CHAPTER 2
ASSET MANAGEMENT AND LIFE CYCLE ASSESSMENT

2.1 Chapter Overview

The focus of this thesis is to assess the life cycle of a power transformer effectively over its life cycle. In this chapter, the concepts of asset management and life cycle assessment are investigated through their definitions and framework. The study on life cycle cost and the life cycle management of asset is conducted in this thesis followed by life cycle phases. The health index and asset management of power transformer are presented in the later section of this chapter along with loading mechanism. Finally, the proposed life cycle assessment framework of a power transformer is presented.

2.2 Asset Management

The term asset management is widely used in power utilities, real estate, finance and other areas of private industry to refer to the work of managing investments. In general, the point of asset management is to achieve the greatest return on investment. The concept of asset management is widely applied in power utilities to improve performance, manage risk and reduce long-term costs of assets. With aging equipment, changeability in load growth and regulatory uncertainty, power utility companies are now using asset management philosophies to increase earnings, credit ratings, and stock price. Asset management in power utility companies plays a significant role in identifying and evaluating decisions leading to long term financial success and best possible earnings [J. Schneider, 2006].

2.2.1 Definition and Terminology

The financial industry has derived the term asset management and used its concepts to investment portfolios comprising stocks, bonds, cash, options, and other financial instruments. The fundamental meaning of asset management is the trade-off between risk and return [R. E. Brown, 2005].

Lemer mentioned that the Civil Engineering Research Foundation defined asset management as a process to extend infrastructure life at the lowest possible cost [A.C. Lemer, 2000]. The Federal Highway Administration [Department of Transportation, 1999] defines asset management as “a systematic process of maintaining, upgrading, and operating physical assets cost-effectively”. It is “the combination of management, financial, economic, engineering, and other practices applied to physical assets with the objective of providing the required level of service in the most cost-effective manner” [A.C. Lemer, 2000]. These definitions have not specified the life cycle cost of asset.

Shahidehpour et al. have defined asset management as, “the process of maximizing the return on investment of equipment by maximizing performance and minimizing cost over the entire life cycle of that equipment”. Asset management can provide more comprehensive procurement decisions, operational schemes, and maintenance scheduling for improving the return on capital investment [M. Shahidehpour, 2005]. The definition of asset management [J. Woodhouse, 2001] is “the set of disciplines, methods, procedures and tools to optimize the whole life business impact of costs, performance and risk exposures (associated with the availability, efficiency, quality, longevity and regulatory/safety/environmental compliance) of the company’s physical assets”. Similarly, PAS55 has defined asset management [BSI, 2004] as “systematic and coordinated activities and practices through which an organization optimally manages its assets, and their associated performance, risks and expenditures over their life cycle for the purpose of achieving its organizational strategic plan”. The more relevant definition for this context is given by Government of Victoria, Australia, who define asset management as “the process of guiding the acquisition, use and disposal of assets to make the most of their future benefits and manage the related risks and costs over their entire life”.

In this research, the understanding of asset management into this context is to maximize the return on asset investment with its maximum utilization while maintaining the quality of service under the organizational strategic plan in a systematic way. Based on this definition, the life cycle assessment framework of power transformer is investigated.

There are some keywords associated with these definitions which require further explanations include the terms asset, organizational strategic plan, costs-benefit, risk, performance, optimization, life cycle, decision making and systematic process.

Asset: includes plant, machinery, property, buildings, vehicles and other items and related systems having a distinct and quantifiable business function or service.

Organization strategic plan: the overall long term plan for the organization which is derived from and embodies its vision, mission, values, business policies, objectives and the management of its risks [BSI, 2004].

Performance: the ability of an asset to perform to a desired level.

Risk: the future uncertainty of an asset.

Costs-Benefit: the benefit on asset related to spending.

Optimization: the best value that comprises between conflicting factors such as performance, costs and risk with any non-negotiable constraints [A. Rajakrom, 2009].

Life Cycle: the time interval that starts with the identification of the need of an asset and finishes with the decommissioning of the asset [BSI, 2004].

Decision Making: the process of identifying and choosing alternatives on a given problem based on an organizational strategic plan [A. Rajakrom, 2009].

Systematic Process: the step by step process for solving the problem and involve problem definition, searching of alternative solutions and selection of the best alternative.

2.2.2 Asset Management Framework

With the aim of aligning the management of asset related spending to corporate goals, asset management is designed as a business approach. Generally, an asset management approach is utilized by the power utilities in order to either reduce-spending; more effectively manage risks, or drive organizational objectives [K. Morton, 1999]. These things should be considered a result of asset management rather than its objective. Instead of considering asset management as a reliability centered maintenance, equipment condition monitoring, loading equipment to higher levels, reviewing risks for cancelled projects or a “black box”, it is applied to balance cost, performance and risk; align corporate objectives with spending decisions; create a multiyear asset plan based on rigorous and data driven processes [R.E. Brown, 2004].

A utility company comprises of potential stakeholders and it is the responsibility of the utility to compromise all the requirement of each stakeholder. The asset manager needs to balance service, cost and asset investment to best meet stakeholder needs. The relationship between the main stakeholders and drivers and the asset management process is illustrated in figure 2.1.

