. The hypothesis of the impact of dust particles on machine's components reliability and their PM time was given. A framework was proposed to identify the optimum time of PM to meet the reliability specification of the components. In the framework, the experiment and measurement procedure is proposed. It includes identification of machine's component failure cause by dust particles, data collection and data analysis process. FMEA is used to identify the machine's components failure that cause by dust particles. These components will be the focus components for the

ANALYSIS OF FAILURE DATA FROM MACHINES PRODUCTION LINE – CASE STUDY IN AUTOMOTIVE INDUSTRY

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Abstract

This paper presents the failure analysis that carried out on machines of a production line at an automotive industry. The failure analysis in this paper consists of Pareto Analysis (PA), Failure Mode and Effect Analysis (FMEA) and Failure Distribution Analysis (FDA). The PA is applied in order to identify and classify the critical machines that contributed major downtime on the production line. It follows by carrying out the FMEA, which the failures at each machine are classified and clarified into failure mode, failure cause, failure effect and failure percentage. Finally, the FDA is performed in order to identify the characteristics of the machines failure. As a result, the preventive maintenance strategy to reduce failure frequency is proposed.

Introduction

In manufacturing industries, the main criterion for maximising the profit depends on the capability of production line to produce high volume of product in short period of time with satisfactory quality standard. However, the high rates of unexpected or sudden failures during machine operations become a major disturbance to achieve maximum profit. Unexpected failures will affect the whole production process and increase the maintenance cost and production lost (machine downtime) (Nakajima, 1986). Preventive Maintenance (PM) strategies such as periodically inspection, preventive replacement and preventive repair are the examples of the solutions to reduce the unexpected failure (Jardine, 1973).

However, the selection of the best and practical PM strategies to reduce unexpected failure must be based on the failure analysis. Failure analysis is the process of understanding the root cause of failure (failure process) and identifying the characteristics of the failure distribution. Failure analysis can be divided by physical or basic failure analysis and failure time analysis. Rausand and Oien (1996) discussed the physical or basic failure analysis, which a case study was carried out on a gate valve failure. They presented a general approach in identification and classification of failure mode, failure effect and failure cause. The popular techniques of physical failure analysis are Failure Mode and Effect Analysis (FMEA), Failure Mode, Effect and Critically Analysis (FMECA) and Fault Tree Analysis (FTA). In failure time analysis, the emphasis is given in modelling process to identify the characteristics of failure distribution, whether the machine is in Increasing Failure Rate (IFR), Constant Failure Rate (CFR) or Decreasing Failure Rate (DFR) conditions. The common approaches in failure time analysis are nonparametric and parametric approaches (Ebeling, 1997).

In this paper, the theory of physical failure analysis and failure time analysis are applied on production machines problem. The main objective is to identify the critical machines, root causes of machines failure and failure distribution of the machines using Pareto Analysis (PA), Failure Mode and Effect Analysis (FMEA) and Failure Distribution Analysis (FDA), respectively. As a result, the best PM strategy is proposed in order to reduce the frequency of unexpected failure and improve the machines availability.

Methodology

The failure analysis was carried out in three phases and it is illustrated in Figure 1. First phase is the Pareto Analysis (PA), second phase is Failure Mode and Effect Analysis (FMEA) and the final phase is Failure Distribution Analysis (FDA). Further discussion each of phase is given in the following section.

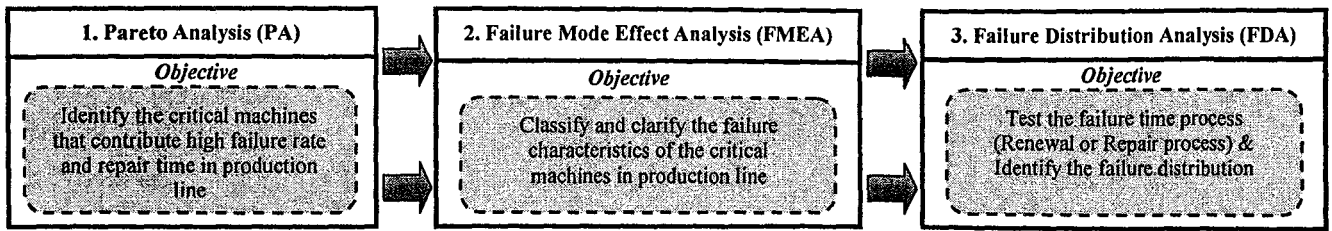


Figure 1: The flow of failure data analysis

Pareto Analysis (PA)

Pareto Analysis (PA) is the basic tool in statistical analysis and it is popular in quality-control applications. For example, PA be able to classify and clarify systematically the types and the number of defect product, thus the lowest to the greatest defects can be presented by the number (percentage value) (Johnson and Kuby, 2000).

In this study, PA was the first analysis use for identifying and classifying the failure rate and repair time rate for each machine on the production line. As a result, the critical machines (mostly higher) that contribute major downtime in production line can be identified and presented in the form of Pareto chart.

Failure Mode and Effect Analysis (FMEA)

FMEA is one of the failure analysis (physical failure analysis) tools. It widely uses in maintainability, safety and survivability analysis (Kolarik, 1995). The main objective of FMEA is to classify and clarify the failure characteristics into failure modes, the failure cause and failure effect (Teng and Ho, 1996; Hawkins and Woollons, 1998). FMEA is carry out based on the steps shown in Figure 2.

