ROBUST ENGINEERING IN MAINTAINABILITY OF BUILDING

NEZA ISMAIL

UNIVERSITI TEKNOLOGI MALAYSIA

ROBUST ENGINEERING IN MAINTAINABILITY OF BUILDING

NEZA ISMAIL

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Alhamdulillah,

Mak dan Ayah, *for their endless prayers. "Ya Allah, ampunilah arwah Mak dan ampunilah Ayahku".*

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ABSTRACT

The process of designing a building is dependent on many requirements. Maintainability is an important design aspect that will affect the cost for management and the maintenance of a building within its expected life cycle. As an effect, there is now a need for a multidimensional diagnosis system that integrates maintainability that in accounting user's environment and other design elements. However, in Malaysia, building maintainability is getting less attention and neglected as more focus is given on constructability and compliance with current regulations and law. Meeting up with this challenges, this study establishes a model that integrates maintainability as an important principle during the designing process using Robust Engineering (RE) principles that captures the interaction between the design elements with the user environment. The study then seeks 1) to evaluate current limitation of the design process in capturing the maintenance requirements; 2) to evaluate the potential of using Robust Engineering principles to capture maintainability consideration in building design; 3) to examine structural relationship between maintainability consideration and high maintainability building for a robust design outcome, and 4) to develop Robust Maintainability Integrated Design (R-MInD) guideline that evaluate maintainability incorporation at the design stage. Concentrating on a single function building usage (i.e. educational institution buildings), the study had utilised Partial Least Square Structural Equation Modelling technique to identify the influencing factors to improve the maintainability incorporation in the designing process. A total of eleven (n=11) experts ranging from designer, project manager, company director and facility managers from the government and private sectors were interviewed, while one-hundred and eleven (n=111) respondents were accounted in a survey to evaluate the current practice to propose improvement in building design practice. From the study, it has been established that there is a positive correlation between conformance and compliance with regulations and standards, integration of systems, space planning and materials and equipment selection for robust maintainability building design. Furthermore, the study had also found that RE principle is suitable to be incorporated during the designing process to improve building's maintainability. The study further suggests a new process model and guidelines that can be adopted by the building designer that may improve the maintainability of a building. In conclusion, the findings of this research revealed that a realistic maintainability evaluation during the designing process depends on a complex system and subsystem consisting of many materials and equipments.

ABSTRAK

Proses rekebentuk bangunan bergantung kepada banyak keperluan. Kebolehsenggaraan adalah aspek rekabentuk yang akan memberi kesan kepada pengurusan dan penyelenggaraan bangunan berdasarkan kepada jangkahayat yang ditetapkan. Terdapat keperluan untuk mengintegrasikan kebolehsenggaraan menggunakan sistem diagnosis pelbagai dimensi yang mengambilkira persekitaran pengguna dan elemen rekabentuk. Di Malaysia, kebolehsenggaraan bangunan kurang diberi penekanan dan diabaikan kerana fokus lebih diberikan kepada kebolehbinaan dan pematuhan kepada peraturan dan undang-undang. Untuk memenuhi cabaran ini, kajian ini merangka model yang mengintegrasikan kebolehsenggaraan sebagai pertimbangan penting semasa rekabentuk menggunakan prinsip Kejuruteraan Teguh (KT) yang mengambil kira interaksi antara elemen rekabentuk dan persekitaran pengguna. Kajian ini bermatlamat 1) menilai limitasi semasa proses rekabentuk dalam mengambilkira keperluan penyelenggaraan; 2) menilai potensi penggunaan prinsip KT dalam mengambilkira kebolehsenggaraan bangunan yang direkabentuk; 3) menguji hubungan struktur antara pertimbangan kebolehsenggaraan dengan bangunan yang mempunyai kebolehsengaraan tinggi sebagai rekabentuk yang teguh, dan 4) merangka garispanduan yang boleh menilai pertimbangan kebolehsenggaraan di fasa rekabentuk yang dipanggil "Robust Maintainability Integrated Design (R-MInD)". Dengan menumpukan kepada bangunan satu fungsi seperti bangunan institusi pendidikan, kajian ini menggunakan teknik Pemodelan Struktur Kuasa Dua Terkecil Separa untuk mengenalpasti faktor yang mempengaruhi peningkatan kebolehsenggaraan semasa rekabentuk. Seramai sebelas (n=11) pakar merangkumi perekabentuk, pengurus projek, pengarah syarikat dan pengurus fasiliti dari sektor awam dan swasta telah ditemubual, manakala seratus sebelas (n=111) responden terlibat dalam kajiselidik yang menilai dan mencadangkan penambahbaikan perlaksanaan rekabentuk bangunan. Dapatan kajian ini menunjukkan terdapat hubungan korelasi yang positif antara pematuhan kepada peraturan dan piawaian, integrasi sistem, perancangan ruang dan pemilihan bahan dan peralatan untuk rekabentuk kebolehsenggaraan yang teguh. Dapatan kajian ini juga mendapati prinsip KT sesuai digunakan semasa rekabentuk untuk meningkatkan kebolehsenggaraan bangunan. Kajian ini seterusnya mencadangkan model dan garispanduan yang boleh digunapakai oleh perekabentuk bangunan bagi meningkatkan kebolehsenggaraan bangunan. Kesimpulan kajian ini menunjukkan penilaian kebolehsenggaraan yang realistik semasa proses rekabentuk bergantung kepada sistem dan sub sistem yang mempunyai kepelbagaian bahan dan peralatan.

