# Development of intelligent evaluation system for product end-of-life selection strategy

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# Summary

As the world population increases exponentially, the number of products purchased and consumed is also increasing. The rapid pace of technological changes renders some products obsolete even though they are still new and in excellent condition. Consequently, the supply of natural resources decreases severely. Additionally, the amount of waste generated at the end-of-life of products has become a serious problem in most countries. In response, manufacturers have to seek other essential resources to provide materials for manufacturing their products. This generates a strong demand for secondary resources such as refurbished parts and recycled materials. This problem can be best resolved by promoting end-of-life (EOL) selection strategies.

The main objective of this research is to develop an evaluation system for selecting EOL strategy specifically for remanufacturing. The developed framework consists of several sub-objectives. The first sub-objective is to evaluate the remanufacturing selection strategy at the product level. In order to achieve this, the integration of analytic hierarchical process (AHP) and case-based reasoning (CBR) is used to evaluate the EOL options at the product level. The AHP, which allows pair-wise comparison and consistent judgement, is used to determine the weight in nearest neighbourhood (NN) algorithm of CBR. The second sub-objective is to evaluate the EOL of parts and components. The integration of the economic and environmental cost (EOL cost) model is used to determine the EOL of parts and components. The third sub-objective is to optimize the disassembly sequence of the EOL product. This study integrates the travelling salesman problem with genetic algorithm (TSP-GA) for finding the optimal disassembly sequence and disassembling the EOL product. Additionally, this study uses EOL profits and net present value (NPV) of parts and subassemblies of the EOL product to determine the best EOL option of components and parts of the EOL product.

The model validation, using five commercial products, has confirmed the usefulness of the integration of the AHP and CBR methods for supporting the judgement toward remanufacturing as the EOL strategy at the product level. This

method also enables the decision makers to evaluate the EOL strategy of the EOL products in a sensible and quick-decision-making manner. Additionally, for selecting the best EOL option of parts and subassemblies of the EOL product, a desk phone is used to validate the EOL cost model. The result has confirmed the usefulness of the EOL cost model. The EOL cost enables decision makers to evaluate the EOL options from economic and environmental perspectives. Moreover, the results of the integrated AHP-CBR method are compared with an established traditional method of the previous works. These results are in good agreement with the previous established studies.

In evaluating the optimal disassembly sequence, the disassembly of a body of the desk phone is used to confirm the usefulness of the TSP-GA in optimizing the disassembly sequence and supporting the decision-making for selecting the best EOL options of parts and subassemblies of the EOL product. The results show that the TSP-GA has corresponded well with the traditional TSP and GA methods. Additionally, the results also demonstrate that the EOL profits and NPV enable the decision makers to evaluate and select the EOL options of the parts and subassemblies of the EOL product. The results are in good agreement with the previous established studies.

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# Chapter 1
# Introduction

## 1.1 Background

At present, most countries are facing the repercussions of a wide circulation of consumer goods and a shortening of the lifetime of those goods. As a result, the amount of used product is increasing. This phenomenon will increase the difficulty of the disposal since the capacity of landfill sites is decreasing.

As the world population increases exponentially, the number of products purchased and consumed also increases. The rapid pace of technological changes within a short time renders some products obsolete even though they are still new and in excellent condition. Consequently, the availability of natural resources decreases severely. Additionally, the amount of waste generated at the end-of-life of products has become a serious problem in most countries. In response, manufacturers have to seek other essential resources to provide for the input of the materials for manufacturing their products. This generates a strong demand for secondary resources such as refurbished parts and recycled materials. This, therefore, also can reduce the impact on the environment (Mat Saman, 2009).

In recent years, ecological issues and environmental impacts are always in the forefront of government decision making worldwide. Public concerns about diminishing natural resources, limited landfill space, and hazardous waste disposal have prompted legislators to leave end–of–life (EOL) product recovery issues to the manufacturers (The European Parliament and of the Council of European Union 2000, 2003a, 2003b, Herrmann *et al.*, 2006). In response, producers have devoted a considerable effort to proposing new methods and activities that reflect environmental consciousness in producing products. Products need to be processed in an environmentally benign and cost-effective manner.