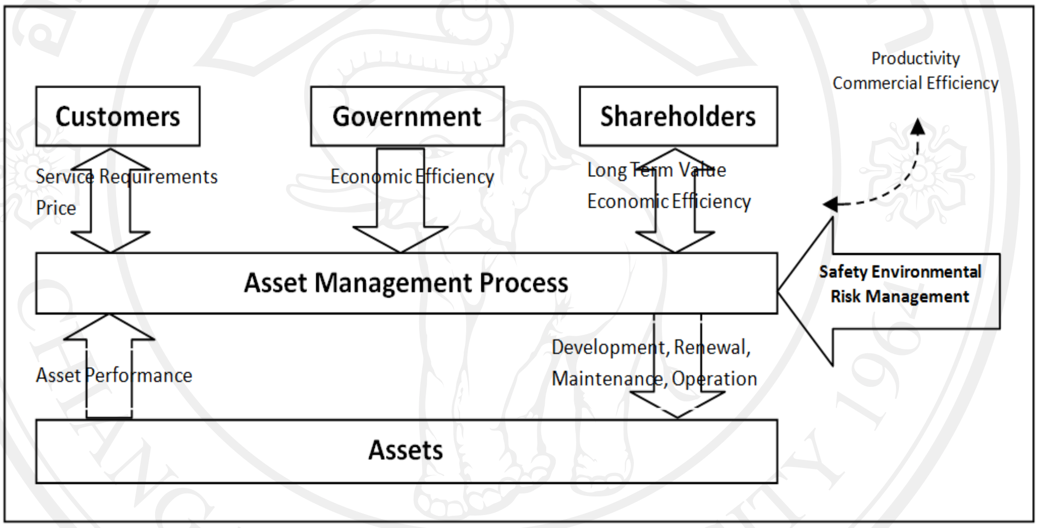

Figure 2.1 Asset Management Process [Power^{CO}, 2002].

The consumers are the people, businesses and organizations who rely on the delivery of electricity from power utilities. In addition, Brown et al. provides an asset management framework, being endorsed by many organizations and experts [R.E. Brown, 2004]. This framework allows each asset function to focus on operational excellence, shown in figure 2.2. The asset owner is responsible for setting financial, technical and risk criteria. On the other hand, the asset service provider is responsible for executing these decisions and providing feedback.

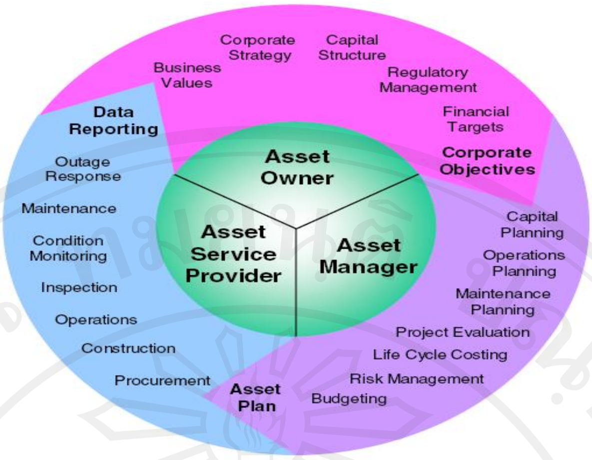

Figure 2.2 Asset Management Framework [R. E. Brown, 2004].

In conclusion, asset management is a single process rather than a hierarchical organization, which connects asset owners, asset managers, and asset service providers in a manner that allows all spending decisions to be aligned with organizational objectives supported by asset data [R.E. Brown, 2005].

2.2.3 Publicly Available Specification: PAS 55-1

PAS 55-1 is a standard for carrying out asset management in any organization where physical assets are a key or critical factor to attain its objectives in an effective way. It is a formal document for asset management as a publicly available specification, and is based on BS ISO format standards. The development is led by the Institute of Asset Management (IAM) with the consultation with other organization and is prepared and published by British Standards Institution (BSI).

This PAS is designed to cover the management of physical infrastructure assets such as utility networks, power station, building, etc. and asset management from an organizational perspective. The main objective of PAS is to ensure that the assets deliver the required function and level of performance in terms of service or production, in a sustainable manner, and at an optimum whole-life cost [BSI, 2004].

In order to achieve the organizational strategic plan, the physical assets must be managed holistically and placed at the center of the business process while considering the relationships with, and interfaces between, the financial, human, information and intangible assets of the business. The scope of this PAS in relation to the other critical categories of assets is presented in figure 2.3.

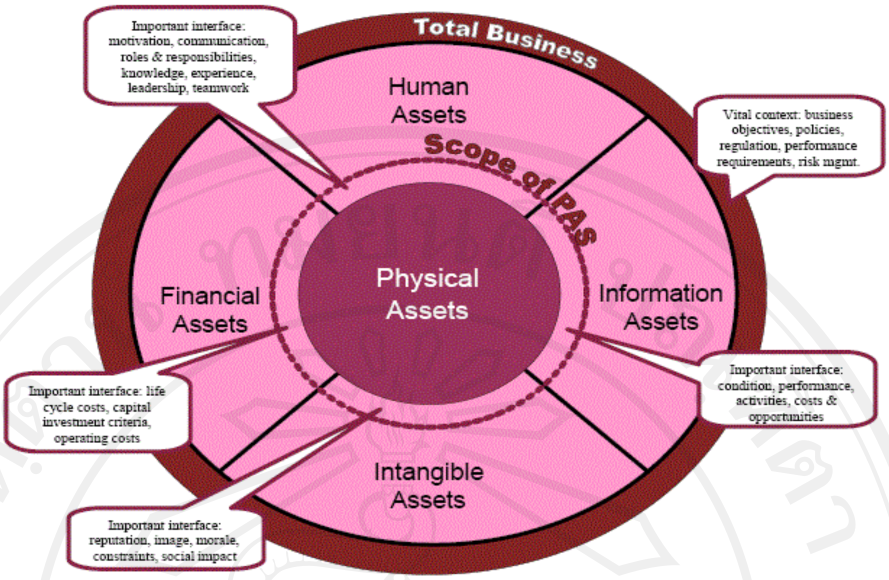

Figure 2.3 Scope and Business Context of Physical Asset Management [BSI, 2004].

The structure of PAS is aligned with ISO 14001:1996 and OHSAS 18001:1999 and has taken provisions of ISO 9001:2000. This is based on Plan-Do-Check-Act methodology. An asset management system is a continual improvement process and the elements specified in this PAS are illustrated in figure 2.4.