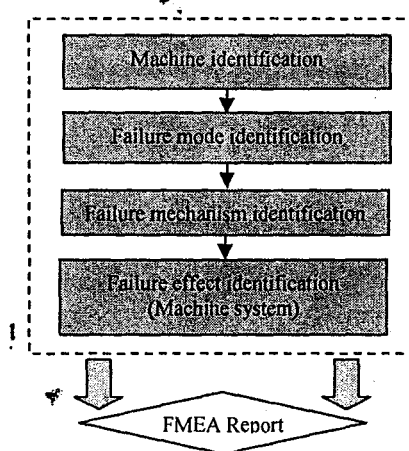


Figure 2: The steps in implementing FMEA

In relation to the work, FMEA was carried out in order to understand the failure characteristics (physical measure) of the machine. The failure characteristics are classified and clarified into failure mode, the failure cause, failure effect and failure percentage.

Failure Distribution Analysis (FDA)

Failure Distribution Analysis (FDA) will present the performance or condition of the machines in quantitative (index) form (Tsai et al, 2001). In this study, the modeling process for fitting the failure distribution is carried out in order to identify the failure characteristics (index measure) of the machine in quantitative form.

Verification of Failure Time Process

Before the failure distribution can be modelled (fitted), the process / trend of failure time must be verified either it follows the Renewal Process (RP) or Power Low Process (PLP) (Ebeling, 1997). The RP means the

machine is assumes ‘as good as new’ after restoration, whereas PLP means the machine is assumes ‘as bad as old’ (the same condition the system was in prior to failure) after restoration. The test procedure of failure time process is shown in Figure 3.

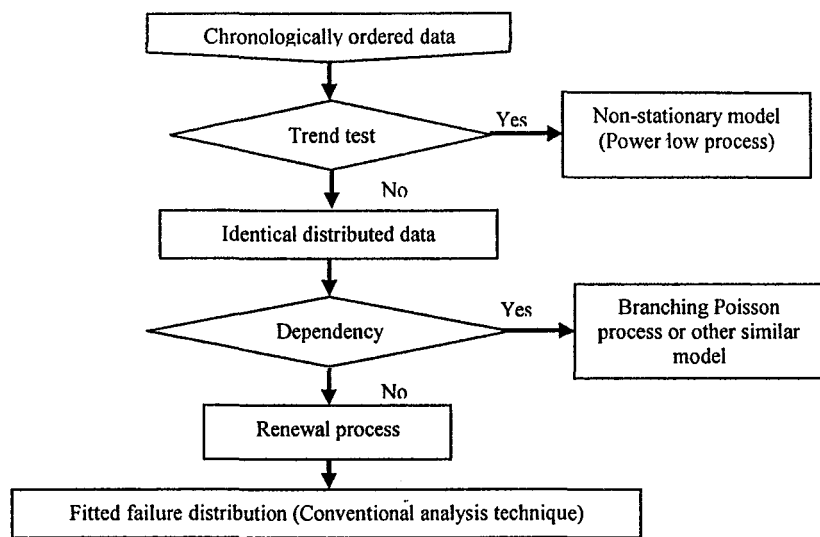


Figure 3: Possible exploratory steps in field failure data analysis before fitting distribution model (Coetzee, 1997)

The trend test for Time To Failure (TTF) is carries out by plotting the graph of cumulative TTF versus cumulative failure numbers. If the graph shows the straight line or most, it assumes no trend and vice versa it assume has trend. If the test shows it has trend (not straight line) then the failure time process of the machine is assumes follows the PLP. If it shows a straight line, then the failure data is tests for identical distributed data (correlation test). The test for correlation can be performed by plotting the i^{th} TTF against $(i-1)^{th}$ TTF, $i = 1,2,3,...,n$. If the results shows it has the correlation then the failure time process is assumes follows the PLP and vice versa follows the RP (Coetzee, 1997).

Failure Distribution Model

The failure distribution is modelled based on result from the verification of failure time process. The most popular model in failure distribution modelling is Weibull model. Weibull model is widely used for mechanical system analysis because it flexible to show the characteristics of failure time based on the value of shape parameter (Józwiak, 1997). Table 1 show the characteristics of Weibull model for minimal repair process and renew process.

Table 1: The characteristic of Weibull model for minimal repair process and renew process

Failure time model	Parameter	Model Characteristic
Minimal repair model	$\rho(t)$ = intensity function	If $b < 1$ the system is improving over time If $b > 1$ the system is deteriorating over time
$\rho(t) = abt^{b-1}$	b = shape parameter a = scale parameter t = failure time	
Renew repair model	$F(t)$ = density function	
$F(t) = 1 - e^{-\left(\frac{t}{\theta}\right)^\beta}$	β = shape parameter θ = scale parameter t = failure time	If $\beta < 1$ the system is improving over time If $\beta > 1$ the system is deteriorating over time

The focus is to determine the values of ‘b’ and ‘a’ for minimal repair process or the values ‘β’ and ‘θ’ for renew process. Therefore, the system condition can be identified either in improving (decreasing failure rate) or deteriorating (increasing failure rate) conditions. This information is useful for selection of maintenance strategies. For example, if the system is in deteriorating condition with shape parameter, b or β > 1, the application of Preventive Replacement (PR) is useful to improve the system, while if the shape parameter, b or β < 1, the inspection strategy is suggested for system monitoring and early detection from sudden failure.

