A STRUCTURAL MODEL FOR COST EFFECTIVE BUILDING MAINTENANCE THROUGH DESIGN FOR MAINTAINABILITY

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DEDICATION

"To My Beloved Appa and Amma

Mr. Ganisen and Mrs. Shashikala Devi

for your ever ending love and supports throughout my life."

"To My Dearest Husband Nantha Kumar

for your unconditional love, encouragements and supports."

"Not forgotten my three siblings

Jayshini, Thulashini and Mitrashini."

"Hopefully my hard work for the past 4 years will be

your inspiration to work even harder."

"To My Juniors Rinitah & Prabha,

"My Friends Vaani and Gunavathy

for your help and supports"

"And my Almighty

Nothing possible without Him"

"Couldn't complete this research without all of you"

….Thank you for always being there for me….

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ABSTRACT

Building maintainability is renowned in the lack of integration with building design. This has been seen as one of the major factors contributing to various problems facing the building industry, precisely the increasing building maintenance costs. Initial study and critical reviews on literatures reveals that there is a need to identify a comprehensive building design for maintainability criteria and indicators to reduce the overwhelming cost of building maintenance through mitigation of defects. To address the above issues, this research was carried to establish an exhaustive building design for maintainability criteria and indicators to achieve cost effective building maintenance. Total of nine design for maintainability criteria, thirty-eight indicators and eighteen cost effective building maintenance indicators were identified and validated in two phases of survey and analysis. In the first phase, Delphi survey was conducted and in the second phase Structural Equation Modeling (SEM) technique was used to validate, develop and determine the structural model of building design for maintainability for cost effective building maintenance. This research aims to address the long pending quest of incorporating maintainability during the building design phase and form as basis to promote facility management practices in the building design phase. The results of this research firmly established the structural relationship model among building design maintainability criteria and indicators to achieve cost effective building maintenance. The structural model developed through this research can greatly benefits and being a useful reference in the construction industry particularly for the architects and designers to incorporate maintainability during the building design phase to achieve cost effective building maintenance.

ABSTRAK

Keboleh penyelenggaraan bangunan terkenal dengan kekurangan integrasi reka bentuk bangunan. Ini dilihat sebagai salah satu faktor utama yang menyumbang kepada pelbagai masalah yang dihadapi oleh industri bangunan atau lebih tepat lagi, kos penyelenggaraan bangunan semakin meningkat. Kajian awal dan kajian kritikal literatur menunjukkan bahawa terdapat keperluan untuk mengenal reka bentuk lengkap bagi kriteria keboleh penyelenggaraan bangunan dan petunjuk-petunjuk untuk mengurangkan kos yang kian meningkat. Bagi menangani isu-isu di atas, kajian ini telah dijalankan untuk mewujudkan kriteria reka bentuk bangunan bagi keboleh penyelenggaraan yang menyeluruh dan petunjuknya untuk mencapai kos penyelenggaraan bangunan yang efektif. Sembilan petunjuk-petunjuk reka bentuk bagi kriteria keboleh penyelenggaraan bangunan, tiga puluh lapan petunjuknya serta lapan belas petunjuk kos pembinaan berkesan telah dikenal pasti dan diuji dalam dua fasa kajian dan analisis. Dalam fasa pertama kaji selidik Delphi telah digunakan dan dalam fasa kedua, analisis permodelan persamaan berstruktur (SEM) telah digunakan untuk mengesah, membangun dan menentukan model berstruktur keboleh penyelengaraan bangunan bagi kos penyelengaraan bangunan yang efektif. Kajian ini bertujuan untuk mengemukakan persoalan yang telah kian lama tertangguh dalam menggabungkan keboleh penyelenggaraan semasa fasa reka bentuk bangunan dan membentuk asas bagi menggalakkan amalan pengurusan fasiliti pada peringkat reka bentuk bangunan. Hasil kajian ini dengan jelas membentuk model hubungan struktur diantara kriteria keboleh penyelenggaraan bangunan dan petunjuk-petunjuk bagi mencapai kos penyelengaraan yang efektif. Model struktur yang dibangunkan dari hasil kajian ini boleh memberi manfaat yang besar dan menjadi rujukan yang berguna dalam industri pembinaan terutamanya kepada arkitek dan pereka bentuk bangunan untuk memasukkan unsur keboleh penyelenggaraan pada fasa reka bentuk bangunan untuk mencapai kos penyelenggaraan bangunan yang efektif.

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LIST OF ABBREVIATIONS

AVE	-	Average Variance Extracted
BCA	-	Building Construction Authority
BCA	-	Building Construction Authority
BDM	-	Building Design for Maintainability
BM	-	Building Maintenance
BMI	-	Building Maintenance Information
BRE	-	Building Research Establishment
BRE	-	Building Research Establishment
BS	-	British Standard
CB-SEM	-	Covariance based Structural Equation Modelling
CEBM	-	Cost Effective Building Maintenance
CFA	-	Confirmatory Factor Analysis
CIDM	-	The Construction Industry Development Board
CLA	-	Certain Level Agreement
CMV	-	Common Method Variances
CR	-	Composite Reliability
EFA	-	Exploratory Factor Analysis
FA	-	Factor Analysis
FM	-	Facility Management
FYMP	-	Five Year Malaysia Plan
HVAC	-	Heat, Ventilation and Air Condition
LAM	-	The Board of Architects Malaysia
LCC	-	Life Cycle Cost
LV	-	Latent Variables
MAFM	-	Malaysia Association of Facility Management

MPJBT	-	Majlis Perbandaran Johor Bahru Tengah
MRA	-	Multiple Regression Analysis
MV	-	Manifest Variables
NPP	-	National Physical Plan
PA	-	Path Analysis
PAM	-	Malaysian Institute of Architects
PLS	-	Partial Least Square
SEM	-	Structural Equation Modelling
SPSS	-	Statistical Package for Social Science
UTM	-	Universiti Teknologi Malaysia
WBDG	-	Whole Building Design Guide