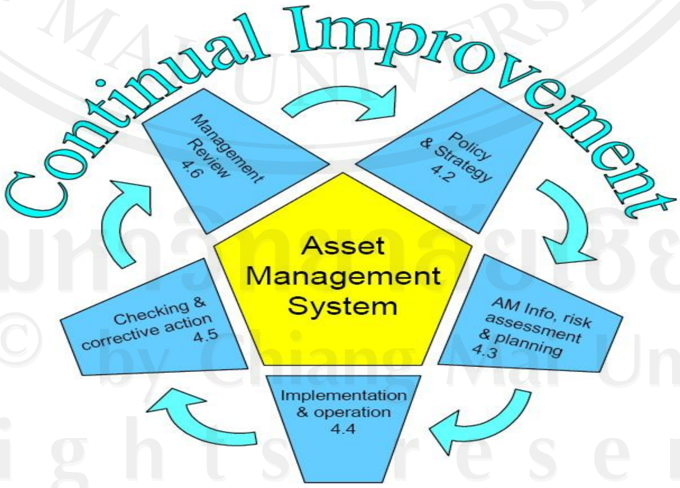

Figure 2.4 Asset Management System Elements [BSI, 2004].

It has main five elements with 21 sub elements. The organization shall establish documents, implement and maintain an asset management system and continually improve its effectiveness as per the requirements stated below [BSI, 2004].

1. Asset management policy and strategy
    1.1 Asset management policy
    1.2 Asset management strategy
2. Asset management information, risk assessment and planning
    2.1 Asset management information system
    2.2 Risk identification, assessment and control
    2.3 Legal, regulatory, statutory and other asset management requirements
    2.4 Asset management objectives
    2.5 Asset performance and condition targets
    2.6 Asset management plans
3. Implementation and operation
    3.1 Structure, authority and responsibility for asset management
    3.2 Training, awareness and competence
    3.3 Consultation and communication
    3.4 Documentation
    3.5 Document, data and information control
    3.6 Operational control
    3.7 Emergency preparedness and response
4. Checking and corrective action
    4.1 Performance and condition measurement and monitoring
    4.2 Asset related failures, incidents, non-conformances and corrective and preventive action
    4.3 Records and record management
    4.4 Audit
5. Management review and continual improvement

This Publicly Available Specification is relevant to any asset intensive organization where the greatest expenditure, effort, dependency and risks are linked with assets. It is applicable to all stakeholders associated with managing assets [BSI, 2004].

2.2.4 Asset Management Process in Power Utility

In a deregulated environment, power utilities have constant pressure to reduce operating costs, increase the equipment availability and improve quality and service to customers. They have to maintain high asset availability not only due to deregulation processes, but also to high demand growth, economic pressures and profit constraints. Lucio et al. have proposed a decision support system based on asset management theory to simulate the performance of the transmission equipment including different maintenance strategies, costs, risk analysis and reliability indexes. The important strategies and management techniques for asset management are; maintenance strategies, determination of component condition, asset simulation, fault analysis and life management [J.C.M. Lucio, 2009]. Maintenance strategies lead to varying maintenance costs and asset availability. The decision process has three separate levels; the first level is focused on components, the second level is focused on network (reliability) while the third level makes decisions about risk which have mainly a corporate focus [J. J. Smith, 2006]. Maintenance plan and condition monitoring techniques are essential tools for asset management activities. However, each asset management activity is different from one piece of equipment to another [A. Abu-Elanien, 2010]. To implement different maintenance strategies and select decision, there must be a good understanding about the life cycle of assets.

To sum up, the asset management techniques described above can assist utility asset manager in making life cycle decisions on an asset. However, these techniques have emphasized more on quality and reliability [J. Schneider, 2006]. When implementing in a real world situation, the decision is based on the working environment of power utility. Therefore, in later section, this thesis discusses the life cycle assessment of assets.

2.2.5 Challenges in Asset Management

The following challenges faced by the organization during asset management are outlined below:

- An asset management is emphasized on sustainable organization outcomes, risk management and value. It is concerned with the asset throughout its life cycle, which is from the identification of the need of an asset and the definition of the requirements, through the acquisition process and maintenance management to asset decommissioning and disposal. The main challenges in asset management are capturing knowledge about the asset in each phase of the life cycle and sharing and disseminating this knowledge between the personnel involved in the various phases of the life cycle [M.R. Hodkiewicz, 2006].

- Asset management is concerned with the life cycle management of equipment. The challenging issue is that it is more difficult to monitor and assess the condition of the electrical equipment. The following questions [D.M. Allan, 2005] need to be answered in terms of asset maintenance management within a power utility;

❖ How to assess if the asset is in normal condition
❖ How to assess the working life time
❖ What maintenance and testing procedures to set
❖ Whether to refurbish, or replace or use up

In addition to this issue, the structure of many organizations have changed from collective decision making to a centralized system, which causes an impact on the accessibility of technical and engineering expertise if not well managed. Another challenge is due to the increase in the quantity and quality of condition monitoring data [D.M. Allan, 2005].

- The continuous evaluation of the benefits of individual techniques and equipment against the cost of installation and operation is challenging for the asset manager [K. Morton, 1999].

- An addressing critical transmission and distribution problems is challenging due to an aging infrastructure because of the following reasons [R.E. Brown, 2005]:

❖ It directs asset owners to provide clear goals in terms of budgets, system performance, and acceptable risk.

❖ It needs an asset registry so that engineers can perform detailed technical analysis.

An asset utilization strategy is essential to the power utilities in order to take a comprehensive look at equipment utilization since it helps power utility to reduce capital spending and increase returns on its asset value. Furthermore, asset planning is necessary to identify the best combination of capital, operations, and maintenance spending to achieve performance, risk and budget targets for the least possible life cycle cost [R.E. Brown, 2005].

2.3 Life Cycle Assessment

The term Life Cycle Assessment (LCA) was recognized in 1990 by the physical sciences and engineering disciplines as a tool to help reconcile values, technological impacts and the environment. The United Nations (UN) then began to envisage the global rollout of life cycle assessment practice. It is a systematic evaluation of environmental impacts arising from the provision of product or service [R. Home, 2009]. The principles and framework for life cycle assessment are described by ISO 14040.