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LIST OF ABBREVIATIONS

AVE	-	Average Variance Extracted
BDPMHP	-	Building Design Process Model for High – Performance Projects
BIM	-	Building Information Modelling
BSI	-	British Standard Institute
CIBSE	-	Chartered Institution of Building Services Engineers
CFA	-	Confirmatory Factor Analysis
CA	-	Cronbach's Alpha
CR	-	Composite Reliability
CB SEM	-	Co-variance-based Structure Equation Modelling
DQI	-	Design Quality Indicator
DQM	-	Design Quality Matrices
DPM	-	Design Performance Measure
D&B	-	Design and Build
EFA	-	Exploratory Factor Analysis
FAST	-	Functional Analysis System Technique
HQI	-	Housing Quality Indicator
IBPM	-	Integrated Building Design Process
IBS	-	Industrial Building System
LCC	-	Life-cycle cost

LV	-	Latent variables
MDS	-	Multidimensional Diagnosis System
MMG	-	Matrix Measurement Guideline
POE	-	Post Occupancy Evaluation
PM	-	Performance measurement
PROBE	-	Post-Occupancy Review of Buildings and their Engineering
PLS SEM	-	Partial Least Square Structural Equation Modelling
RE	-	Robust Engineering
R-MInD	-	Robust Maintainability Integrated Design
R^2	-	Coefficient of determination
SEM	-	Structural Equation Modelling
S/N	-	Signal-to-Noise ratios
WBDG	-	Whole Building Design Guide

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Building performance often been criticize as not meeting user expectation for maintainability need consideration during operation and maintenance phase. Maintainability is an important design consideration for making maintenance and management of building easier while operating with expected life cycle cost. It is commonly encountered by building owner that huge amount of expenses needed for maintenance of new buildings because of inefficient design related to maintainability consideration, which could be incorporated at the design stage. Among main maintainability consideration are maintenance work area, material and equipment selection. At design phase, it translates into space planning, selection of material and ease of materials procurement with respect to availability and time to obtain the required parts.

As for Malaysian's construction industry, the importance and proper approach to address the incorporation of building maintainability consideration is far lacking. The issue of maintainability is considered critical as it largely influencing the usage condition of building facilities. Maintainability is a wide scope that not only addresses reparability and durability, but also ensuring the ease of maintenance to its original function in the design stage. The objectives of this research were to provide an understanding of interaction between design elements (control factors) and user environment (uncontrolled factors) in building design, developing a model of maintainability-integrated design by providing a conceptual framework. The control factors related to compliance to regulation and integration of all building services element. The uncontrolled factors focus on elements, which will eventually change over the design life, such as the space utilization and the material and equipment due to fair, wear and tear or advancement of technology.