Environmentally conscious manufacturing and product recovery (ECMPRO) is gaining in popularity, especially when new products are developed. Environmental awareness and regulations have pushed manufacturers and designers to recycle, remanufacture, and reuse the components at their end-of-life (EOL). Additionally, consumer demand and government legislation require that manufacturers reduce the quantity of manufacturing waste (Mat Saman, 2009). Common practice is to treat these products with end-of-life (EOL) processes. These processes aim to minimize the amount of waste sent to landfills by recovering materials and parts of old or obsolete products by recycling and remanufacturing them (Kaebernick *et al.*, 2002, McGovern and Gupta, 2007, ElSayed *et al.*, 2010). Therefore, the EOL selection strategy is extremely crucial in enhancing product recovery (McGovern and Gupta, 2007).

## 1.2 Research statement

An initial literature survey was conducted to determine the general directions and needs for further research. The findings initiated the research in this study and formed the basis for formulating the objectives. Chapter 2 outlines the literature study, which focused on the method of selecting the EOL strategy.

Manufacturers have to produce environmentally benign products in order to remain competitive. Hence, many manufacturers have developed several methods such as Design for Environment (DfE), Design for Disassembly (DfD), Design for Recycling (DfR) and so on (Kaebernick *et al.*, 2002).

The studies that are concerned with environmental issues such as product recovery, remanufacturing, and disassembly are increasing rapidly. The manufacturers tend to tackle these issues separately (Ilgin and Gupta, 2010). Unfortunately, few studies have dealt with product recovery, remanufacturing, and disassembly simultaneously. Additionally, many manufacturers have adopted recycling as their strategy for treating the EOL of products. However, remanufacturing of components, parts, or complete products is a more efficient EOL strategy than recycling (Steinhilper, 1998, Hata *et al.*, 2000, Zussman and Zhou, 2000, Kaebernick *et al.*, 2002). Although some previous works have addressed the issues for selecting the EOL strategies, less attention has been paid to integrate artificial intelligent (AI) tools for remanufacturing. The rapid pace of technological changes also eliminates some of the new products from the market. This provides a strong demand for developing the evaluation system, which can provide manufacturers a relatively rough but quick estimation of EOL products. Realizing the importance of the strong demand, this study proposed the integration of AHP with CBR.

Many studies have been conducted on disassembly planning to evaluate the EOL at the part and component level. However, few studies have been done on considering the environmental cost factors to evaluate the EOL at this level. These issues open the door to develop an integrated cost model that considers the economic and environmental aspects for evaluating the EOL options of the parts and subassemblies of the EOL product.

On the other hand, few studies have addressed the issues of maximizing the EOL profits and minimizing the cost incurred while disassembling the EOL products or components. Realizing the importance of implementing an optimal disassembly and a cost-effective recovery of the EOL product after the end of its useful life, we utilized the TSP-GA as an approach for determining the optimal disassembly sequence.

## 1.3 Objective and scope of the research

The main objective of this research is to develop an evaluation system for selecting EOL strategy. The developed model consists of:

- The integration of AHP and CBR to evaluate the EOL options at the product level.
- The integration of environmental and economic aspects to evaluate the EOL options of the EOL products. The model includes both the environmental and the economic aspects:
    - Environmental aspect: Integration of environmental impacts into the cost structure.

- Economic aspect: An economic model to evaluate the viability of EOL options.

- The integration of TSP and GA to evaluate the optimal disassembly sequence of the EOL product.
- The case study is specific to electronic products.

## 1.4 Justification for research

Hitherto, with the increase of social and consumer pressures, many governments, specifically in the developed and OECD countries, enacted environmentally benign directives. Regulations such as the Extended Producers Responsibility (EPR) Law, the Integrated Product Policy (IPP), Environmentally Superior Products (ESP), and Sustainable Product and/or Service Development (SPSD) encourage manufacturers to design and produce environmentally benign products (Fishbein, 1998). In response, many manufacturers have developed methods mainly dedicated to recycling as the EOL strategy. However, remanufacturing is the more efficient EOL strategy.

Additionally, the manufacturers tend to tackle issues such as product recovery, remanufacturing, and disassembly separately. Unfortunately, few studies have dealt with product recovery, remanufacturing, and disassembly simultaneously. Although some previous works have addressed the issues for selecting the EOL strategies, less attention has been paid to integrate AI tools for remanufacturing. This work proposes an evaluation system for selecting the EOL strategy. This framework proposes an EOL selection strategy that considers product recovery, remanufacturing, and disassembly concurrently while evaluating the EOL selection strategy at both product and parts levels.