A life cycle assessment is defined by an International Standard [ISO 14040:2006] as the “compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle”. In addition, it is a technique to assess the environmental aspects and potential impacts associated with a product throughout its life from raw material acquisition through production, use and disposal [LCA, 2004].

LCA is used to compare the total environmental impact of a product or service with an alternative product or service. Hence, LCA is a tool that provides the answer to the question of which product has least environmental impact. Normally, it is widely used in the manufacturing industry for environmental assessment. The definitions of LCA cannot be directly used in this research context however its concept can be applied.

2.3.1 Life Cycle Assessment Methodology

The methodology of life cycle assessment [LCA, 2004] consists of four distinct steps shown below:

Step 1: Goal and scope definition

Step 2: Inventory analysis

Step 3: Impact assessment

Step 4: Interpretation of results

Goal and Scope definition: includes life cycle definition, functional units, system boundaries, data quality requirements, and critical review process. Life cycle definition means that those systems required to generate, use and dispose of the product are all relevant. The usefulness of the product is identified through its functional unit. Boundaries identify the extent to which specific processes are included or excluded according to the goal and scope. Finally, the critical review process is used to ensure the quality of the study [LCA, 2004].

Inventory Analysis: involves data collection and calculation procedures to quantify relevant inputs and outputs of a product system. It comprises data collection and the refining of system boundaries. The refining process may involve or exclude the life cycle stages or subsystems if they are insignificant [LCA, 2004].

Impact Assessment: It can be subdivided into four categories [LCA, 2004]:

- Category definition: provides guidance to select and define the environmental categories addressed by the study.
- Classification: is performed to assign inventory input and output data to the defined categories.
- Characterization: facilitates the ability to model the categories in terms of standardized indicators.
- Weighting: provides a process that ranks categories according to their relative importance to each other, and assigns numerical values to represent degrees of significance.

Interpretation of LCA Results: include an identification of significant environmental issues, an evaluation of the underlying study and the generated information and is intended to lead to conclusions and recommendations [LCA, 2004].

The methodology described above is mainly focused on environmental issues. Nevertheless, keeping the definition and methodology of LCA in mind, a new life cycle assessment model is proposed in this study focusing on the financial limitation of the power utility company.

2.3.2 Life Cycle Phases of Power Transformer

The major influence on life cycle analysis is forecasting the life of an asset. The life cycle phase of asset is divided into three stages; acquisition, utilization and disposal [G. Balzer, 2004]. Asset aging is a fact of life causing frequent failure of assets although there may be different causes of aging. Life extension of asset is an important issue for the utilities due the involvement of more safety and risk in operating aged assets [M. Arshad, 2004a]. Thus, there is a requirement to know the lifetime of an asset. There are three different concepts regarding the life time of asset: physical lifetime, technical lifetime and financial lifetime [W. Li, 2006].

- Physical lifetime: An asset starts to work from its brand new condition to a position in a life cycle where it cannot be used in a normal operating state and must be retired.
- Technical lifetime: the period until technical obsolescence forces replacement due to technical reasons although the asset may still have physical lifetime.
- Financial lifetime: An asset is no longer financial valuable, although it may have a physical lifetime. There are two methods for evaluating the financial lifetime;
    - The capital value of any asset depreciates every year. The asset reaches to the end of its financial lifetime when the remaining capital value approaches to zero.
    - Operating and maintenance costs are also considered along with capital cost of asset.

The life cycle characteristic of an asset is essential to determine its performance as the life increases. It is represented through plotting the bathtub curve of an asset as shown in figure 2.5. This shows that the failure of asset is categorized into three phases of its life cycle. The failure rate is maximum in the acquisition phase due to manufacturer problem. However, it is included in the warranty period of the asset. Then, the failure rate is low, almost constant until the end of its financial designed life. Finally, the failure rate is high due to the aging of an asset. In this research, the last stage of the asset has not been considered.

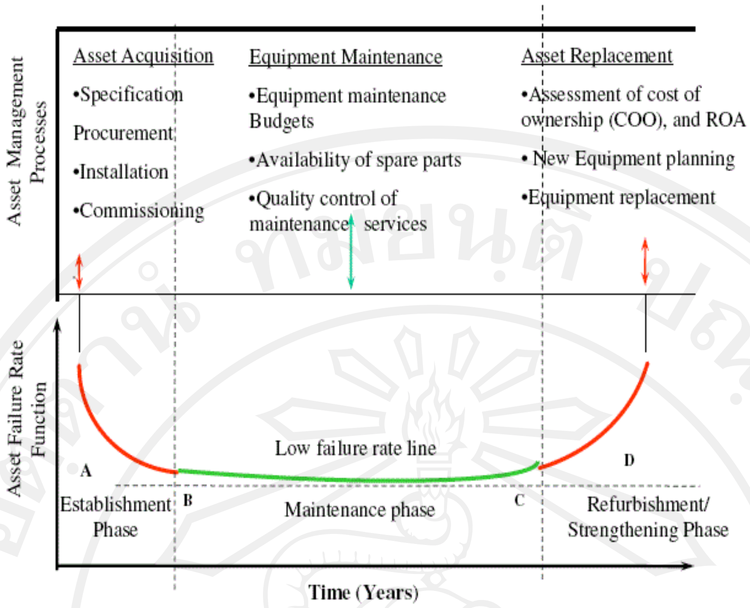

Figure 2.5 Bathtub Curve of an Asset [I.E. Davison, 2005].

The life cycles of a transformer can have nine major events; specification, manufacturing, tests, shipment, receiving, storage, installation, operation and maintenance [P.J. Pillitteri, 2006]. The financial end of the life of an asset is usually less than its technical end of life [G. Swift, 1997]. The different activities or tasks involved in each phases of life cycle of power transformer are shown in figure 2.6. In the acquisition phase, the following activities are accomplished:

- Preparation and selection of bidding document;
- Design, manufacture and assemble of asset;
- Shop testing;
- Dispatching;
- Installation and commissioning;
- Training to the working personnel of power utility.