For identifying the parameter values of Weibull model for minimal repair process or renew process, the Maximum Likelihood Estimator (MLE) is used (Ebeling, 1997). Table 2 presents the formulas for calculating the values of ‘b’ and ‘a’ for minimal repair process and the values of ‘β’ and ‘θ’ for renew process.

Table 2: The formula to determine the shape and scale parameters

Formula	Notation
<p>Minimal repair model</p> $b = \frac{n}{(n-1) \ln t_n - \sum_{i=1}^{n-1} \ln t_i} \quad a = \frac{n}{t_n^b}$	<p>Failure times $t_1 < t_2 < \dots < t_n$ a and b are the minimal repair model parameters if, $b < 1$ = Decreasing failure rate $b > 1$ = Increasing failure rate $b = 1$ = Constant failure rate</p>
<p>Renew repair model</p> $b = \beta = \frac{\sum_{i=1}^n x_i y_i - \bar{x} \sum_{i=1}^n y_i}{\sum_{i=1}^n x_i^2 - n \bar{x}^2}$ $a = \bar{y} - b \bar{x}$	<p>Failure times $t_1 < t_2 < \dots < t_n$ $X_i = \ln t_i$, $y_i = \ln \ln [1/1-F(t_i)]$, $F(t_i) = (i - 0.3) / n + 0.4$</p> $\theta = e^{\frac{a}{b-\beta}}$

Result and Discussion - Case Study

The case study focuses on the camshaft line at an automotive industry. The production (camshaft) line has fifteen machines and the machines layout and production process can be shown in Figure 4. Each of machines has their own operations such as drilling, grinding, etc.

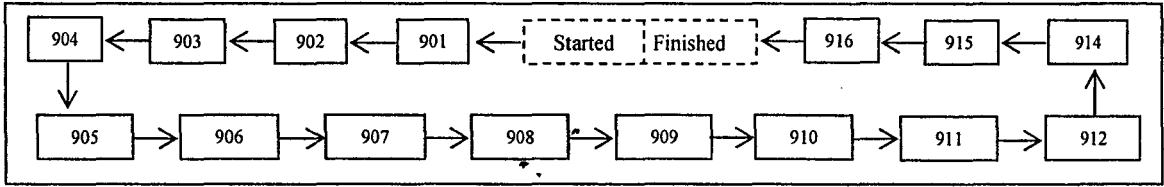


Figure 4: The machines layout in production line

Currently, the major problem on the line is high rate of unexpected failure that randomly occurred on the machines. Once unexpected failure occurs, the whole line will stop and this will increase the production lost (downtime).

Nine months failures record and report of each machine in camshaft line has been collected. For analysis purpose, data have been classified into the machine failure time, repair time, repair actions, replacement components etc. The result of the analysis can be presented in following section.

Pareto Analysis (PA)

Pareto Analysis (PA) is carried out to identify the trends of the failure rate and repair time for each machine in this line. Figure 5 shows the result from the PA for failure rate and repair time of the machine in the camshaft line.

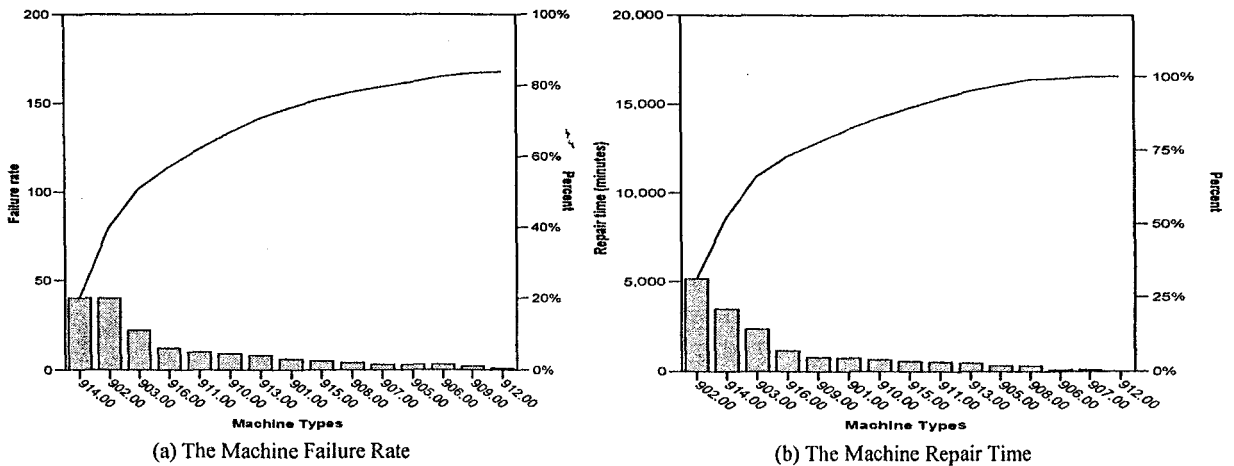


Figure 5: Pareto analysis for failure rate and repair time of each machine in camshaft line

The Pareto chart in Figure 5(a) shows the conspicuous failure rate are recorded on machines 914, 902, and 903, which their failure rate percentage are 23.8%, 23.8% and 13.1%, respectively. From Figure 5(b), the Pareto chart shows the high repair time are recorded on machines 914, 902 and 903, which their repair time percentage are 31.0%, 20.8% and 14.1%, respectively. In addition, both total percentage of failure rate and repair time for machine 914, 902 and 903 exceed 50%. As a result, the machine 914, 902 and 903 are identified as the critical machines.