## 1.5 Research methodologies

In order to achieve the stated objectives, the following research methodologies will be employed:

- An adequate and comprehensive review of the literature in order to facilitate the understanding of the principle in this study. The literature review covers broad areas including:
    - The state-of-the-art in the end-of-life (EOL) selection strategies.
    - The factors that affect the product EOL selection strategies.
    - The tool used for selecting the EOL strategies. It covers the case based reasoning (CBR), nearest neighbourhood algorithm (NN algorithm), and analytic hierarchical process (AHP).
    - The tool used for optimizing the disassembly planning. It covers the genetic algorithm (GA), travelling salesman problem (TSP), and the EOL cost model, which cover the economic and environmental cost model.
- Development of a framework to evaluate the EOL selection strategy using the integration of AHP and CBR.
- Development of an EOL cost model to evaluate the EOL options at the parts and subassemblies level.
- Development of an integration of the TSP-GA model to evaluate the optimization of disassembly sequence.

## 1.6 Contribution of thesis

Holistically, this research contributes to the EOL selection strategy, i.e., the remanufacturing selection strategy, using the intelligent evaluation system. Several expected sub-contributions are described as follows:

1. Providing a quick estimation of EOL strategy selection at product level; the integration of AHP and CBR can provide a relative estimation of and information about the EOL strategy at product level in the early stage of design.
2. Providing the selection of EOL options at parts and subassemblies level by considering the economic and environmental aspect; the EOL values can assist manufacturers to determine the EOL options of parts and components.
3. Providing an estimation of the most optimal disassembly sequence of the EOL product; the optimal disassembly sequence aims to minimize the cost incurred during disassembling the EOL product.

4. Maximizing the net revenue from the benefits accrued from the recovery of parts and subassemblies of the EOL product.

## 1.7 Organization of the thesis

The thesis is classified into five chapters.

1. Chapter 1 presents the introduction of the thesis; the statement of the problem, objective, methodology, and contribution of the research are discussed.
2. Chapter 2 presents the theoretical foundation of the research based on a comprehensive literature review. This chapter discusses the individual attributes affecting the EOL selection strategy and the tools used for selecting the EOL strategies at both product and part levels. The EOL cost models for selecting the EOL options are discussed. This chapter is used as the basis of the model development.
3. Chapter 3 presents the development of the evaluation system. This chapter presents an integration of AHP and CBR models to evaluate the EOL selection strategy at the product level of EOL. The integrated EOL cost model and the decision-making for determining the best EOL option of parts and subassemblies of EOL product are also presented.
4. Chapter 4 provides the extensions of the EOL selection strategies at the part level presented in Chapter 3. This chapter presents the integration of TSP-GA with the EOL cost model for EOL selection strategy.
5. Chapter 5 summarizes the main research findings of this thesis including the crucial lessons and observations resulting from the research. In addition, this chapter identifies opportunities for future research.

# Chapter 2

# Literature Study

In this chapter, the literature related to the research presented in this thesis is reviewed. The works on this research belong to the area of EOL selection strategy that forms the foundation of the research. The EOL selection strategy i.e., remanufacturing, recycling, and landfill is described in the first section, followed by the review of the important aspects affecting the EOL of products in the second section. The tools used for selecting the EOL at product level i.e., Analytic Hierarchical Process (AHP) and Case Based Reasoning (CBR) are discussed in the third section. Finally, the Travelling Salesman Problem (TSP), Genetic Algorithm (GA) and EOL cost model, which are used to evaluate the best EOL options in this research, will be discussed.

## 2.1 End-of-life selection strategy

The definition of end-of-life in this work is the point at which the product no longer performs the intended functions due to failure or wear-out. The end-of-life strategies are the approach used to deal with the product at the end-of-life (Rose, 2000). It includes the activities to recover the value of the EOL product, ranging from strategic planning, collection, and treatment of the EOL products to society and environments. (Rose *et al.*, 1999, Rose, 2000).

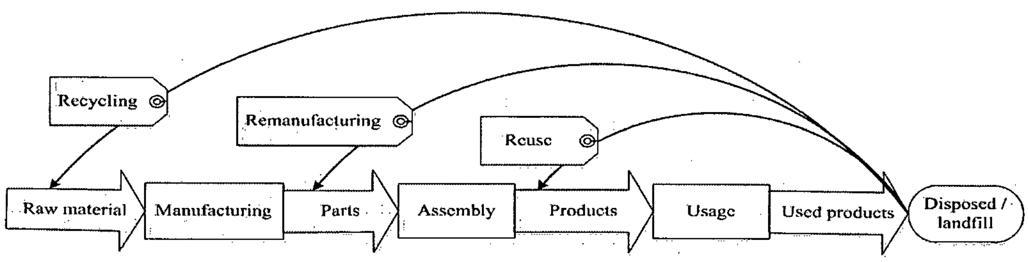


Figure 2.1: Closed-loop system (Anityasari, 2008)