The focus of this research is to identify the maintainability consideration in building design for a robust building design outcome. It explores the key maintainability consideration and the main concern of the user for designer to capture at the design stage. These improvements aimed at improving the needed characteristics and simultaneously reducing the number of deficiencies by studying the key maintainability considerations controlling building design to yield the best results. It also explores to develop an interaction model and guidelines to be utilised by the building designers in capturing the building maintainability considerations at design stage. This will influence the design outcome enabling ease of maintenance for the building operators during the use stage.

1.2 Background of the Research

In the Ninth Malaysian Plan (2006-2010), the development plan allocation for repair and maintenance works has increased to RM1,079 million compared to only RM296 million during the Eighth Malaysian Plan (Ali *et al.*, 2010; Sheelah, 2014). However, in the Tenth Malaysian Plan (2011-2015), the allocation was decreased to 500 million. The decrease of the budget allocation for building maintenance activities forces practitioners to develop solutions to reduce building maintenance costs

(Au Yong *et al.*, 2012). Since maintenance cost increases as the building aging, it is crucial that maintainability requirement is applied in the design stage.

Maintenance are crucial to ensure the performance of a building. Operation and maintenance phases are the longest portion of building life cycle with approximately, up to 80% of the total ownership cost (Christian and Pandeya, 1997). In view of value engineering, developer can save up to 10% of their investment cost and 30% of their operating cost if facilities management services are incorporated into design phase of a project (Sheelah, 2014). Consideration of maintenance requirements at design stage able to lowering the operation and maintenance cost of facility (Helen and Soibelam, 2003). Therefore, a high maintainability building can be achieved if there is a direct contribution from the maintenance and design activities at the design stage.

Building design outcome aims to ensure compliance to regulation for safety of occupants and cost agreed by the owner. The design must satisfy the basic needs of building to perform and function as intended in the term of references. Commonly accepted fact that complying with stated client's need usually seen as producing good design. This is in contrast to actual situations where it is argued that building design that satisfy all the stated client's need may not be the optimum design outcome in term of building performance in use. The stated client's need must consider building maintainability to improve building performance. Evidence shows that indicators such as building maintainability is influenced by design decision, and promoted to be used (Egan, 2010) as measures of optimum design outcome. The importance of ensuring the incorporation of maintainability also been stressed by many researches such as Arditi and Nawakorawit (1999a); Nur Haniza *et al*. (2007); Das *et al*. (2010); Wood (2012); and Nicolella (2014).

Building interact with user through time (Stewart, 1994). While most design solution seen as frozen in time, building interact with the user and live through time.

The interaction will influence the day to day operation and lasting use of the building. The higher conflict occurs between building and user, the more maintenance needed and less time the building will last. The conflicts may come from inherit deficiencies or low maintainability consideration throughout its design life. As a result, the building needed high cost of maintenance to enable for future use. It is argued that this is due to trade off made during the selection of design option at the design stage (Ahmad *et al.*, 2006; Nur Haniza *et al.*, 2007). To remedy the deficiencies, rectifying works needed after the handover is costly.

Renovating and rectifying a building after the handover due to design deficiency is much costlier and resulting losses not just to the user but society as a whole. In modern product development processes, it is viewed as a quality loss function (Taguchi *et al.*, 2000, 2005; Cudney *et al.*, 2007). The losses influenced the actual user and reducing the optimisation of resources in the long term. To avoid losses design must be able to withstand the test of time. Current design tools seen as not efficient as it focuses more to evaluation of proposed design toward needs. Efficient method must consider the interaction between control (design elements) and uncontrolled (user environment) factors. Uncontrolled factors in building use stage are space planning and material and equipment selection. These uncontrolled factors also known as time laden consideration.