Failure Mode and Effect Analysis (FMEA)

The FMEA is carried out on machines 914, 902 and 903 to identify the failures characteristics. Figure 6 summarises the FMEA. The FMEA is classified into failure mode, failure cause, failure effect and failure percentage of each machine.

Machine Type	Failure Mode	Failure Cause	Failure Effects	Failure Percentage %
NC Lathe (902)	Tail stock failure / broken	Block by chip and dust (bearing jammed), miss loading part,	Quality problem, machine can't start operation, production lost	68
	Fix centre failure / broken	Tear & wear, loss grip, high cutting speed, programming error,	Quality problem	36
	Belting spindle abnormal sound	Aging, tear & wear	Machine shutdown	4
	Tool cutter broken	Mechanical error, tail stock problem	Machine shutdown	4
	Spark at cable exhaust fan	Touching with blade fan	Short circuit	4
	Chip conveyor failure (alarm detected)	Electrical failure (power supply unbalance, short)	Operation stop	4
CBN CAM Grinding (914)	Temperature increase drastically (temperature alarm detected)	Water float coolant low level, pump low pressure (dust blocking), valve problem, lubricant oil empty, filter dirty (dusty)	Quality problem, operation jammed	55
	Door cannot open/close	The screw and nut at door and cylinder connection missing	Operation stop	39
	Abnormal sound at wheel spindle	Bearing and belting in tear & wear condition, dirty condition (dusty), lubricant oil low,	Machine operation abnormal (lead to failure)	3
	Belting and bearing failure (break or broken)	Tear & wear	Operation stop	3
NC Lathe (903)	Product out of specification	Spindle in wear & tear condition, miss alignment	Product reject (production lost)	31
	Chip conveyor jammed (alarm detected)	Spark killer failure, motor jammed, dust and dirty condition, pin and nut missing	Production stop, bottle neck	38
	Oil leaking at bearing and hydraulic component	Seal failure (wear & tear)	Abnormal sound / vibration	15
	Timing belt broken	Aging, tear & wear	Operation stop	15

Figure 6: The analysis of FMEA on machines 914, 902 and 903

From the FMEA, the major breakdown on machine 902 (NC Lathe) are contribute by tail stock and fix centre failures (broken), which their failure percentage are 68% and 36%, respectively. The factors of chip or dust and miss loading part are the causes for tail stock failure, while the wear & tear, loss grip, high cutting speed and programming error are the causes of fix centre failure. Both of tail stock and fix centre failures affect the quality of the product and disturbed the whole line process.

Over heated, which increase drastically (detected by alarm) and machine door failure (cannot open/close automatically) are the major problem that occurs on machine 914 (CBN CAM Grinding). The failure percentages are 55% and 39%, respectively. Result of FMEA shows that low level of coolant, pump function at low pressure (dust blocking) and dirty (dusty) filter are the causes of over heated. Meanwhile, the missing of screws and nuts at door and cylinder connection are the causes of door failure (cannot open/close automatically). The effects of over heated and door failure will cause whole machine system jammed and lead to quality problems.

For machine 903 (NC Lathe), the quality problem (product is out of specification) and conveyor jammed are the major reason of machine 903 breakdown, which their failure (breakdown) percentage are 31% and 38%, respectively. The factors of wear & tear and miss alignment on machine spindle are causes of quality problem. Meanwhile the spark killer failure, motor jammed, dusty condition, pin and nut missing are the causes of conveyor jammed. The effects of quality problem will increase the product rejects and conveyor jammed will lead the bottle neck on the production line.

Failure Distribution Analysis

The next analysis is modelling the failure distribution on machines 914, 902 and 903. Before the failure distribution can be identified, the test of failure time process is carried out to identify either the failure time follows the renew process (RP) or the power low process (PLP). The types of failure time process is determined by carrying out the trend test for Time To Failures (TTFs). It done by plotting the graph of cumulative Time To Failures (TTFs) versus cumulative failure number. The results of trend test for machines 914, 902 and 903 are show in Figure 7.