The EOL activities are a closed-loop system. The system aims to increase the environmental and economic performances of a product by returning materials and energy into the system (See Figure 2.1). A closed-loop system brings the used products back to the manufacturers for further treatment. Depending on the material types and the quality level of the returned products, they could be reused, remanufactured, or recycled. Researchers (Overby, 1979, Luttropp, 1997, Rose, 2000, Anityasari, 2008) outline the following end-of-life strategies:

- Reuse. Reuse has the minimum environmental impact among the options in EOL strategies. It aims to sustain the functions of old products or components for the second life by preserving the material and energy of the EOL product.
- Remanufacture. Remanufacture is a process in which used products are reprocessed after being sorted, disassembled, inspected, and cleaned. Remanufacture aims to recover the functions of the EOL product instead of its material content. The remanufactured products will have a new status and gain as-good-as-new quality after reprocessing. Thus, remanufacture offers higher savings in terms of materials and energy, as well as in manufacturing and overhead costs.
- Recycling. Recycling is a method to dissolve a component′s shape and solely reclaim its material properties. Recycling is a preferable strategy when the value of a product is lower than the value of the material content of that product. Even though recycling has attracted a lot of attention in recent decades, it is less environmentally benign and economically attractive than remanufacture and reuse.
- Landfill. Landfill has the maximum environmental impact among the options in EOL strategies. Here the product is disposed of without energy recovery.

### 2.1.1 Attributes affecting the EOL selection strategy

Although the EOL selection strategy is the environmentally benign approach for treating EOL products, many factors obstruct EOL popularity in actual practice (Kimura et al., 1998, Hata et al., 2000, Fukuzawa et al., 2005, Hata and Kimura, 2005). Rose (2000) developed a decision tree model called End–of–Life Design Adviser (ELDA) to determine the EOL strategies. The author identified four major and six individual characteristics that influence the EOL selection strategy. These attributes will be discussed in the sub-sections 2.1.1.1-2.1.1.4. This section will review the most influential attributes in EOL selection strategies.

#### 2.1.1.1 Market demand

Market demand is the demand or pressure from the market i.e., consumers and governments about what the product should feature. For instance, the consumer wants a durable product with a leading-edge technology. Environmental awareness will lead to customer acceptance and ultimately will form environmentally friendly behaviour (Leire and Thidell, 2005, Van Amstel-Van Saane, 2007, Thøgersen *et al.*, 2010, Van Thai *et al.*, 2011).

#### 2.1.1.2 Technological change

The rapid pace of new technology development renders some products obsolete even if they are still in excellence condition. Technology change is influenced by consumer demand, environmental directives from governments, and the competition of introducing the new technology to attract consumers (Rose, 2000):

Technological advancement also threatens the availability of components for maintaining current products. Additionally, it should be noted that the advancement of technology usually does not replace all components currently in use; instead, it only replaces or upgrades a few primary functions or components (Fernandez and Kekäle, 2008, Mutha and Pokharel, 2009). Consequently, the double impacts of technological changes are obvious and do not necessarily limit the reusability of used products for the second life.

#### 2.1.1.3 Product design

Any design based on the consumer's voice has a major influence on the wear–out life and the reason for redesign. In principal, the EOL strategies i.e., remanufacturing and recycling attempt to preserve product and part functions or materials (Umeda *et al.*, 2006, Umeda *et al.*, 2007). Thus, product design plays a crucial role in EOL selection strategy. The design of the product must comply with the environmentally benign directives such as the directives of ELV, RoHS, WEEE, and so on (Klausner *et al.*, 1998, Condea *et al.*, 2010).

### 2.1.1.4 Legislation

Legislation plays a crucial role in driving the EOL selection strategy (Reijnders, 2003, Honkasalo *et al.*, 2005, Helland, 2009, Jänicke and Lindemann, 2010, Wang *et al.*, 2011). The regulations such as Extended Producer Responsibility (EPR), End-of-Life Vehicles (ELV), Release of Hazardous Substances (RoHS), or Waste of Electrical and Electronic Equipment (WEEE) are among the commonly used guidelines during product design (The European Parliament and of the Council of European Union, 2003a, 2003b, Gehin *et al.*, 2008).