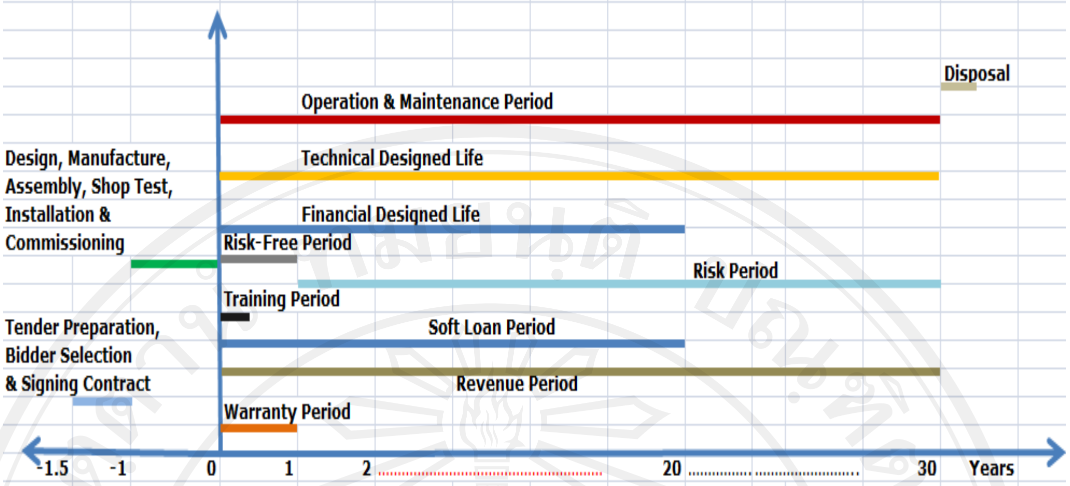

Figure 2.6 Life Cycle Phases of Power Transformer [S.S. Bhandari, 2009]

After putting it into an operation, revenue is generated by the power utility and there is expenditure by the utility on different items such as soft loan payment, operation and maintenance cost, administrative cost. It helps to identify reusable knowledge of asset embedded within both documents and experts who have been operating on particular asset with their significance. This reusable knowledge is referred to as hidden knowledge in this thesis. It provides both financial and technical benefits to the power utility with its utilization. It is explained in chapter 4.

2.3.3 Life Cycle Costing

Life cycle costing (LCC) is an essential term used in assessing the life cycle of an asset. LCC is a cradle to grave costs-summarized as an economic model of evaluating alternatives for equipments and projects. In addition, it helps to optimize the cost of acquiring, owning an operating the physical assets over their useful lives by identifying and quantifying all the significant costs associated with that life. Several definitions of Life cycle costing exist. Generally, “life cycle cost of an item is the sums of all funds expended in support of the item from its conception and fabrication its operation to the end of its useful life” [D.G. Woodward, 1997]. So, the LCC is the total cost of ownership of machinery and equipment, which includes acquisition, operation and maintenance, conversion, and decommissions costs.

The objectives of LCC determined by Royal Institute of Chartered Surveyors are as follows [D. G. Woodward, 1997] [H.P. Barringer, 2003]:

- To enable investment options to be more effectively evaluated;
- To consider the impact of all costs rather than only initial capital costs;
- To assist in effective management;
- To facilitate choice between competing alternatives.

It identifies all future costs and benefits and reduces them to their present value using discounting techniques. The main elements of LCC to achieve the objectives stated above are initial capital costs, life of the asset, the discount rate, operating and maintenance costs, disposal cost, information feedback and uncertainty and sensitivity analysis [D. G. Woodward, 1997]. Braun et al. have proposed the following model [D. Braun, 1994] to evaluate the life cycle cost of asset:

$$LCC = LCA+LCS+LCU+LCD \qquad (2.1)$$

The first component in the equation 2.1 in is the acquisition cost (LCA). It comprises the initial cost of equipment plus the installation, commissioning and training costs. The second term (LCS) is life support cost consisting of operation and maintenance cost of the asset. The third term (LCU), life unavailability cost, is the outage cost of asset. Finally, the last term (LCD) is the disposal cost that includes the cost of demolition, scrapping or selling the asset. Such costs would be deducted from the residual life of the asset at the end of its useful life [D. G. Woodward, 1997].

The LCC model has been widely used in power utilities to provide quantitative values on assets to assist them in managing it during its life cycle [G. J. Anders, 2005] [G. Swift, 1997][J. Palola, 2006][M. Hinow, 2008]. In order to determine the reusable knowledge cost over the life cycle of an asset, the concept of LCC is applied in this research.

2.3.4 Life Cycle Management

Life cycle management is a concept rather than a method or tool to optimally manage the asset over its life cycle. It is concerned with comparisons of the long-term economics of alternative plans, all of which satisfy safety and reliability requirements and are technically feasible [G. J. Anders, 2005]. LCM of an asset is important due to economic and technical reasons [M. Wang, 2002]. It is impossible to establish an industry-wide set of rules or standards to manage the life cycle of assets due to the list of variables and individual utility circumstances [W. H. Bartley, 2002].