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Facility management (FM) defined as “combines skills from design disciplines, such as architecture, engineering and interiors, from business fields like, management, marketing and real estate, and from behavioral sciences as an umbrella of professions”, that responsible for "coordinating all efforts related to planning, designing and managing buildings and their systems, equipment and furniture to enhance the organization's ability to compete successfully in a rapidly changing world" (Becker, 1990). Professional bodies such as; British Institute of Facilities Management (2012), International Facilities Management Association (2004) and The Facilities Management Association of Australia (2012), define FM as a profession that encompasses multiple disciplinary activities that integrating people, place and technology within the context of built environment. The scope of FM discipline covers a broader range of services such as, building/ ground management and maintenance, asset management, construction management, environmental management, catering, cleaning, security, IT management, postal, secretarial, health and safety and human resource. Therefore, FM often viewed as a field of operational process that lies beyond design, construction, installation and need to be in the delivery of the buildings.

Building maintenance considered huge activity in the context of emerging discipline of FM. Maintenance crucial for overall life cycle process (planning, design, construction, occupancy) of a building. However, maintenance and few other FM input such as sustainability, landscape and space are renowned in the lack of integration with building design. Based on the studies conducted by Mohammed and Hassanain (2010); Ramly (2006); Wilson (2002); Chanter and Swallow (1996), the inconsideration of maintainability during the building design has been seen as one of the major factors contributing to various problems facing the building industry. Among those problems are namely, building services related defects, early deterioration of building components, inadequate structural design (foundation), inadequate waterproofing and drainage, inadequate accessibility for repair, replacement and cleaning process, improper material selection and so on (Al-Shiha *et al*., 1993; Al- Hammad *et al*., 1997; Silva *et al*., 2004; Ishak *et al*., 2007; Das, 2010). These increasing numbers of design deficiencies can be reflected through the lofty maintenance costs (Silva and Ranasinghe, 2010; Ballast, 2010; Al- Hammad *et al*., 1997), high rate of environmental and biological defects (Chew and Tan, 2003) as well as social consequences (Chew *et al*., 2005 and 2004).

The integration of maintainability during the building design is of essence since able to pursue a balance among economic, social and functional, as well as environmental performance of a construction project. Various building scholars and literature have evidenced the significant of integrating maintainability during the building design, as shown in **Table 1.1**.

Table 1.1: Significant of integrating building maintainability

Authors	Significant of integrating maintainability
Blanchard *et al*. (1995)	Increases the life of infrastructure assets, reduces the costs & increases benefits of the final delivered project.
Dunston & Williamson (1999)	Reduced costs for the contractors and the facility owners.
Nayanthara *et al*. (2004)	Minimize building life-cycle cost (LCC) & increase efficient use of asset.
Chong and Low (2006)	Prevent nearly 66% of building defects.
Felten *et al*. (2009)	Save approximately 20% of the annual operating cost.

Authors	Significant of integrating maintainability
Das & Chew (2011)	Able to mitigate defects to balance decreasing maintenance budgets and increasing building standards.
Saghatforoush *et al*. (2012)	Making Project Life-cycle longer by eliminating the failures during the maintenance phase.
Wood (2012)	Able to maintain a building economically & effectively through its life.
Ismail and Mohammad (2014)	Building adaptable to future needs and maintain a stable usage cost throughout the building's design life.
Nicolella (2014)	Lead to minimization of difficult and costly operation to users.

1.2 Research Background

In recent years, the developed world increasingly facing the overwhelming total costs of operating and managing buildings due to huge maintenance workloads during the post occupancy phase (Wood, 2012; Das et al., 2010 and Building Maintenance Information (BMI), 2000). Studies indicate that American industry spends more or less $200 billion each year on maintenance (Fogel and Petersen, 1997). Additionally, it is estimated that in the UK, up to 50% of the construction budget was spent for repair and maintenance works in buildings (Boussabaine and Kirkham, 2004). While BMI (Wood, 2005) reported in the last 10 years, building maintenance are increased about 66% and between 1989 and 2000, it's take about 43.6% increasing (El-Haram, Marenjak and Horner, 2002). A recent research in US, reported the increase of maintenance costs over the last ten years (1997-2007) is 3.3% for residential, non-residential and military facilities buildings (Whitestone Research, 2007). Meanwhile Hong Kong recorded an increase in the cost of maintenance work over the past 5 years. In Singapore, the average annual maintenance expenditure for residential buildings is claimed to be S$37.99 per square meter, which is significant, when compared to the average turnover in construction (Building Construction Authority (BCA) Singapore, 2000). These numbers of studies are enough to demonstrate that, there is indeed high maintenance cost burdens facing by the building industry globally.

In the context of Malaysia, every year billions of ringgits were losing by the government due to the increasing building maintenance cost (Ali, 2009; Lateed, 2008). Malaysia is developed by the National Physical Plan (NPP), under which the Five Year Malaysia Plan (FYMP) is carried out. In this Malaysia Plan, focus will be given to the investigation on the preparation of annual budget for the maintenance of government-own building. In order to attain clearer picture on increasing maintenance cost of building in Malaysia, it is necessary to highlight the budget allocation for maintenance and repair works of public buildings. Under the 9th Malaysian Plan (2006 – 2010), the government has allocated the sum of US$ 330m for upgrading, renovating, and maintaining various facilities as part of the development budget (Government of Malaysia, 2006; Mohd Sidek, 2007). Under the 6th (1990-1995), 7th (1996 -2000) and 8th Plans (2001-2005), allocation for maintenance and upgrading as a percentage of the development allocation was 0.2% under each of the Plans, while under the 9th Plan (2000-2010), the allocation increased substantially to 0.5%. This marked an increment of 150%.