The implementation of these regulations usually brings penalties and incentives for both manufacturers and customers as a means to ensure their execution (Hicks *et al.*, 2005, Lee *et al.*, 2005, He *et al.*, 2006, Sepúlveda *et al.*, 2010, Wang *et al.*, 2010). Moreover, support, infrastructure, and facilities usually come with the introduction of a new regulation. In this case, the legislative aspect becomes one of the factors determining the EOL selection strategy of a product. Companies can utilize the support and infrastructure provided by government and could gain an economic incentive if they reuse particular product groups regulated by the government.

## 2.1.2 Product characteristics affecting the EOL selection

### 2.1.2.1 Wear-out life

The definition of wear-out life used in this work is the length of time from product purchase until the product no longer meets its original functions (Rose, 2000, Shih and Chang, 2003, Shih *et al.*, 2006). For example, the average wear-out life of automobiles is 10-15 years. The wear-out life is influenced by the demand from the end user, the design of the product, the choice of materials, manufacturing quality, consumer use, and service.

#### 2.1.2.2 Technology cycle

The definition of technology cycle used in this work is the length of time that the product will be on the leading edge of technology before new technology makes the original product obsolete or less desirable (Rose, 2000, Shih and Chang, 2003, Shih *et al.*, 2006). Typically, the technology cycle is 10-20 years for automobiles. On the other hand, the technology cycle of computers is approximately 6-12 months. The technology cycle of a product depends on market demands, scientific advances, and company focus.

#### 2.1.2.3 Level of integration

The level of integration is defined as the inter-relation between modules and functions of the parts and subassemblies of the product (Rose, 2000, Shih and Chang, 2003, Shih *et al.*, 2006). If there are many unique functions for each module, then the level of integration is high. On the other hand, if each module performs one or two different functions, the level of integration is low.

#### 2.1.2.4 Number of parts

The number of parts is the number of assemblies in the product relevant for end-of-life treatment (Rose, 2000, Shih and Chang, 2003, Shih *et al.*, 2006). The number of parts is not intended to account for each individual part in the product, but rather the ones relevant for recycling.

#### 2.1.2.5 Reason for redesign

The reason for redesign is the reason for (re)designing products based on customer demand, competitor behaviour, and scientific progress. It allows companies to add new functions to products. It is categorized into (Rose, 2000, Shih *et al.*, 2006):

- Original design-design of a novel product, which is new to the company without an existing design history.

- Evolutionary design-a significant redesign of the existing product. The aim of redesign is either to improve the function or change the aesthetic features of the product.
- Feature change-a small change of design of the existing product in the forms of function improvement and aesthetic change.

Customer demand and competitor behaviour push the company to release products with aesthetic alterations to follow trends. Aesthetic changes are related to presentation or external design. Changes in function require improvement in mechanics or electronics controlling performance of the product. With regard to changes in products, they can be small or large. Evolutionary design is a significant redesign of an existing or current product, and is the most common type of design. Feature change is a small feature or function change to an existing product (Rose, 2000).

#### 2.1.2.6 Design cycle

The design cycle is the frequency with which companies design new products or redesign their existing products. It address the frequency with which designs change in relation to the competition's release of new products, marketing plans, and actual research and development successes (Rose, 2000, Shih *et al.*, 2006).

## 2.2 Tools for selecting the EOL strategy

### 2.2.1 Multi criteria decision analysis approach

Several studies used the multi criteria decision analysis (MCDA) approach in the selection of EOL strategies. Rose (2000) developed a decision tree model called End–of–Life Design Adviser (ELDA) to help determine the EOL strategies. The ELDA contains the characteristics that influence the EOL. These characteristics are wear–out life, technology cycle, level of integration, number of parts, reason for redesign, and design cycle. Yu et al.(2000) adopted an analytical hierarchy process (AHP) to find the best EOL strategy. The AHP-based evaluation considered environmental impact, cost, and reclaimed materials as major criteria for strategy determination.

Bufardi *et al.* (2004) applied MCDA to select the best EOL alternative. Jun *et al.* (2007) applied a multi-objective evolutionary algorithm (MOEA) to optimize the EOL selection strategy. Staikos and Rahimifard (2007a, 2007b) integrate AHP, life cycle analysis (LCA), and benefit cost analysis (BCA) to find the EOL strategies. Fernandez *et al.* (2008) developed a fuzzy approach to finding the EOL strategies. Iakovou *et al.* (2009) developed the "Multicriteria Matrix" to evaluate the EOL selection strategies of a product.

