Technical University of Crete
Department of Production Engineering and Management

THE PHYSICS AND ECONOMICS OF RECYCLING

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requirements for the degree of Doctor of Philosophy

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ΠΟΛΥΤΕΧΝΕΙΟ ΚΡΗΤΗΣ

ΦΥΣΙΚΗ ΚΑΙ ΟΙΚΟΝΟΜΙΑ ΤΗΣ ΑΝΑΚΥΚΛΩΣΗΣ

Διατριβή που υπεβλήθη για την μερική ικανοποίηση των απαιτήσεων για την απόκτηση Διδακτορικού Διπλώματος

υπό
Xiaomin Zhu

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Η διατριβή της Xiaomin Zhu εκρίνεται
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Contents

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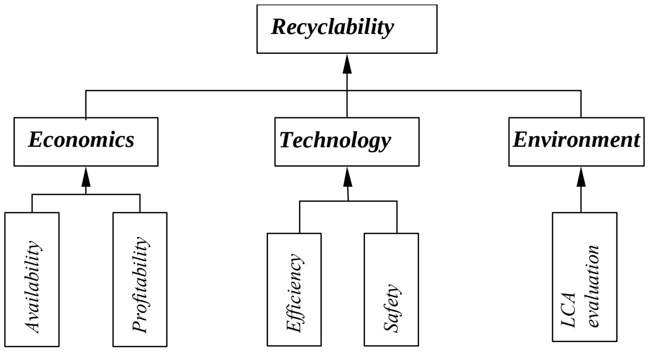
Short CV

Xiaomin Zhu was born in Chongren, Jiangxi province, in China, on the 14^{th} of December 1964. She received the B.S. and M.S. degrees in precision instrument engineering from Tianjin University, Tianjin, China, in 1985 and 1988, respectively, as well as the second M.S. degree in economics from Mediterranean Agronomic Institute of Chania, Chania, Greece, in 1996. Then she was admitted as a Ph.D. student in the Department of Production Engineering and Management at the Technical University of Crete in 1996. Her research interests are in economic analysis, project management, knowledge management, as well as fuzzy evaluation and its application in ecological economics.

Abstract in Greek

Η *ανακυκλωσιμότητα* είναι μία επιθυμητή ιδιότητα των υλικών. Ο ορισμός και η μέτρησή της, αν και αποτελούν ανοικτό πρόβλημα, είναι πολύ σημαντικά για την βιομηχανία ανακύκλωσης γιατί προσδιορίζουν τον βαθμό στον οποίο επιβάλλεται ή συμφέρει να ανακυκλώνεται ένα υλικό.

Σε αυτή τη διατριβή δίνεται ένας συστηματικός ορισμός της ανακυκλωσιμότητας υλικών με τη σύνθεση τριών βασικών συνιστωσών της που περιλαμβάνουν οικονομικούς, τεχνολογικούς και περιβαλλοντικούς παράγοντες. Αναπτύσσεται μία μέθοδος η οποία χρησιμοποιεί ασαφή λογική για την σύνθεση του ολικού μέτρου ανακυκλωσιμότητας από τις βασικές συνιστώσεις του και των συνιστωσών από επιμέρους δείκτες. Οι συνιστώσες και οι δείκτες ανακυκλωσιμότητας φαίνονται στο επόμενο σχήμα.

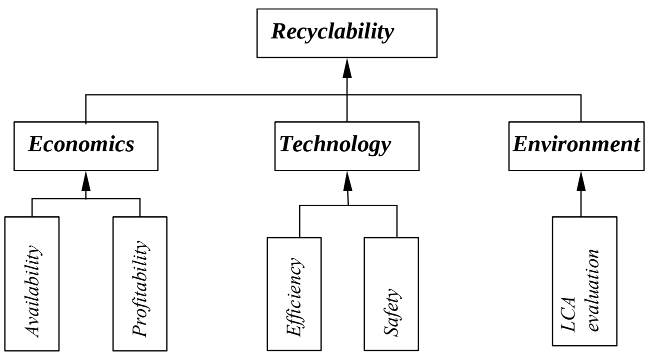


Για την εφαρμογή της μεθόδου σχεδιάζονται βάσεις κανόνων οι οποίες περιγράφουν λεκτικά τον τρόπο με τον οποίο κάθε δείκτης επιδρά στην αντίστοιχη συνιστώσα και κάθε συνιστώσα στην συνολική ανακυκλωσιμότητα. Σχεδιάζονται επίσης κατάλληλες συναρτήσεις συμμετοχής οι οποίες αποδίδουν ποσοτικά τις προηγούμενες πληροφορίες.