In financial terms, the allocations increased from RM 101 million under the 6th Plan to RM 203.2 million under the 7th Plan. This is an expansion of about 100%. Further, there was some 6% expansion under the 8th Plan compared to that of the 7th Plan. However, under the 9th Plan, it further increased from the RM 214.5 million to RM 1,079 million, an expansion of some 403%. Additionally, in 2006, the Malaysian Government allocated about 1 trillion ringgits towards repairing and maintaining public building facilities (Government of Malaysia, 2006). Adding to this, in year 2005, 2007 and 2009 the Government allocates a special allocation of RM 2.5 billion, RM 1.0 billion and RM 615 million respectively for maintenance works (Mohd-Noor *et al*., 2011). These allocations proves that the maintenance cost of public building in Malaysia is now clearly increasing and directed to ineffective building maintenance cost.

In addition, Eizzatul et al., (2012) highlighted in her research that buildings in Malaysia are suffering from ineffective building maintenance cost. Analysis by Lateef (2008) illustrates that the expenditure on maintenance in Malaysia is on the increase due to a huge backlog of building maintenance. He further stated that, buildings in Malaysia require effective maintenance; otherwise they will become liabilities. Also, it has been established that there is a gross inadequacy in the way of schools' buildings is managed (Zainal Abidin and Roslan, 2006). Even, Mohd Zulakhmar (2006) stressed that the procedures of maintaining buildings in Malaysia are not effective. As refer to numerous building maintenance related researchers namely; Sani et al. (2012); Mohd-Noor et al., (2011); Ali et al. (2009), (2010); Lateef, Khamidi and Idrus, (2010) and Zuhairuse et al., n.d.; asserted that, the ineffective building maintenance cost issues are known among the biggest obstacle facing by the building industry in Malaysia.

Consequent from the alarming building maintenance cost (Chew and Silva, 2004), the building maintenance and management issues has arisen in mounting significance. Hence, many countries are increasingly realized the importance of understanding, recognizing and assessing the overwhelming total costs of building maintenance (Arditi and Nawakorawit, 1999(a), (b) and Wood, 2009). Along with it, one of the more impending tasks which has been increasingly become a matter of growing importance in many countries is reducing the amount of significant building defects and thus minimize the rising cost of building maintenance. Building defects were defined as results of failures or shortcomings in the function, performance, statutory, or user requirements of the structure, fabric, services, or other facilities of buildings (Low and Wee, 2001). Defects arising in a building often exhibit a chain effect, hinder performance, increase maintenance workloads and contribute to increasing building maintenance cost (Josephson and Hammarlund 1999; Ilozor *et al*., 2004).

To date many research had been conducted in the face of identifying the factors causing increasing building defects. As refers to researches, design limitations (Building Research Establishment, (BRE), 1983; Adejimi, 2005; Ishak *et al.*, 2007; Alhaji and

Hassain, 2010; Sivanathan *et al*., 2012), poor construction quality and knowledge (Al-Hammad *et al.*, 1997; Dunston, 1999; Mills *et al.*, 2009), inadequate maintenance planning and practice (Bleanchar *et al*., 1995; Horner *et al*., 1997; Shabha, 2003), material limitations (Peacock, 1986; Olubodun, 1996; Chew *et al.*, 1999; 2000), as well as external factors such as climate; environment, soil condition, and chemical attack (Gambardella and Moroni, 1990; Honstede, 1990; Richardson, 1991) are among the factors causing inherent maintenance problems and induce high maintenance cost. However, vast amount of researches has highlighted that, increasing cost of building maintenance is highly attributed to design limitations. Design limitations known as the defects or problems causes due to faults in building design.

Survey of Assaf et al. (1996) on 11 major groups of defects through a literature review and interviews showed that building defects were mostly generated by design, specifications. The survey by Josephson and Hammarlund (1999), on seven buildings through observations and surveys showed that 32% of all defect costs originated from the client and design. Additionally, in Hong Kong Lam (2000) broadly stressed that, the causes of building maintenance problems and defects under design were accountable up to 40% of the overall cause. On the other hand, in Singapore, building defects due to poor design specifications led to 60% of the overall cause of building maintenance related problems (Chong and Low, 2006). Meanwhile in Malaysia, studies by Abdul Mohsen and Sadi (1997) and Nor Haniza et al. (2007) affirmed that building failures and defects in buildings are resulted due to design faults. In a research carried out by Mohammed Alhaji et al. (2010), they stated that most of maintenance problems existing in the facilities are not caused by construction failure but from building design failure. On the other hand, Sophia (2011) had carried out a pilot study to identify the causes of ineffective maintenance cost in Malaysia buildings. The results show that increasing building maintenance costs is attributed to the failure of building design. For an instance, The Majlis Perbandaran Johor Bahru Tengah (MPJBT) administration building's external walls were made from glass and needed to be maintained every 6 months. The maintenance costs for this work have reached about RM25,000 every six months. Another issue

identified by Sophia was in relation to the Taman Impian Emas public market, which has an aesthetic roof design. However, due to design faults, the roof of the market need undergo repair at the cost of RM300, 000. Further, Ramly et al. (2006) reviewed 4,389 records from 36 public housing areas in Kuala Lumpur, and found that 47% of the building defects were caused due to design faults.

Recognizing the increasing building maintenance cost due to inherent maintenance problems, building industry is moving forward on identifying the solution for this situation (Chew *et al.*, 2004 and Wood, 2009). It is apparent that, ineffective building maintenance cost has forced the industry to recognize the immediacy to rectify and to reduce such incidences and consequently reduce the increasing building maintenance cost.