The simple strategy is to leave all assets in service until they fail and let insurance pay for it. But, the cost of an unexpected failure can be several times the cost of the original installation. In addition, the maintenance could take a long time. For instance, the transformer can take several months to rewind or rebuild. Therefore, the ideal strategy is choosing the best alternatives among the six life cycle decisions given below:

- Use-Up: means using the asset until the end of its financial designed life. The maintenance cost and reliability of asset have to be investigated.
- Retrofit: means that one or more of the components of the asset are replaced with modern equivalents. It targets those components having highest maintenance cost and failure risk.
- Refurbishment: In case of transformer, it means rewinding to an identical or new design and reusing the core, core frame, tank, internal connections, tap changer, cooler and bushing. It is a costly process, usually amounting to about 80% of the cost of new transformer [A. White, 1998]. This option is selected for an aging asset.
- Replacement: means to replace the current asset with the new asset or from the existing asset in the utility due to technical or financial failures or both. It has to be planned well since later replacement may increase the risk of failures and early replacement may cause unnecessary investment. The expected lead for a replacement of power transformer is about 8 months [R. Houbaer, 2000].
- Relocation: means to move an existing asset from its current location to another location where the requirements are met. In case of the power transformer, it is relocated due to the following reasons [W. H. Bartley, 2002]:
    - Better voltage regulation;
    - Loading/overloading limitations;
    - Customers who require a more reliable power source
    - Life extension
- Retirement: is the final step in a life cycle program. Normally, it is undertaken when the life of an asset reaches its technical end of life. The asset

manager is expected to make a timely retirement decision on aging asset. The retirement decision process on asset must depend on substantial technical and financial data and its performance [W. H. Bartley, 2002].

The fundamental objective of the life cycle management of a power transformer is to get the most out of an asset ensuring the longest possible service life or to minimize the life time operating costs, whichever is the most appropriate [CIGRE, 2002]. The power transformer life management is an ongoing process, required to identify and review the critical risks [L.M. Geldenhuis, 2005]. In this research, use-up, replacement and relocation strategies are used in the life cycle assessment model to select the optimal life cycle decision on the power transformer.

2.4 Health Indices of Power Transformer

Health indices (HI) provide a basis to assess the overall health of an asset. It is based on identification of the failure modes for the asset and its components, and then establishing measures of degradation of key components that can lead to end of life for the entire asset. The asset health index (AHI) is defined as the percentage of assets rated in fair or poor health through an annual assessment of its asset health. It is a practical method that supports quantifying the results of operating observations, field inspections, and site and laboratory testing in to an objective and quantitative index [A. Naderian, 2008].

It combines relatively complex information into a consistent and logical means. It is means of using and communicating engineering knowledge and expertise. HI can manage assets and identify investment needs and prioritize investments into capital and maintenance programs. In addition, it provides an accurate indication of the probability of asset failures and associated risk [A. Naderian, 2008].

The following steps [T. Hjartarson, 2005] are involved in representing the asset health index in a consistent way:

- Deterioration assessments are converted to health scores from perfect health to end of life.

- Importance weighting is assigned to each factor from modest importance to very high importance.

- General deterioration index is formulated by calculating the maximum possible score by summing the multiple of steps 1 and 2 for each factor.
- The general deterioration index is normalized to maximum score of 100 based on having a defined acceptable number of condition criteria available.
- Normalizing the dominant factors to a maximum score of 100.
- Calculation of the overall health index where 100% is excellent health and 0% is poor health.

To determine the health index of a power transformer, it is necessary to know its deterioration condition. Transformer deterioration phenomenon is the condition of a transformer or its component parts that undergoes a change in its chemical or physical properties under various stresses and environmental conditions and decreases in its characteristics and performance. The following factors [T. Kawamura, 2004] that cause deterioration of transformer are described below:

- Thermal factor: is due to a stress induced by a temperature change by the transformer in operation either for long period of time or overloading,
- Electrical factor: is due to either from surge voltage or electrostatic charge.
- Mechanical factor: is due to external fault current causing vibration and noise.
- Environmental factor: includes acid rain, ultraviolet rays, corrosive gases, particles of sea salt etc. The tank and accessories are affected by these factors.

In each of the deterioration processes, when the final phase of deterioration is observed, it is important to take suitable measures against the deterioration. The suitable measures include coil replacement or transformer renewal, internal repair, insulating oil treatment or replacement and tank repair. Thus the service life of transformer depends on its components and accessories [T. Kawamura, 2004] [R. Schwarz, 2008]. Based on these degradation mechanisms, routine test, diagnostic method or monitoring technique are used to rate the health index of transformers. The health index of a transformer is summarized in table 2.1.

Table 2.1 Health Index of Power Transformer [A. Naderian 2008].

HI	Condition	Probability of Failure (pof)	Expected Lifetime	Requirements
85-100	Very good	Low	More than 15 years	Normal maintenance
70-85	Good	Low but slightly increasing	More than 10 years	Normal maintenance
50-70	Fair	Rapidly increasing	From 3-10 years	Increase diagnostic testing, possible remedial work or replacement
30-50	Poor	Higher than pof at mean age	Less than 3 years	Start planning process to replace or rebuild considering risk and failure
0-30	Very poor	Very High	Near to end of life	Immediately assess risk; replace or rebuild based on assessment

Hence, the health index provides condition and probability of failure of asset and correlates them to an expected lifetime and required action. This method is applicable to assess the life cycle of an asset beyond its financial designed life in order to determine the remnant life of the asset.

2.5 Power Transformer Loading

The term power transformer is used to refer to those transformers used between the generator and the distribution circuits, rated at 500 KVA and above. The transformers are rated based on the power output they are capable to deliver continuously as a specified rated voltage and frequency under normal operating conditions without exceeding the prescribed internal temperature conditions. The temperature that insulation is allowed to reach under operating conditions provides the output rating of the transformer, called the KVA rating. The normal life expectancy of a power transformer is assumed to be about 30 years of service when it is operated within its rating [J.H. Harlow, 2007]. The nameplate MVA rating is the continuous load at rated voltage which produces an average winding temperature rise within 65^{o} C limit and hot-spot temperature rise within the 80^{o} C limit. Operators and planners express loading capability in a percent of the maximum MVA rating [J.H. Harlow, 2007].