Time laden considerations are associated with condition of design after a certain period of time. Lacking of time laden consideration such as ageing of material, variability of material use in building part and user use of the design part will reduced the maintainability of building. Time laden consideration in building design such as space use, material and equipment selection associated with preserving the building for long-lasting use of building services (Dunston and Williamson, 1999; Gambatese and Dunston, 2003; Chew *et al.*, 2004c) able to improve and ensure a robust building design outcome. In terms of day to day housekeeping tasks the material and equipment election is important to ensure smooth and lasting supply of part and repair of building part.

Building design with good time laden consideration can be seen until today. Through the history of mankind, some historical building still in use until today. They survive the test of time while a few even fail once after completion or over a short period of design life. Question that we may asked is why do some building fail and some building have longer design life? What are the attributes that interact with user that make the building last longer? Can we identify these common attribute? It is argued that among the main similarities of these buildings is the ease of maintenance throughout its design life. The consideration can be seen as enabling the use and function of building stand the test of time. As suggested by Stewart (1994), the better the maintainability consideration with respect to time laden consideration, the longer the building will last.

The aim of design tasks is to fulfil as much as possible the needs stipulated by the owner. Once the design need met, it stops for decision by the owner to accept or reject the design option. Accepting design choice also involved two important factors known as sufficiency and necessity (Feld, 1968). Sufficiency is to ensure safety to the user, and avoiding undue decay specifies by current rules and code of practices. Necessity is a cost consideration because construction project has a limit on cost. The total cost is drawn from all the building services and subsystem of the building base on the needed performance and function. However, evidence shows that design carried out within the mentioned needs not necessarily met the maintenance-related needs. Many trades off made in deriving selection and decision of which design to be accepted. Most of the time, maintainability consideration being traded off to reduce cost.

1.3 Problem Statement

Building design is not just building a structure, but a commitment to the long-term use of resources. Resources relates to energy thinking for a sustainable and long lasting of the built assets. At the operation stage it is translated in term of building maintenance throughout its design life consuming much of available resources. The maintenance of building being influence greatly by the maintainability consideration at the design phase. Maintenance affecting the building performance and maintainability incorporation at design stage influenced building performance. Building maintenance needs large amount of allocation for every organisation with built asset. Maintenance also known as a necessary evil for all organisations with built asset. The frequency and cost of building maintenance depend on building maintainability considerations inherit in the design and installation.

Maintainability addresses the ease of restoring an item to its design state. Good building maintainability consideration will be translated into ease of maintenance tasks, lowest life cycle cost, low downtime of equipment and part when subjected to maintenance intervention. It also can be translated in term of good interaction between the design element and user usage condition. Good interaction of building maintainability controls the extend of maintenance tasks in term of ease of maintenance works with respect to replacing and repair and acceptable cost. Building maintainability is important to lessen maintenance problems because of design shortage or trade off, thus making the building last longer.

Maintainability was established to address maintenance problems earlier on in the design stage of a building (Feldman, 1975). Maintainability provide way to assist maintenance, but designing for a maintenance free building is currently technologically and economically impractical due to the huge uncertainty of design element and components. Thus, there is a need to study the planning and design of a building to improve building performance at usage stage, while enhancing the efficiency and reducing the cost of maintenance. Building maintainability is becoming increasing significant because of the alarming high maintenance cost of buildings (Silva and Ranasinghe, 2010; Silva *et al*., 2012; Al-Hammad *et al.*, 1997; Chew and Tan, 2004). Maintenance cost breakdown analysis for building less than 25 years old showed that 56% of the cost was due to fair wear and tear, 20% of the cost was due to design specification errors, 12.5% was due to repair cause by defective materials and 11.5% was due to other causes (Al-Hammad *et al.*, 1997). The cost of rehabilitating a building could also be as high as newly constructed building (Al-Khajat and Fattuni, 1990). Maintainability incorporation will subsequently enhance building maintainability and this will lead to various benefits such as maximizing the investment value of a property (Ramly, 2002; Yahya and Ibrahim, 2012), reduction of maintenance cost (Chew and Tan, 2004; Silva and Ranasinghe, 2010), and minimizing global environmental and health hazard to users (Chew *et al.*, 2005; Chew and Tan, 2004; Colen and Brito, 2010).