1.3 Problem Statement

Recognising the importance of achieving cost effective building maintenance (CEBM), it is vital to decrease the mounting numbers of building defects generated due to design faults. Design decision and substitution made during the initial phase of building construction have major impact on the overall performance of a building. Hence, maintenance workloads plus increasing maintenance cost can effectively resolve if building design takes into account the need for careful and methodical planning, monitoring and execution of future maintenance. For this statement, previous researchers; Silva, Ranasinghe, and De Silva, (2012); Wood (2012); Das and Chew (2011); Chew *et al*. (2010); Banaitiene (2008), have supported and stated that ‘the incorporation of building maintenance into the building design phase denotes ease of maintenance through mitigation of defects and consequently contribute to reduce maintenance cost and time. The integration of maintenance activities during the building design phase is a concept refers as ‘building design for maintainability’ (BDM).

Predominant amount of reports and studies signifies that, BDM is a significant issue to be considered during a building development process (Silva and Ranasinghe, 2010; Che-Ani *et al*., 2009; Liu, 2006). Lack of BDM consideration, has been seen as one of the major factors contributing to various problems facing by the building industry (Wilson, 2002; Chanter and Swallow, 1996; Ramly, 2006). It is substantiate that, the consideration of BDM able to reduce the building defects decrease the increasing building maintenance cost and consequently achieve cost effectiveness. This statement is supported by a case study conducted by Chong and Low (2006), which found that design integrated maintenance able to prevent nearly 66% of building defects. In addition, investigation of Dunston and Williamson (1999) revealed evidence that, few projects in the building construction industry that have focused on the maintenance concerns during the design have typically realized reduced maintenance costs. Even Ismail and Mohammad (2014) highlighted that, incorporating maintainability consideration into building design lead to cost effectiveness throughout the building life. Further, Emirates Business (2009) declared, 10% of investment cost and 30% of operating cost can be saved if maintenance incorporated during the design phase. Thus, one prospective solution to address the issue of higher maintenance cost is to make certain the marriage of maintainability with the building design.

Unfortunately, architects and designers often overlook this most important factor, which has the potential to carry out future maintenance tasks easefully (Koo, 2000). As a result, building industries are still suffering with mounting numbers of maintenance problems and increasing maintenance cost. In Malaysia, maintainability has higher significance due to its tropical climate. This is because, in tropics building components need additional maintenance as alternate dry and wet seasons shorten the lifespan of materials to a great extent (Chew *et al*., 2004). Further, Malaysia also needs to outwit the standard of building and its facilities in order to attract and retain global investors as well as increase and strengthen the economic profile of the country. Hence, the incorporation of BDM is considered as necessary for buildings in Malaysia. However, the integration of BDM seems to be lack in Malaysia

(Ramly, 2006; Razak and Jafar, 2012), although in the 2009 manual of asset management, the Government of Malaysia has published that, requirements such as maintenance, space, landscape and energy should be considered in the design stage.

The statement by Ramly (2006); Razak and Jafar (2012) is also supported by Rozita (2006). In her study, that involved 38 designer firms (architectural, civil and structural) and 30 maintenance firms in Malaysia, Rozita (2006) concluded that maintainability is rarely considered during the building design phase by architects in Malaysia. In the effort to validate the relevance of Rozita's findings after an 8 year gap the author of this research conducted a preliminary survey (refer section 4.5.2, Chapter 4) that involved architects, engineers (mechanical, electrical and civil) and facility managers/ maintenance managers to study the awareness on maintainability and its consideration during the design phase. The result of the survey reveals that building practitioners in Malaysia are still oblivious in considering BDM strategies. The summary of the preliminary survey is shown in Table 1.2.

Table 1.2: The Awareness of Malaysia Building Practitioners on Building Maintainability Knowledge.

Questions Asked	**Architects**		**Engineers (Mechanical; Electrical; Civil)**		**Facility Managers/ Maintenance Managers**	
	YES	**NO**	**YES**	**NO**	**YES**	**NO**
1) Awareness on Maintainability	80%	20%	85%	15%	30%	70%
2) Awareness on Building Design for Maintainability	70%	30%	60%	40%	30%	70%
3) Consideration of Maintainability during the design phase.	42%	58%	35%	65%	25%	75%

Source: Preliminary Study (2013)

The percentage figures shown in the Table 1.2 demonstrates the level of awareness of Malaysia's building practitioners on the knowledge of maintainability. The questions were divided into 4 main categories namely;

i) Awareness of building practitioners on building maintainability
ii) Building practitioners awareness on building design for maintainability.
iii) Consideration of maintainability aspects during the design phase of a building by the building practitioners.
iv) Reasons for considering and not considering BDM practice.

Category (i) included to identify whether the practitioners are aware on maintainability concept applied to a building and its facilities. Category (ii) is to identify the awareness of practitioners on the BDM concept. It is important to focus on BDM concept as the research focuses on maintainability considered during the design phase although maintainability can be implemented throughout the entire life-cycle of a project. Category (iii) is to identify the consideration of maintainability aspects during the building design phase by the building practitioners. This is to know whether the practitioners consider the maintainability characteristics during the project design phase. Category (iv) is to identify the reason behind considering or not considering BDM practice by the building practitioners. This is to know what would be the reason for considering and not considering the BDM practice. The result of pilot survey shows that a large majority of the practitioners aware on maintainability and BDM. However, most of them less consider the maintainability and BDM aspects. The result of this preliminary study also supported by the study conducted by Rozita (2006) as both demonstrating the similar result.

The practitioners (48% architects, 35% engineers and 25% facility managers) that agreed for considering maintainability during the building design phase notified that they mainly stress ‘easy access’ (maintainability characteristic) during the building design phase. It is important to highlight that, the respondents agreed and assumed that a building would be ‘maintainable’ if the easy access feature is considered. Thus, in the previous project they consider easy access features solely during the design of a building. Further, the respondents that never experience taking maintainability into consideration during the design phase they not familiar with BDM characteristics. From their responses, respondents highlighted that

unavailability of maintainability guideline, limited amount of construction cost, plus with the presence of several demand; especially complex design, higher level of building system and services from the building stakeholders, occupants and owners, are the reasons for not considering BDM. Thus, it is so obvious that, the unclear understanding of BDM criteria are the main reason for not considering maintainability during the building design phase by the Malaysia's construction industry (Preliminary Survey, 2013).