It is necessary to understand the behavior of a power transformer under varying conditions of ambient temperature, load and winding temperature in order to optimize the utilization of the existing power transformer without affecting its life. Deterioration of the insulation systems results from the cumulative effect of heat on the system over a period of time. The heat is directly related to the loading of power transformer. The following risks areas should be considered when loading power transformers beyond their nameplate rating [IEEE Std., 1995]:

- Evolution of free gas may reduce dielectric strength.
- Operation at high temperature will cause reduced mechanical strength of both conductor and structural insulation.
- Thermal expansion of conductors, insulation materials or structural parts at high temperature could contribute to mechanical or dielectric failures.
- Pressure build-up in bushings could results in leaking gaskets, loss of oil, and ultimate dielectric failure.
- When the temperature of the top oil exceeds 105^{o} C, it causes the pressure relief device to operate and expel the oil. The loss of oil may create problems.

Therefore, it is necessary to determine the hot-spot temperature of the windings. It represents the worst (highest) temperature the insulation system is subjected to [W. E. Featheringill, 1983]. The hot-spot temperature is the sum of ambient temperature, the winding temperature rise, and hot-spot gradient. The calculation of hot-spot temperature is described in [IEEE Std., 1995]. In theory, it is mentioned that modern power transformers can load temporarily up to 200% of nameplate rating or 180^{o}C hottest-conductor temperature [IEEE Std., 1995]. However, it can load up to 110% of its nameplate rating or 115^{o}C winding temperature in noncyclical load at ideal condition [J. H. Harlow, 2007]. It is important to understand the relationship between loadings and the general condition of and moisture in the insulation system, along with voltage regulation. In addition, the following important guidelines must be followed during overloading of a power transformer [J. H. Harlow, 2007]:

- Verify that cooling fans and pumps are in good working conditions and oil levels are correct.
- Verify that the oil condition is good.
- Verify that the gauges are reading correctly when the loads are heavy on power transformers.
- Use winding power factor tests as a measure to confirm the integrity of transformer’s insulation system.
- If the power factor is less than 0.92 lagging, lower the recommended loading by 10%.

In this research, the maximum loading of a power transformer is up to 100% of its rated capacity with some margin.

2.6 Power Transformer Asset Management

Due to deregulation of electrical industry, the capital investment on transmission and distribution facilities has been deferred, but the power demand is still increasing, which causes the load on each power transformer to continue to grow. In addition, utilities are finding the average age of the power transformer population is now increasing. In this situation, power utilities need to efficiently manage the existing power transformers that are closed to their expected life or violating the loading condition. Therefore, asset management provides an important role to bring them to an acceptable risk level and retain competiveness through reducing capital expenditure.

Fan et al. have used risk evaluation model as a tool for making decision on power transformers based on their health condition. In this model, two components are used; probability of failure and consequences of failure of power transformer. Possible monetarily loss and impact of failures are considered in the consequences of failures. Probability of failure is based on the different factors that lead to failure of power transformer and each factor is assigned an index number from heuristic approach. The decision includes replacement, reduce load operation, shorten the test and maintenance period, additional test items and install online monitoring system [C.L. Fan, 2011]. The asset management plan of power transformer is essential to provide comprehensive assessment of condition, risk exposure to the business, and recommend future management strategies to minimize life cycle costs [R. Houbaer, 2000]. It takes about 8 months for replacement. Houbaer et al. have developed a power transformers condition-based management plan to manage their life cycle. It includes condition quality index supported by other assessment criteria. Utilities can defer or advance refurbishment or replacement to optimize decisions by knowing the effective age. It is achieved through the establishment of a transformer database, setting of condition assessment criteria, development of a software tool to calculate criteria, and setting maintenance and risk management strategies. It estimates the transformer's true insulation age from which the annual business risk and its refurbishment and replacement timing is obtained [R. Houbaer, 2000]. Mutawah et al. have proposed methods to effectively plan power transformers based on system reliability and risk assessment to reduce costs and avoid huge capital investment on inventory stock up. The following approach is adopted [N.S. Mutawah, 2011]:

- Group power transformers based on voltage ratio and vector group.
- Sub group them based on percentage impedance and voltage regulation.
- Determine their numbers installed in each group and sub group.
- Determine the present loading based on n-1 security criteria.
- Incorporate the future load forecast of power transformers.
- Check their health through various tests in order to know possible defects.
- History of number of short circuit trips seen by them to determine their residual life.
- In each group, identify the substations that are overloaded and under loaded and apply the risk management strategy.
- Review of on-site criteria to carry out any major work for them.

These methods need to evaluate the following five criteria: whether to repair or refurbish or replace aged power transformers; the value of redundant and spare units; overloading versus replacement; and postpone maintenance or repair by installing on-line monitoring device [N.S. Mutawah, 2011]. The aged power transformer's utilization can be improved by implementing proper operational criteria and efficient/effective maintenance to maintain and upgrade the insulation system. In addition, reliability centered maintenance provides better results as it incorporates the actual condition of the equipment and the level of reliability [B. Nemeth, 2008]. The life extension of aged power transformers is illustrated in figure 2.7 and utilities can plan the timely refurbishment, replacement or relocation of their power transformers [M. Arshad, 2004a].