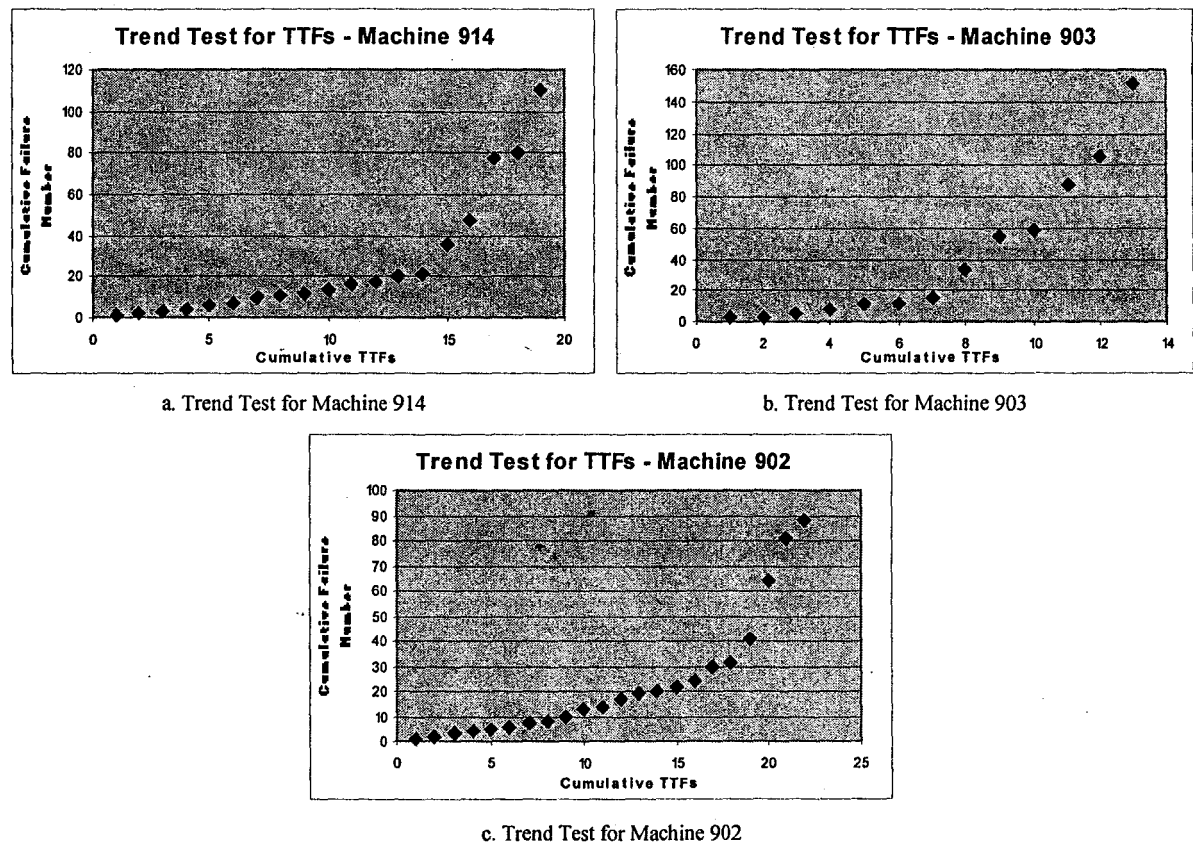


Figure 7: The test for failure time process on machines 914, 902 and 903

Referring to Figure 7 a, b and c, it shows that the lines are increased in the curve form. These results prove that most of the repairable system follows the PLP with minimal repair concept (Coetzee, 1997). Therefore, the failure time process on the machines 914, 902 and 903 are assumed to follow the PLP and their failure distribution will be modelled using minimal repair model.

The characteristics of failure distribution for machines 914, 902 and 903 are modelled using minimal repair model and the results are show in Table 3.

Table 3: Characteristics of failure distribution on machines 914, 902 and 903

Minimal repair model parameters	Machine 914	Machine 902	Machine 903
b	0.47425	0.52672	0.48900
a	1.52024	1.56739	0.63194
$\rho(T)$	0.06091	0.09919	0.02380
MTTF (Mean Time To Failure) – Working shift	16.4	10.1	42.0
90 percent confident interval for MTTF (Working shift)	$10.74 < \text{MTTF} < 32.15$	$6.75 < \text{MTTF} < 18.63$	$25.84 < \text{MTTF} < 98.87$
	Actual MTTF'	Actual MTTF'	Actual MTTF'
	21.4	12.7	62.4

Result in Table 3 shows that the MTTF' of machines 914, 902 and 903 at 90 percent confident interval are 21.4, 12.7 and 62.4. Because the failure unit used in this analysis is number of working shifts, it means that the machine 914 will fail every 10.8 working shifts, while the machines 902 and 903 will fail every 6.8 and 19.3 working shifts.

The values of parameter, b are 0.47425, 0.52672 and 0.48900 for machines 914, 902 and 903. Because of the values, b are less than 1 (refer Table 1), a conclusion can be made that the machine 914, 902 and 903 is in decreasing failure rate or in improving phase. In other words, these machines are in good condition and the maintenance strategy such as preventive replacement is not appropriate because it not affected to the system condition (Jardine, 1973). However, periodically inspection strategy is suggested in order to improve machines availability and reduce the failure frequency (unexpected failure) by eliminating the root causes of failures.