Although many maintainability related studied had been carried out by the academic research and comprehensively discussed the issue of maintainability in journals and conferences, yet, in the practical world, most organizations have no comprehensive and established criteria to induce towards the aim to achieve maintainable as well as CEBM. It is undeniable, that various scholars and professionals in the construction industry have brought forward some maintainability criteria to be considered. Adding to this, the emergence of recent maintainability studies has brought similar and some particularly related maintainability criteria into view (see Table 1.3). These limited maintainability criteria may lead to the inadequate maintainability decision to be considered during the design phase. Therefore, it is apparent to impose a comprehensive list of BDM criteria and indicators to be considered during the building design. The Table 1.3 lists down the BDM criteria identified by previous researches in different maintainability studies.

Table 1.3: The BDM criteria identified by previous researches in different maintainability studies.

Criteria	Indicators	Authors
1) Accessibility 2) Commercial Availability of Spare Parts 3) Cost for Replacement Parts 4) Standard Tools 5) Clear instructions for Maintenance tasks	-	Her & Russell (2002)
1) Accessibility 2) Downtime 3) Material Performance 4) Environment	-	Chew *et al*. (2004)

Criteria	Indicators	Authors
1) Construction Quality 2) Environment 3) Material Durability, Sustainability & Maintainability 6) Maintenance Quality	-	Chew *et al*. (2006)
1) Efficient Access 2) Adequate Safety 3) Maintenance needs 4) Plan for Easy maintenance 5) Environment Consideration	-	Silva & Ranasinghe (2010)
1) Accessibility 2) Clean ability 3) Functionality 4) Compatibility 5) Complexity	-	Saghatforoush *et al*. (2012)
1) Accessibility 2) Material Selection 3) Communication 4) Environment 5) Standardization 6) Maintenance Cost 7) Easy Assembly 8) Diagnose ability	3- 4 Indicators for each criteria	Sivanathan (2014)

As can be seen in Table 1.3, there are only limited and comparatively similar maintainability criteria had been identified. Yet, if we think more broadly about enabling the whole building, it will be realized that, to make the whole building 'maintainable', it is vital to include many more dimensions associated with appropriate supports from the built environment professionals (Duggan and Blayden, 2001). The availability of inadequate maintainability criteria blur the clarity on what the factors need to be considered in order to achieve better maintenance. Additionally there are only countable research was conducted to identify more specifically the indicators of each maintainability criteria and thus it leads to the inability of comprehensive information to be applied during the building design phase. The unavailability of indicators for each maintainability criteria had result the identification of maintainability criteria to be incomplete. This is because, having maintainability criteria independently had vague the ability of maintainability decision to be considered during the design phase. Therefore, the identification of indicators for each of the BDM criteria is apparent to form more comprehensive and clearly delineated decisive maintainability criteria.

As the main objective of identifying comprehensive BDM criteria and indicators are to reduce the overwhelming cost of maintenance through mitigation of defects, it is vital to discover the relationship among both of it. This aspect is vital in providing the building practitioners a clear picture of structured way or commonly described as "structural relationship" of BDM criteria and CEBM. The term CEBM is defined as a building which deemed design to be lowest maintenance costs and with greatest return on investment (Whole Building Design Guide (WBDG), 2012; Krstic and Marenjak, 2012; File, 1991). Further, the word "structural" is defined as relating to the arrangement of and relations between the parts or elements of a complex whole (Pearsall & Hanks, 1998). Structural relationship or "what factor lead to what factor" will eventually help the building professionals determine the relevant BDM criteria and indicators to achieve CEBM. Hence, it is strongly assumed that providing the structural relationship among BDM criteria and indicators with CEBM will help the findings be more comprehensive and clear.

Despite of all these facts, the question is, did the previous researches on maintainability consider the BDM criteria and indicators to reduce the spiralling building maintenance cost burdens? Unfortunately, the identification of comprehensive BDM criteria to be applied during the design phase of building in particular to achieve CEBM is still known as unsolved riddle. This is based upon a review of former researches that focus on the BDM issues. The Table 1.4 below shows the summarize version of researches carried out by various researchers related to maintainability issues from the year of 1970's till lately. Although the consideration of maintainability has been studied by various research since 70's, the tables shows that, the studies carried out by the previous research can easily explain as twofold; On the one hand, much attention have been given to the temporal aspects of building maintenance; maintenance workloads (common maintenance defects) encountered result of neglecting maintainability aspects (Gibson, 1979; Ransom, 1981; Ikpo, 1983; Seeley, 1987; Al-Hammad *et al.*, 1997; Dunston *et al.*, 1999, Ishak *et al*., 2007 and Das *et al*., 2010) and barriers to implement maintainability during the design phase (Che-Ani, 2009; Lin *et al*., 2003). On the other hand, few have taken

initiatives to develop drivers such as organizational success factors, best practices and guidelines to be followed by built environment professionals to implement maintainability input during the design, construction and maintenance (Ismail and Mohammad, 2014; Silva *et al*., 2004; Duggan and Blayden, 2001; Meier and Russell, 2000 and Mills, 1994), some studied on significant design, construction and maintenance risk factors for better maintainability (Das and Chew, 2011; Chew and Das, 2007 and Silva and Ranasinghe, 2010). Few more researches seems to extreme and possible to develop maintainability framework, index, scoring device and even assessment model to evaluate the maintainability level of building (Das and Chew, 2010; Chew *et al.*, 2008(a), (b); Chew and Tan, 2004 and Nicolella, 2014).