The current design approach that we used in building design does not address maintainability explicitly. The focus much for constructability and complying with current regulations and law. The problem dealing with building maintainability left to be solve by owner and building manager. Even the current maintenance philosophies employed during day-to-day operation does not deal with maintainability but rather focusing on the logistic information, usually in term of algorithms or equation consisting important parameters such as cost to supply, installation and time related parameters. Most of the studies on maintainability over the years have produced algorithms that support the building services part of building design with less emphasis to the built environment parameters. There is no set of criteria to use in the maintainability analysis using built environment parameters except persuasive reasoning based on lesson learn and experience to incorporate for good maintainability of the design.

Although there are numerous studies on maintainability, the particular aspect of interaction between design features with user usage condition is not study thoroughly. Most study focus on integration part of design element assuming that the code of practice taken into account the maintainability of a building. Therefore, a knowledge gap exists, in understanding and finding actual maintainability consideration required to produce a robust design outcome. Current design approach evaluates the interaction between design feature or control factors with control factors. There is a minimum evaluation done on the interaction between design elements with user environment also known as uncontrolled factors during the design. The user of the building in this study is the owner of the building, which executed the maintenance tasks throughout the building life cycle. Incorporating these interactions, it usually depends on the experience of the designer.

There are some limitations concerning information based design in term of lesson learn application and acquisition in building design. These limitations include an overemphasis on previous project lesson learn with low empirical knowledge gained by experimental research, a narrow focus that excludes design knowledge generated outside of building design fields, and a lack of interest in empirical evaluation gained by qualitative studies. The information based design raises a multitude of deep problems, including the conceptualization of needs and their expression as formal requirements, the development design option was based on previous project which may inherit defect may create a problem at operation stage. In order to overcome these limitations, it must acknowledge that design knowledge relevant to building design can be found in disciplines unrelated to building design and one of design approach to overcome these limitation is applying design approach by other industry such as Robust Engineering (RE). It gives an insight of a design to apply and gain empirical evidence to design and ensuring less variation at the usage stage.

The current design code focus on meeting safety and institutional need. Meeting need does not address the building maintainability. Building maintainability can be address through evaluation of interaction between user environment and design elements. The interaction will improve building maintainability as the design becomes robust or less sensitive to user environment. We need an assessment model that can hasten and justify the interaction between the user environment and design elements involving multidimensional diagnosis system for robust maintainability integrated design. The model must identify the main maintainability needs that governs the design outcome. The proposed model must be eloquent with the issues of maintainability. It must aid the building design team to focus on problems associated with maintenance of the critical features of the building. The assessment of building design must be conducted on several maintainability considerations. The main focus is to interact the design features with the user environment of design outcomes on maintainability, the ease of maintenance and ability to make an informed decision. The primary data collection method in this research is an expert interview and a questionnaire survey. Partial Least Square Structure Equation Modelling (PLS-SEM) method used for the survey data. Respondents of the interview are professional building designers and facility managers having experience in building design and operation.

The process of designing a building is dependent on many requirements. Maintainability is an important design aspect that will affect the cost for management and the maintenance of a building within its expected life cycle. As an effect, there is now a need for a multidimensional diagnosis system that integrates maintainability that account user's environment and other design elements. However, in Malaysia, building maintainability is getting less attention and neglected as more focus is given on constructability and compliance with current regulations and law. To overcome this challenge, there is now a requirement to establish a model that identify comprises maintainability as an important principle during the designing process. As building maintainability involving the use stage of building, several questions needed answering in this research as follows:

Research Question 1 – What are the maintainability consideration at usage stage?

Research Question 2 – What principle to assimilate the idea of building design to lesser the conflict between design element and user environment for a robust design?

Research Question 3 – Is there a significant relationship between the design element and user environment interaction of high maintainability building?