Conclusion

This paper presented the application of physical or basic failure analysis and failure time analysis on critical machines in production line. From the Pareto Analysis (PA), the machines 914, 902 and 903 are identified as the critical machines that contribute major downtime on the production line. The Failure Mode and Effect Analysis (FMEA) is carried out to identify the root cause and the failure process on machines 914, 902 and 903. Then the FMEA results is classified and clarified into failure mode, failure cause, failure effect and failure percentage. From the results of Failure Distribution Analysis (FDA), the machines 914, 902 and 903 are found in decreasing failure rate, which the parameter b is less then 1. Even machine 914, 902 and 903 is in good condition (decreasing failure rate), the failure frequency (unexpected failure) still can be reduced by implementing a periodically inspection.

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MAXIMUM MACHINES AVAILABILITY VIA INSPECTION POLICY – CASE STUDY IN AUTOMOTIVE INDUSTRY

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Abstract

Unexpected failures of machines lead the high downtime in production line. Inspection policy can help to detect the current condition and the root cause that leads to the machines failure. Therefore, regular servicing (cleaning, misalignment, tightening etc) or minor repair or replacement can be carried out to make sure the machines availability is at maximum level. In this paper, the application of inspection model based availability requirement is presented. A case study is carried out on repairable system (machine) in a production line at an automotive industry. The model concentrates on the determination of the optimum inspection time to reach maximum machines availability.

Introduction

The application of Preventive Maintenance (PM) in manufacturing industry has become a necessary in order to increase the system reliability, maintainability and availability. As a result, the system lifetime will be longer, performance will be better and productivity will be higher. In a repairable system, unexpected failure that occurs during machining process will increase the maintenance cost and production lost (Nakajima, 1986). Inspection is one of the PM strategies that are appropriate for a repairable system in order to increase the system availability by eliminating the root causes of unexpected failure.

Inspection can help determined the current status of a repairable system and detect minor error due to major failure (Bahrami-Ghasrhami and Mathew, 1998). Therefore, the appropriate actions such as cleaning, tightening, oil checking and minor repair or replacement can be taken to prevent major failure during machine operation (unexpected failure). In the development of inspection policy, there are several criteria that need to take into account. First is cost criterion, to generate optimal inspection policy. For example, Chelbi and Ait-Kadi (1999) developed an inspection model to minimise the average total cost per unit time, which the model was applied to provide operator with time sequence for inspecting the cutting tool. Mathew (2004) also used the cost criterion in the development of inspection model, where the cost consisting of both breakdown and inspection is minimise. The model was applied for maintenance planning and forecasting. Second criterion in the development of inspection policy is downtime minimisation. For instance, Bahrami-Ghasrhami and Mathew (1998) proposed an inspection model for manufacturing system with the objective is to minimise the total downtime that associated with the inspection and failure times, while Mathew and Kennedy (2002) developed an inspection model also for minimising the equipment downtime for the case of shock load conditions. The third criterion in the inspection policy is maximising system availability. Practically, the application of inspection policy under availability requirement usually appropriate for security, alarm and storage systems because the cost and downtime criteria may became the second aim in real situations (Chelbi and Ait-Kadi, 2000). For example Chelbi and Ait-Kadi (1996) proposed an inspection model under availability requirement for security and alarm systems such as power system and censor equipment. Cui et al (2003) also studied and developed an inspection policy under availability requirement for storage system such as fire extinguisher.

In this paper, the application of inspection policy under availability requirement for repairable system is presented. Because of the failure cost and downtime cost are not seriously affected to the system, the inspection policy under availability requirement became useful in order to certify the system will operates under require function. Next section, the modelling assumption and the expression of the inspection model under availability requirement are presented. Last section, the application of the inspection model on repairable system at an automotive industry is discussed.

Inspection Model based on Availability Requirement

In the development of inspection model based on availability requirement, the availability per unit of time is defined as a function of the inspection time, T and it can be expressed as;

$$A(T) = \frac{\text{Expected availability per cycle}}{\text{Expected cycle per length}} \quad \text{----- (1)}$$

The expected availability per cycle time is given by;

$$\int_0^T R(t) dt \quad \text{----- (2)}$$

Which,

$R(t)$ is the reliability function of failure distribution

The expected cycle length is;

$$T + t_1 + t_2 [1 - R(T)] \quad \text{----- (3)}$$

Which,

T is optimum inspection time

t_1 is the time required for general inspection such as cleaning and servicing.

t_2 is the inspection that time required for minor repair or replacement

$R(T)$ is reliability function at inspection time

Therefore, the complete inspection model based on availability requirement can be expressed as;

$$A(T) = \frac{\int_0^T R(t) dt}{T + t_1 + t_2 [1 - R(T)]} \quad \text{----- (4)}$$

The objective of this model is to determine the optimum inspection time, T to maximise system availability per unit of time. The system is assumed to be as good as new after inspection. Note that, inspections is not perfect maintenance (do not restore the system to as good as new condition), which it cannot improve the system reliability, but can only increase the system availability (Ebeling, 1997).

Case Study

The application of the inspection model under availability requirement is presented in a case study. The case study is carried out on the camshaft line at an automotive industry. The machines layout in the line can be illustrated in Figure 1. The line consists of sixteen machines and each machine is arranged in serial relationship. Therefore, if one machine breakdown (unexpected failure), the whole process is affected and bottleneck will occurred at certain machine on the camshaft line.