Table 1.4: A Review of Previous Studies on Building Design for maintainability Issues

Year	Author	Maintainability Issues
1979	Gibson	The **effect of faulty design on building maintenance**. The importance of implementing maintainability during design.
1981	Ransom	
1983	Ikpo	
1987	Seeley	
1997	Al-Hammad *et al.*	
1999	Dunston *et al.*	
2000	Meier & Russell	**Maintainability best practices** into a model implementation process as starting point for implement maintainability.
2001	Duggan & Blayden	**Organizational collaboration** to implement design stage maintainability to ensure productivity, cash flow & profitability.
2002	Her & Russell	**Milestones** of the Construction Industry Institute model process for maintainability implementation.
2003	Chew *et al.*	A **model was developed to assess the maintainability of façade** using neural network techniques.
2003	Lin *et al.*	**Develop a computer based decision support system** for improving the communication between building design and maintenance through Building Automation Systems.
2004	Chew *et al.*	Offers 2 approaches to integrate with the maintainability concept to augment building **performance** throughout its **economic life**.
2004	Bamisile	Explained how the **maintainability analysis** could be carried out before construction.
2004	Silva *et al.*	Identification of **key factors** (knowledge & benchmark) to enhance the level of maintainability in buildings.
2007	Ishak *et al.*	**The effects of design on the maintenance bring awareness and approaches** for better maintenance works.

	Author	Maintainability Issues
2009	Che-Ani *et al.*	**Identification of design for maintainability factors** that contributing to stabilize the sustainability and maintenance.
2010	Silva & Ranasinghe	**Maintainability Problems and strategies** to solve those problems.
2010	Alhaji & Hassanain	Investigate the **role of the facility manager** in the architectural design process.
2010	Das *et al.*	**Decision-analysis framework** for building maintainability management.
2011	Das & Chew	Developed **defect grading tool** to improve building maintainability by preventing defects.
2012	Wood	A Mind mapping developed as a framework for buildings that are **economical and efficient to build and to run**.
2012	Sivananthan *et al*.	**Overview** Design Deficiencies on Ease of Maintenance.
2014	Ismail and Mohamad	**Incorporate building maintainability factors** in building design **to improve the building design life.**
2014	Nicolella	**A methodology** for evaluating maintainability as a tool **for durable and sustainable buildings.**

Thus, it is obvious that there is a still a gap of what are the inclusive BDM criteria and indicators that need to be considered during the building design in order to achieve CEBM (Duggan and Blayden, 2001). The unavailability of comprehensive as well as clearly delineate BDM criteria and indicators result in uncountable building defects and impose high maintenance cost. In short, there is a need to identify the comprehensive (or important) building BDM criteria and indicators that provide maintainable building and subsequently influence CEBM. Consequently, this will lead to an improved future building designs, construction quality, maintenance management, and etc. Hence the author find, it is necessary to study more broadly on the term ‘maintainability’ and its associated criteria to open up a possible path for the practitioners, particularly Malaysia’s construction industry to apply those criteria during the building design phase.

In summary, the issues that are addressed in this research are:

i) The comprehensive design for maintainability criteria and indicators to be applied during the design phase of a building to achieve cost effective building maintenance need to be identified and clearly explained.

ii) The structural relationship of the design for maintainability criteria and indicators to achieve cost effective building maintenance need to be identified.

1.4 Research Questions

This research attempts to answer the following questions;

1) What are the cost effective building maintenance indicators?

2) What are the building design for maintainability criteria and indicators to be considered during the building design phase to achieve cost effective building maintenance?

3) How are the structural relationship among the design for maintainability criteria and indicators to achieve cost effective building maintenance?

1.5 Research Objectives

Addressing the issues mentioned in Section 1.3, this research aims to study the influence of building design for maintainability on achieving cost effective building maintenance. Subsequently, a structural model for establishing the relationship between building design for maintainability and cost effective building maintenance will be developed. In pursuance to achieve the aforesaid aim, the research will focus on the following objectives.

i) To identify the cost effective building maintenance indicators.

ii) To identify the building design for maintainability criteria and indicators to be considered during the design phase to achieve cost effective building maintenance.

iii) To determine the structural relationship among the building design for maintainability criteria and among the indicators to achieve cost effective building maintenance.

1.6 Scope of the Research

The first scope of this research involves a panel composed of experts closely related in building design, maintenance and its related field (Architecture, Civil Engineering, Structural Engineer, Building Service Engineer, Building maintenance or management, Facilities maintenance or management and Quantity Surveying etc) in the Klang Valley, Penang, Ipoh and Johor. In the absence of much literature on the comprehensive building BDM criteria and indicators, it is imperative to validate the identified criteria and indicators through the expertise who possess substantial experience in building design and maintenance practices. This expertise does not

have to be academic; it could be the knowledge of an experienced practitioner (Valerdi, 2013). The panel of experts will be selected based on a number of criteria including their research interest (knowledge) and experience with the issues under investigation (Jeffery *et al*., 2000; Hardy *et al*., 2000; Skulmoski *et al*., 2007; Valerdi, 2013), hierarchy or position (Mead and Moseley, 2001; Valerdi, 2013), publications (academicians) (Duncan *et al*., 2004; Valerdi, 2013) or involvement in projects (practitioners) (Powell, 2003; Cantrill *et al*., 1996; Haughey, 2010), and their willingness to participate (Powell, 2003; Skulmoski *et al*., 2007). Delbecq *et al*. (1975) further stated that the professional staff members together with their support team are well qualified to be subjects of a Delphi study.

A number of experts in the area closely related with building design, maintenance and its related field have been identified by the researcher using judgemental sampling as the potential population (see Appendix A, Table 1) of Delphi panel. The panels of experts who showed their willingness and interest to participate in the research from the potential population had been listed (see Appendix A, Table 2). Around 16 experts' panels in the area of study have confirmed to participate in this research. They are all experienced and well performed in building design and maintenance topics. The panel of experts served to validate the CEBM indicators and building BDM criteria and indicators identified from the literature. In addition, the panels of experts also will determine the BDM criteria and indicators that associated with particular building elements (basement, facade, floor, roof, lighting system, HVAC, lift, sanitary plumbing and fire-protection).