However, the disadvantage of these methods is that they required experienced decision makers to understand the problem, the feasible alternatives, different outcomes, conflicts between the criteria, and level of the data uncertainty in finding the best EOL strategy. Moreover, few studies provide a systematic evaluation method for inexperienced decision makers to evaluate the EOL strategy. To cope with these limitations, we consider the case based reasoning (CBR) approach to find the best EOL strategy at product level. The advantage of CBR is that it provides a quick approach to finding the best EOL strategy of EOL products regardless of the experience level of decision makers.

## 2.2.2 Case based reasoning

Case based reasoning, one of the artificial intelligence (AI) tools, mainly focuses on the reuse of knowledge and experience. A multi-disciplinary subject creates and uses a database of old problems to resolve new problems. In CBR, knowledge is represented in the form of experiences (or cases) (Kolodner, 1991, Lin *et al.*, 2009, Chang *et al.*, 2010, Liu and Xi, 2011). The essence of CBR is to identify past cases very similar to a new problem and extract experiences from them for solving the new problem. A case is a conceptualized piece of knowledge representing an experience. It involves the activities of storing previously solved problems in a case database, retrieving a similar previous case based on a set of product characteristics, and finally adapting the solution of the previous case to the new case (Kolodner, 1991, Aamodt and Plaza, 1994, Chougule and Ravi, 2005). Figure

2.2 illustrates the hierarchy in a general CBR cycle as follows (Aamodt and Plaza, 1994, Chen *et al.*, 2009, Chang *et al.*, 2010):

- Retrieve the most-similar case or cases.
- Use the information and knowledge in the case/cases to solve the new problem.
- Revise the proposed solution.

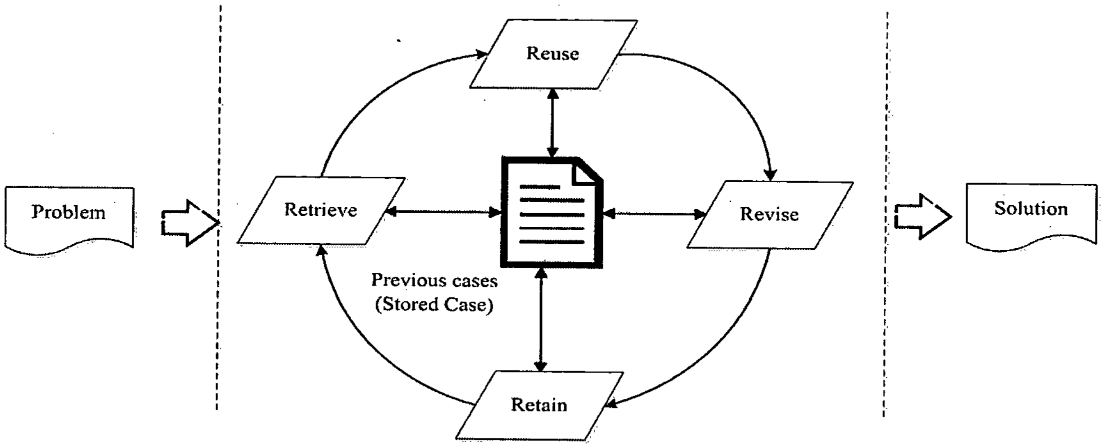


Figure 2.2: The general cycle of CBR (Aamodt & Plaza 1994)

The CBR methodology has become popular in the last few years because of a number of benefits, such as quickly finding the solutions to complex problems, capturing the experience of a skilled specialist, and discovering decision knowledge in hidden data (Chougule and Ravi, 2005, Chang *et al.*, 2010). The success of a CBR system depends on its ability to retrieve the most relevant case in support of the solution to a new case. A number of methods are available for case retrieval, such as induction, knowledge-based indexing, and nearest neighbour algorithm (Kim and Han, 2001). The studies related to the CBR are summarized in Table 2.1.

Kwong *et al.* (1997) proposed a CBR system to determine injection molding parameters for producing a plastic part. Zeid *et al.* (1997), and Veerakamolmal and Gupta (2002) developed a CBR approach for automating disassembly process planning. The episodic memory organization packets (EMOPs) were used to store and index the planning for disassembly (PFD) and disassembly process planning (DPP) plans so that they can be retrieved by comparing them with the new case. However, the trial and error approach to match