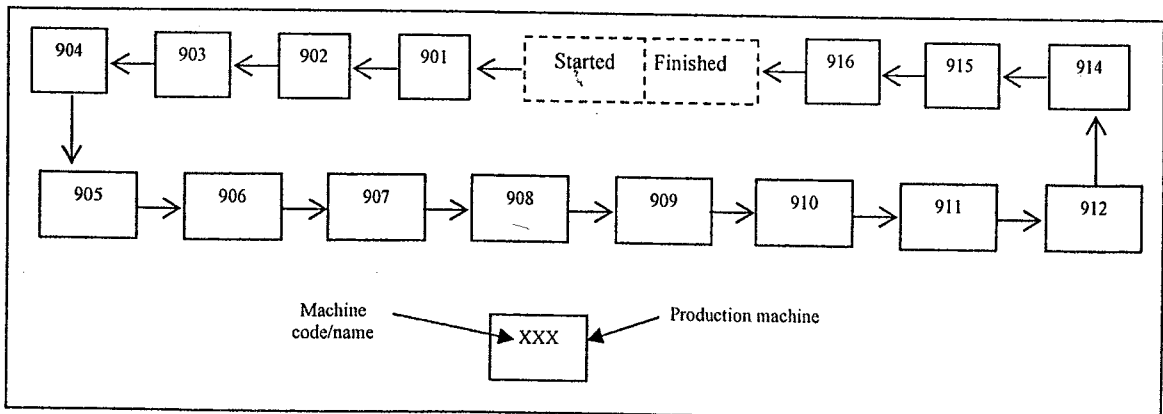


Figure 1: The machines layout in production line

Three machines, namely machines 914, 902 and 903 are identified as the critical machines that have experience with high rate of unexpected failures. From an early analysis, most of the unexpected failure that occurred on these machines are due to the dusty condition, misalignment and wear & tear process. Therefore, inspection policy is believed to be the practical solution to increase the machine availability. The objective of inspection policy is to design an optimal inspection time, T for maximising the machines availability.

In order to determine an optimal inspection time for machines 914, 902 and 903, the following information is defined.

- The failures times on machines 914, 902 and 903 occur according to the exponential distribution with failure rate, λ are 0.0067, 0.0112 and 0.0023, respectively.
- t_1 , (time required to general inspection such as cleaning and checking), for machines 914, 902 and 903 are 30 minutes (0.5 hour), respectively.
- t_2 , (time required to minor repair or replacement), for machines 914, 902 and 903 are 60 minutes (1.0 hour), respectively.

Because of the machines failure rate follow the exponential distribution, the reliability function will be;

$$R(t) = e^{-\lambda t},$$

Which,

λ , is failure rate, then from (4)

$$A(T) = \frac{1 - e^{-\lambda T}}{\lambda[T + t_1 + t_2(1 - e^{-\lambda T})]} \quad \text{----- (5)}$$

From equation (5), the inspection model based exponential case for machines 914, 902 and 903 can be written as;

Machine 914

$$A(T)_{914} = \frac{1 - e^{-0.0067T}}{0.0067[T + 0.5 + 1(1 - e^{0.0067T})]} \quad \text{----- (6)}$$

Machine 902

$$A(T)_{902} = \frac{1 - e^{-0.0112T}}{0.0112[T + 0.5 + 1(1 - e^{0.0112T})]} \quad \text{----- (7)}$$

Machine 903

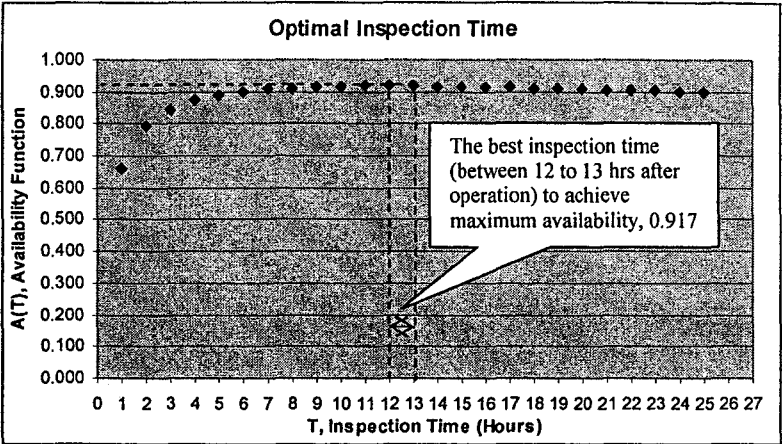
$$A(T)_{903} = \frac{1 - e^{-0.0023T}}{0.0023[T + 0.5 + 1(1 - e^{0.0023T})]} \quad \text{----- (8)}$$

The analysis results of the optimal inspection time T in maximum availability for machines 914, 902 and 903 is tabulated in Table 1. The values of $A(T)$ is calculated for different values of T . Table 1 highlights the maximum values of $A(T)$, which correspond to optimum inspection time, T for each machines 914, 902 and 903. Machine 914 shows that the maximum $A(T)_{914} = 0.917$ at optimum inspection time, $T_{914} = 9$ to 10 hours. For machine 902, the maximum $A(T)_{902} = 0.892$ at optimum inspection time, $T_{902} = 12$ to 13 hours, while machine 903 shows the maximum $A(T)_{903} = 0.951$ at optimum inspection time, $T_{903} = 17$ to 25 hours.