Second, for the purpose of main survey the people closely related to the design and maintenance of buildings was involves. This consists of architects, civil engineers, building maintenance personnel (facilities and property maintenance personnel), building engineers and building surveyor that operate in Klang Valley, Penang, Ipoh and Johor. Their opinion on the building performance criteria and indicators to be identified in this research is the backbone to the achievement of the research objectives.

Third, as the research focuses on integrating maintainability during the building design and certain elements of a building from maintainability point of view, the structural model that was developed have been limited neither by complexity, size or type of building.

1.7 Significance of the Research

This research contributes to;

1.7.1 Filling in the gap that exists in the delineation of the building design for maintainability criteria and indicators and contribute to the knowledge.

Though numerous literatures and studies has been conducted on building maintainability, yet there is still a gap of what are the actual and significant building maintainability criteria and indicators that need to be considered during the building design, construction and maintenance phase. As for the time constraints and several other limitations, this research intended fill the gap of identifying building design related maintainability criteria and indicators to achieve CEBM especially in the context of Malaysia. Thus, by studying and identifying the BDM criteria and indicators, this research expands knowledge on the influence of BDM towards achieving CEBM.

1.7.2 Provide beneficial reference for local architects, design engineers, facility managers, engineers, construction manager and building owners.

The research will solve the long pending quest of inadequate awareness of building professionals on maintainability and the consideration of maintainability

during the design phase. In general, this research believed to be beneficial reference for local architects, design engineers, facility managers, engineers, construction manager and building owners to incorporate maintainability in the design stage to ensure a successful cost reduction during the building maintenance phase particularly for future projects in Malaysia. This is because the result of this research will assist the professionals in the building design phase to put extra care to attain better maintenance during the building maintenance phase. As a result, the maintainability related problems occur during occupancy stage that relatively increase cost burdens could be reduced.

1.7.3 Seeks to obtain useful knowledge and an in depth understanding as well as introduce new courses for postgraduate and undergraduate of built environment students on incorporating maintainability aspects during the design stage.

This study also seeks to obtain useful knowledge as well as an in depth understanding on integrated BDM issues. This study will also enhance the research potential of the investigators to explore all other issues related to the subject area in the future. Additionally, the educational aspect of the research has been designed to provide an excellent opportunity to both the postgraduate and undergraduate of Facility Management and Construction Engineering students to improve their understanding on incorporating maintainability aspects in the design stage. Incorporating maintainability during the design stage is still relatively new concept and yet to be investigated and taught in construction programs. To meet this new challenge, this paper plans to introduce new courses in our graduate level facility management program and the emerging results of the study will be integrated into the coursework, senior design project and thesis work. The findings of the paper will be disseminated through major international journals and magazines.

1.8 Research Methodology

The research work is executed in two main phases as discussed below. The research methodology is illustrated in the flow chart shown in the Figure 1.1.

The first phase in the research methodology is aimed to obtain a holistic idea of the research problem and recognized the knowledge gap. A thorough review on various literatures was conducted to obtain the issues and problem associated with the study area. In order to investigate and verify the issues obtained through reviews with the Malaysia's situation, a simple pilot survey was conducted in the early phase of the research. Three groups of respondents were selected for the pilot study, consisting of architect, maintenance personnel and engineer (civil, electrical and mechanical). The main aim of the research in the first phase is to identify, from the available literatures, the BDM criteria and indicators to achieve CEBM. Through critical review of the available literatures the indicators of CEBM were first identified. The CEBM indicators were used as a needle to form the theoretical BDM criteria and indicators.

Following the critical review on literature, next step is aimed to verify the CEBM indicators and BDM criteria and indicators obtained through literature review. Delphi Method (expert's opinion) is the method that will be used to conduct the verification. In first phase of Delphi survey the CEBM indicators and the BDM criteria and indicators will be verified. In the second phase of Delphi survey experts will be required to determine the BDM criteria that applied for the associated building elements (basement, facade, floor, roof, lighting system, HVAC, lift, sanitary plumbing and fire-protection). Respondents used for this Delphi study will be expert from building design, maintenance and its related field (Architecture, Civil Engineering, Building Maintenance, Quantity Surveying, etc).

In the second phase of the research methodology, the verified theoretical design for maintainability criteria and indicators were converted into questionnaire form and distributed to the respondents of the survey in order to examine and validate the proposed relationship between the constructs. Therefore, first questionnaire will be developed based on the output received from expert's survey, to collect empirical data to test the proposed theoretical model. As BDM deals with design and maintenance, the designers, architects, property or facility managers were considered the best respondent. Respondents will be selected from the membership list of professional bodies in Malaysia namely, The Board of Valuers, Appraisers and Estate Agent, Malaysia Association of Facility Management (MAFM), The Board of Architects Malaysia (LAM), Malaysian Institute of Architects (PAM) and The Construction Industry Development Board (CIDB). Before the main survey distribution is conducted, a pilot study will be conducted in order to test the reliability of the main questionnaire. Finally the questionnaire distribution will be conducted.

The last phase (second process of phase two) of the research methodology, aims to analyse the obtained data from the main survey to develop a structural model to reveal the causal relationship of the proposed model. The data obtained from the main survey will be analysing using the partial least square (PLS) approach of SEM.