1.4 Aim and Objectives

The aim of this research is to develop a Robust Maintainability Integrated Design (R-MInD) framework for building design by adapting RE principles. This framework seeks to improve the building design outcome by focusing on interaction of the user and the building during use while complying with owner's need and current regulations and law. Interaction aims to improve building maintainability by producing a robust design that is less sensitive to the user environment. To achieve this, the following objectives have been identified:

Objective one. To evaluate current limitation of the design process in capturing the maintainability requirements.

Objective two. To evaluate the potential of using Robust Engineering (RE) principles to capture maintainability consideration in building design.

Objective three. To examine structural relationship between maintainability considerations and high maintainability building for a robust design outcome.

Objective four. To develop Robust Maintainability Integrated Design (R-MInD) guideline that evaluate the maintainability incorporation at the design stage.

1.5 Scope of the Research

This study covers the practices of the design process in Malaysia. The factors and attributes identified are hence unique to Malaysian practices, which may or may not be the same for other countries. Aspects that were excluded from this research are as follows:

- The respondents of this research mainly the engineering design and maintenance professionals working with guideline and regulation as in Malaysia. Therefore, this research covers the majority of the design team and maintenance operative perspective of building design. The actual result of operational perspective is not being evaluated because the massive data required. The long term result of the operational perspective is not being evaluated because the massive data required.
- This study focus on the design stage of a building. It focuses directly to designers of the building in their method of incorporating

maintainability considerations. The user in this study is the building owner that execute the day to day maintenance of a building.

- Building performance evaluation may be conducted to different stages for different aspects such as functional, technical and indoor environment. This study focus on the interaction of design element with user condition at the design stage as the interaction can lessen the variation during day to day operation. Other aspects are excluded from the scope of this study.
- This research focus to single function building usage, such as an educational institution building. The function of a building meaning the ability to fulfil the function envisaged. The quality refers primarily to a building's efficiency, practical usability or utility value. Functional quality requires a building to have good accessibility, provide sufficient space and sufficiently flexible that will ensure safe, healthy and good environment.

1.6 Significant of the Research

This study contributes to the growing body of knowledge in maintainability theories. This study has investigated the main maintainability criteria interacting with the user. It has also identified the main maintainability consideration to be applied during the design stage to incorporate maintainability. The current research has bridged the gap by analysing the influence of these considerations to improve building maintainability. In terms of methodology, this research used Structural Equation Modelling (SEM) to examine the hypothesised relationship. In addition, SEM takes into account the measurement error variances; thus, the relationship between the factors in the hypothesis model were more accurate. Further, it contributes to quantitative and qualitative methodology approach in the field of construction management. In the educational aspect, this study has sought to obtain useful knowledge and information as well as obtain in depth understanding of integration with the asset management and design process. This study also enhances the research potential of the investigator to explore all other issues related to the subject area in the future

In terms of the design process for maintainability incorporation the significant in this study are as follows:

- Adapted from manufacturing a process that evaluate interaction between design element and user environment to reduce variation at operational stage. This will produce design that less sensitive to variation.
- Application of the evaluation to improve the design with an R - MInD matrix measurement guideline that incorporated maintainability consideration at design stage.
- Improve current design process by having a guideline for evaluating design for robust outcome.

This study shifts the focus from integrating construction processes to enhancing the interaction of the design element and the user. The shift is assisted by a key metric of four main components measuring a robust outcome. In terms of practical contributions, the research model provides an understanding of the influence of variable to produce high maintainability building. By adopting the above focus, this study allows:

- The basis of building design from the perspective of those involve in maintaining the facilities. It focuses on strategy for a building design around the user experience. User in this study is the building owner that execute daily maintenance of the building.

- Design with the user day to day operation needs and maintenance activities during building in used in mind which increased the ownership of the design rather than producing a building design.
- The outcome of the design is about value of long term used of building with minimum variation and not the cost.