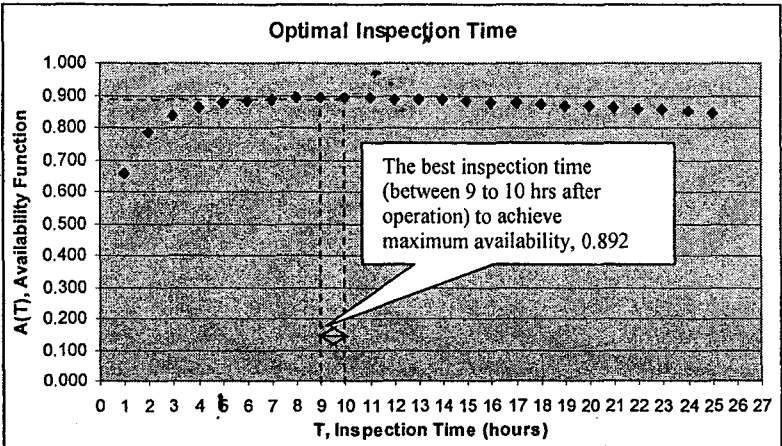
Table 1: The inspection model analysis on machines 914, 902 and 903

Optimum Inspection time (T)	Machine 914	Machine 902	Machine 903
	$A(T)_{914}$	$A(T)_{902}$	$A(T)_{903}$
1	0.661	0.658	0.665
2	0.790	0.784	0.797
3	0.844	0.835	0.853
4	0.872	0.861	0.883
5	0.889	0.875	0.902
6	0.899	0.884	0.915
7	0.906	0.889	0.924
8	0.911	0.891	0.931
9	0.914	0.892	0.936
10	0.916	0.892	0.939
11	0.916	0.891	0.942
12	0.917	0.889	0.945
13	0.917	0.887	0.947
14	0.916	0.885	0.948
15	0.915	0.882	0.949
16	0.914	0.879	0.950
17	0.913	0.876	0.951
18	0.911	0.873	0.951
19	0.909	0.869	0.951
20	0.908	0.866	0.951
21	0.906	0.862	0.951
22	0.904	0.858	0.951
23	0.902	0.855	0.951
24	0.899	0.851	0.951
25	0.897	0.847	0.951
26	-	-	0.950
27	-	-	0.950
28	-	-	0.949
29	-	-	0.949
30	-	-	0.948
31	-	-	0.948
32	-	-	0.947
33	-	-	0.947
34	-	-	0.946
35	-	-	0.945

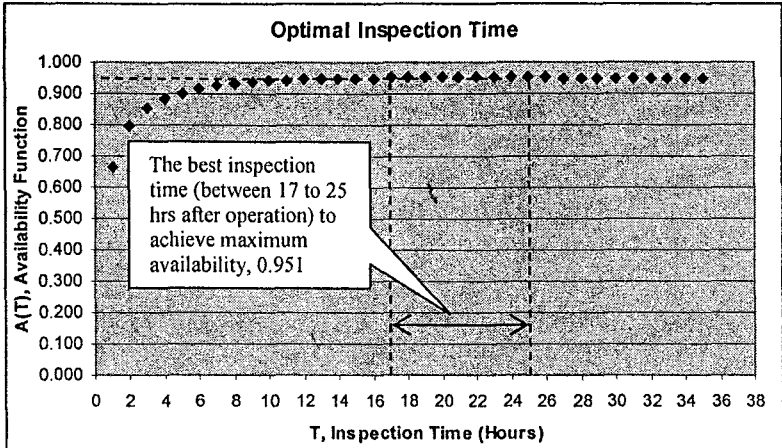
In addition, the data in Table 1 are plotted in Figure 2. Figure 2 shows that the value of availability function, $A(T)$ will increase with inspection times, T^s and reach a maximum availability value, $A(T)_{max}$ at optimum inspection time, T_{opt} hours. Referring to Figure 2, for machine 914, a inspection can be carried out within 12 to 13 hours after operation to reach maximum availability, $A(T)_{914} = 0.917$, while for machine 902, to reach maximum availability, $A(T)_{902} = 0.862$, a inspection can be performed between 9 to 10 hours after operation, and machine 903 shows that inspection must be carried out after 17 to 25 hours of operation to reach maximum availability, $A(T)_{903} = 0.951$.



(a) Optimal Inspection time for machine 914



(b) Optimal Inspection time for machine 902



(c) Optimal Inspection time for machine 903

Figure 2: The values of availability function, $A(T)$ versus inspection time, T

Conclusion

This paper presented the application of inspection policy in maintenance decision making. The inspection model based on availability requirement is applied for a case study companies that product camshaft. The main objective of the model is to determine the optimum inspection time to achieve maximum machine availability. The model analysis has been carried out on three machines, namely machines 914, 902 and 903, which contribute to the high downtime on the production line. Results show that the optimum inspection time for machines 914, 902 and 903 are 12 to 13, 9 to 10 and 17 to 25 hours after machines operation, respectively. The maximum availability that can be achieve at these optimum inspection times for machines 914, 902 and 903 are 0.917, 0.892 and 0.951, respectively.

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