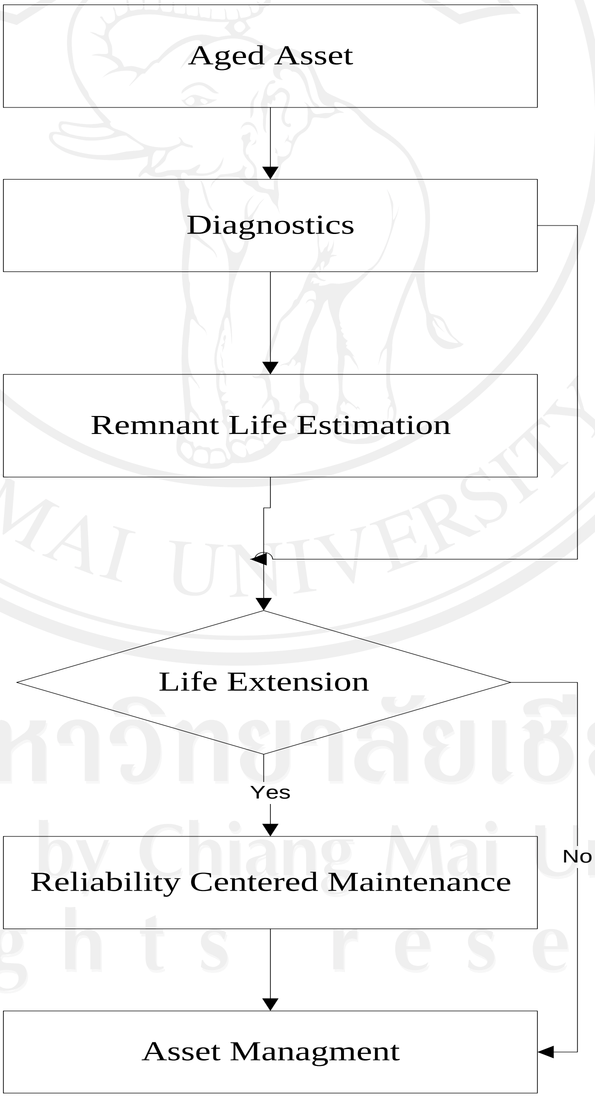

Figure 2.7 Power Transformer Life Extension and Management [M. Arshad, 2004a]

In the life assessment process of the power transformer, condition monitoring data is interpreted and analyzed to define the probability of failure or risks. In the initial stage, power transformers are ranked according to a set criterion defining its network criticality, customer profiles, equipment failure history and network redundancy. Then, a general assessment is applied to the entire power transformers on a routine interval to determine their condition using condition monitoring techniques. If any power transformer has exceeded one or more set benchmarks reflecting the criticality of component, the focused condition monitoring schemas are identified and applied. This techniques help to enhance the life assessments of power transformers [L.M. Geldenhuis, 2005].

Abu-Elanien et al. provide transformer asset management activities in three parts: condition monitoring and condition assessment techniques; performing maintenance plan and aging, health, and end of life assessments. Wang [2002] and Schwarz [2007] explain the condition assessment and diagnostic methods of power transformers. The benefits are maximized from the power transformer by implementing suitable condition monitoring techniques and a good maintenance plan to maximize the usage, reducing the outage time, and increasing the lifetime of the power transformer. With the help of equivalent uniform annual cost, the economic end of life of a power transformer is determined with the inclusion of operation and maintenance costs based on their lifetime [A. Abu-Elanien, 2010].

However, most of the methods or practices presented above are mainly focused on assessing the life cycle of aging power transformers considering only the technical aspects with the investment in condition monitoring technologies. The presented financial model is mainly based on operation and maintenance cost of power transformers. In this research, power transformer asset management is designed to maximize the utilization of a power transformer over its financial designed life with the utilization of its reusable knowledge meeting both financial and technical requirements under the limitation of the investment budget. It is presented in the next section.

2.7 Proposed Life Cycle Assessment Framework

The asset management concepts discussed in earlier sections can be generally applied to any power utilities. In fact, it is necessary to investigate the appropriate system or process for any power utility that fits into its context. The decision on power transformer during load violation shall not only depend on the technical requirements, but also take into consideration the financial strength of the power utility. This thesis attempts to propose a novel life cycle assessment model to assist utility manager in selecting the optimal life cycle decisions for a power transformer. This model consists of three main modules; a knowledge based model, financial model and decision model. The architecture of the proposed life cycle assessment framework of the power transformer is shown in figure 2.8.

Each model is explained in details in the rest of chapters along with its development, examination, and simulation. The simulation software is developed to implement the proposed model. The proposed model provides the financial and technical status of each asset in the network during its life cycle.

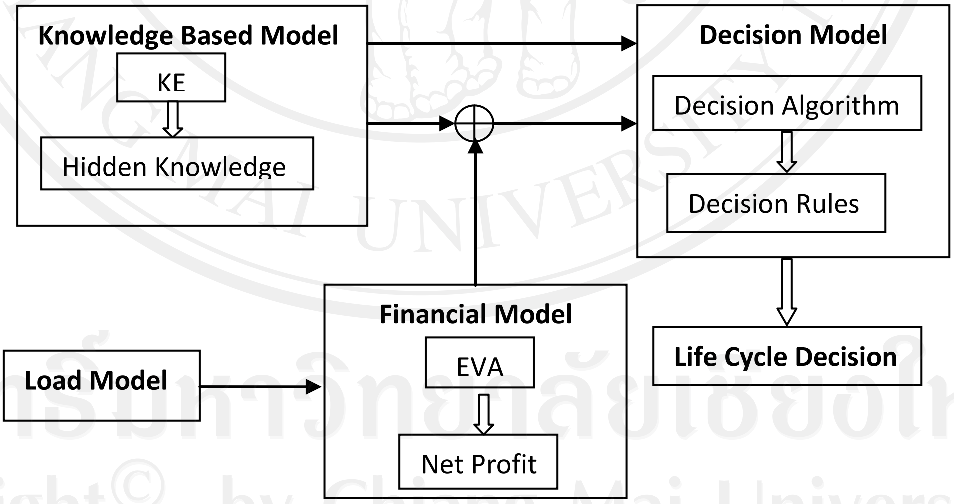

Figure 2.8 Proposed Life Cycle Assessment Framework for Power Transformer.

2.8 Chapter Summary

In this chapter, the definitions and framework of asset management and life cycle assessment of asset have been provided. In addition, the importance of the life cycle assessment is also explained. The life cycle phase of the asset is clearly defined along with the categorization of its life time. The chapter also shows that there is an importance of health index for assessing the life cycle of an asset beyond its financial designed life. The importance of loading characteristics of power transformers has been illustrated along with a discussion on the limitations of current asset management practices and life cycle assessment approaches of the power transformer. This thesis leads to the development of an alternative methodology of managing the life cycle of a power transformer in order to solve the proposed problems set out in chapter one and this literature review.