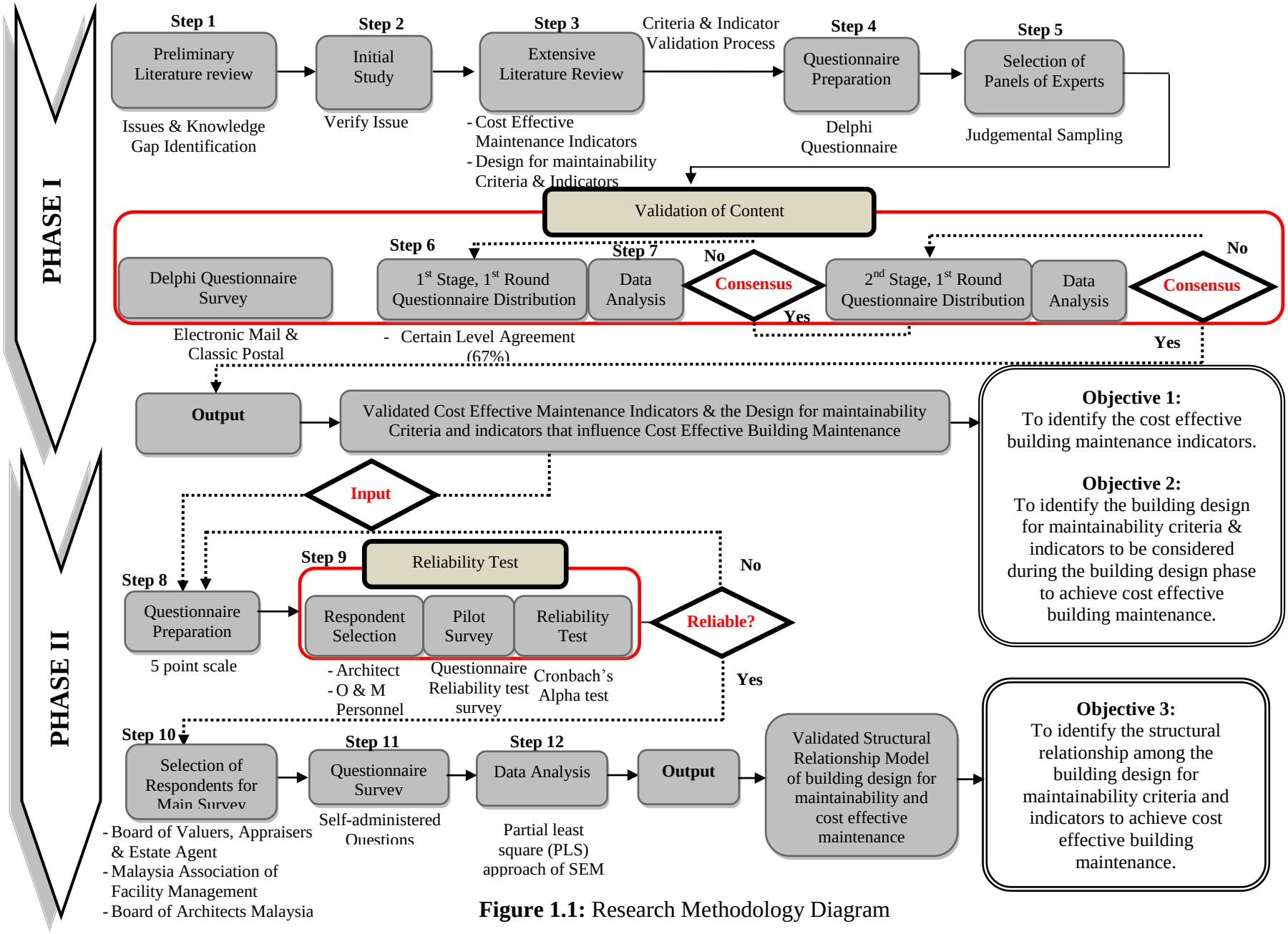

Figure 1.1: Research Methodology Diagram

1.9 Structure of the Research

This dissertation has been organised into 8 chapters according to the logical development that has taken place over the entire period of research. The overall 8 chapters are as organized as following;

Chapter 1. Introduction: In this chapter a general introduction, background and the justification of the research has been provided. A brief overview on the concepts of BDM and its importance were also explained. It further addressed the aim and objectives, scope and purpose, the significance, the methodology applied to conduct this research and a brief summary on the structure of this thesis.

Chapter 2. Integrated Maintenance in Building Design: To obtain a holistic idea of the research problem, and the rationale and concept of integrated maintenance during the building design phase. Therefore, the relevant topics reviewed are: the practice of maintenance in Malaysia, factors causing building maintenance problems, the effect of design deficiencies on building maintenance, design deficiencies related building maintenance cost, the role of Facility Management in building design and finally the rationale and concept on integration of maintenance during the building design phase. This helped to recognize the knowledge gap, issues and rationale of the study.

Chapter 3. Building Design for maintainability and Cost Effective Maintenance: It provides an argument for the importance of incorporating BDM principles during the building design phase to achieve CEBM. The CEBM definition and indicators were identified. Subsequently, the CEBM indicators will be the needle to identify the BDM criteria and indicators. The influence of the BDM criteria and indicators on achieving CEBM will be discussed in detail.

Chapter 4. Research Methodology: Discusses the methodology employed in this research. The chapter explains the design of the questionnaire developed to identify and verify the CEBM indicators and the BDM criteria and indicators established in Chapter 3 of the research. This chapter subsequently discusses the selection of respondents, data collection and analysis methods employed in this research. The final part of this chapter explicates about the validation process of structural relationship model of the building BDM criteria and CEBM.

Chapter 5. Data Analysis Phase I: It will explain the analyses that will be undertaken for achieving the first and second objectives of this research.

Chapter 6. Data Analysis Phase II: This chapter will discuss the analysis that carried out in order to achieve the third objective of the research. In the final part of this chapter the structural relationship model of building BDM criteria and CEBM will be verified.

Chapter 7. Results and Discussion: This chapter discusses the results obtained and the extent to which the results fulfil the objectives of this research.

Chapter 8. Conclusion and Recommendations: After summarizing the whole research and the key findings, the conclusions are made. The contribution and implications of the findings towards the construction industry in general and CEBM in particular are explained. After the knowledge contribution and practical implications of this study are highlighted, finally the limitations are discussed, followed by improvements and identification of the scope of future research.

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