1.7 Brief Research Methodology

This brief research methodology provides a general plan and necessary steps to execute the research in a scientific manner. It is a logical model for collecting the information, analysing the data and interpreting the findings of the research. Figure 1.1 provides a chronological overview of the research programme. It illustrates the activities, key findings, decisions and outputs during the course of the research. This illustrates the research progression focusing on how findings and decisions resulting from activities were used to influence subsequent investigations as well as highlighting when objectives were realised and programme deliverables produced.

To evaluate current limitation of the design process in capturing the maintainability considerations	
Data collection method and tools: Literature Review, Expert Interview, Document search and Questionnaire Survey	Analysis method: Thematic analysis of interview, content analysis of the document search, triangulation of finding with literature and Partial Least Square – Structural Equation Modelling (PLS-SEM) analysis.

To evaluate the potential use of Robust Engineering principles to capture maintainability consideration in the design stage.	
Data collection method and tools: Literature Review, Expert Interview, and Questionnaire Survey	Analysis method: triangulation of finding with literature and Partial Least Square – Structural Equation Modelling (PLS-SEM) analysis

To examine structural relationship between maintainability considerations and high maintainability building for a robust design outcome..	
Data collection method and tools: Literature Review, Expert Interview, and Questionnaire Survey	Analysis method: triangulation of finding with literature and Partial Least Square – Structural Equation Modelling (PLS-SEM) analysis

Develop R-MInD guideline that evaluate the maintainability incorporation and validating result with an expert		
Data collection method and tools: Expert Interview, and Questionnaire Survey	Validation: Delphi like method with selected expert	Analysis method: Content Analysis
Thesis writing up and conclusion		

Figure 1.1 : Research flow

1.8 Thesis Structure and Organization

This thesis consists of seven chapters: Introduction (Chapter 1), Maintainability Consideration on Building Maintenance (Chapter 2), Robust Engineering and Application in Building Design (Chapter 3), Research Methodology (Chapter 4), Data Analysis (Chapter 5), Model and Validation (Chapter 6), and

Conclusion and Recommendations (Chapter 7). At the end of each chapter, concluding remarks are provided to briefly discuss and summarised the content of the chapter.

Chapter 1 introduces the research by describing the background of the problem associated with limits the current design approach in incorporating maintenance consideration. The impact of the maintenance and the need to improve design approaches to meet user expectation at building usage stage discussed. The Aim and Objectives of the research also presented with important definition. The significant impact of this research toward enhancing building design outcome will be stated. Review of literature is presented in Chapter 2 and 3. As the research covers several area the discussion and linkages of each area is made separately. Chapter 2 discusses the literature of building design limit, maintainability definition, method of maintainability incorporation, characteristic and focus which needed to improve to produce better design outcome. Chapter 3 gives an outline of Robust Engineering application and benefit in term of facilitating product development process. It also suggests the most relevant principle that can influence the building design outcome.

Chapter 4 discussed the Research Methodology adopted in this study. The discussion provides description, comparison, ideas and principle publish in the literature about the research. Data Analysis in this research are explained in Chapter 5. Other than a discussion on the data collection method, this chapter describe the design and implementation of the expert panel interview and the questionnaire survey adopted in this research. The research findings are discussed separately in Chapter 6. This chapter also includes the validation of the proposed interaction model with several experts in the design management field. This chapter also discusses the findings of the research and proposed a guideline and measurement matrix in using the R-MInD framework of design team. The final chapter of the thesis (Chapter 7) covers summary of the thesis and conclusion drawn from the present study as well as the recommendation for further research.

1.9 Summary

Maintenance works are costly and consuming much of available resources for organisation with built assets. The issue of maintainability has to be considered from the conception stage to design as it will implicate the usage stage. Design outcome must be with the intention of maximizing the performance at minimal operating cost. This can be achieved by focusing on the interaction between the design element with the user environment. Design intentions must then be carefully realised by having a good workmanship during the construction stage. To effectively integrate maintainability in design it is important that the development of competencies in all related fields with regards to building maintenance. It is through this synergistic effort from all participant involved the delivery process that will give the maximum impact with acceptable operation cost.

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