Ακολούθως γίνεται υπολογισμός της ανακυκλωσιμότητας τριών μετάλλων (αλουμίνιο, χαλκός, νικέλιο) και τριών αμετάλλων (χαρτί, πλαστικό, γυαλί) και αναλύονται τα αποτελέσματα για κάθε υλικό. Η ανάλυση ευαισθησίας ως προς τις τιμές των δεικτών προσδιορίζει τους δείκτες που είναι οι πλέον κρίσιμοι στην ανακυκλωσιμότητα κάθε υλικού. Από μία δεύτερη ανάλυση ευαισθησίας ως προς τις συναρτήσεις συμμετοχής προκύπτει ότι η μέθοδος είναι εύρωστη. Τα αποτελέσματα της ανάλυσης ευαισθησίας θα μπορούσαν να χρησιμοποιηθούν στη βιομηχανία προκειμένου να αυξηθεί η ανακυκλωσιμότητα υλικών καθώς και στη λήψη αποφάσεων για τη βελτίωση του περιβάλλοντος και της οικονομίας με την μείωση της μόλυνσης που προκαλούν τα απορρίμματα και τη μείωση της χρήσης υλικών.

Abstract

Recyclability is a desirable property of materials. Its definition and evaluation, although an open problem, is quite important in the recycling industry. This thesis provides a formal definition of material recyclability as a complex function of several factors, called indicators of recyclability, which are aggregated into three intermediate components as shown in the following figure.



All indicators used in each component are analyzed in detail and methods of assessment are presented.

Recyclability is a multidimensional and inherently vague notion, and traditional mathematical models have difficulties in dealing with the direct evaluation of it. A

framework for evaluating material recyclability using fuzzy logic is devised. It involves designing rule bases and relevant membership functions. Fuzzy logic can treat non-fuzzy and fuzzy variables simultaneously. This is a general approach that allows for human-like knowledge representation and reasoning, and can evaluate the recyclability of any kind of material quantitatively. It provides a theoretical base to decide which material is worth to be recycled.

The recyclability of three metals and three non-metals is then evaluated, where numerical results are explicitly derived and comprehensive analyses are implemented. A sensitivity analysis shows that the method is robust. Resource economists could set priorities for critical indicators to increase the recyclability of material according to the sensitivity analysis. Such a framework may be used to develop approaches and policies for improving environmental, economical and resource management with the consequence of reducing pollution and material usage.

1. Introduction

1.1 Why Fuzzy Evaluation of Material Recyclability

The practice of recycling is an ancient one. In prehistoric times certain metals were melted down and recast so they could be reused again. Since the 1980s, material recycling has been a key issue around the globe along with the rapid development of economics. Recycled materials are becoming increasingly important as industry responds to public demands that resources be conserved and the environment be protected.

Recyclability is a desirable property of materials. Its definition and evaluation is of paramount importance if one wants to improve the process of recycling. Material recyclability may be used to develop approaches and policies for improving environmental, economical and resource management with the consequence of reducing pollution and material usage. Also political decisions may thus be aided concerning taxation and subsidies.

The measurement of recyclability has been a challenge to researchers. Some efforts have been reported which can be categorized by the aspect of recyclability they measure or by the approach used. Several authors have studied material flows associated with metal recycling from different perspectives. During the 1990s, assessments were published about environmental and health effects as well as feasibility of metal recycling.

Such measures concentrate on physical considerations (Steenkamer and Sullivan, 1998), economic and environmental implications (Ayres, 1997; Byström and Lönnstedt, 1997; Nakamura, 1999), technological advantages (Stefanowicz et al., 1997; Prasad and Pandey, 1998; Amari et al., 1999; Gronostajski et al., 2000; Jha et al., 2001; Fukumori et al., 2002), or a classification schema for recycling based on chemical bonding and thermodynamic considerations (Craig, 2001). In addition, a multiple criteria model to assess recycling measures for the steel industry is developed (Spengler et al., 1998), and a methodological framework for the environmental assessment of materials recycling systems is presented (McLaren et al., 2000).

However, reading the relevant literature, one could observe a lack of a universal measurement scheme. All existing models focus on one or two facets of one kind of material. No general measurement scheme exists in the literature. This dissertation will try to fill the gap.

It is a common belief that recyclability is a multidimensional notion. Generally speaking, (traditional) mathematical models have difficulties in dealing with the direct evaluation of recyclability. For example, algebraic formulae fail in putting together the various aspects of recyclability and concrete functions that describe the relationships between inputs and output of recyclability do not exist. A traditional mathematical approach would ignore certain factors which are impossible to quantify. Indeed there are aspects of recyclability which cannot be quantified and yet are very important as, for example, values and opinions. Furthermore, recyclability is an inherently vague concept whose scientific definition and measurement still lack wide acceptance.

To overcome the obstacles of vaguely or ill-defined concepts, the fuzzy logic approach (Zadeh, 1965, 1973; Zimmermann, 1991) has been developed, bringing together flexibility and simplicity. Fuzzy logic is a scientific tool that permits simulation of the dynamics of a system without a detailed mathematical description. It is well suited to handle such a vague, uncertain, and polymorphous concept as recyclability. Knowledge in fuzzy logic is normally represented by if-then linguistic rules, which describe the logical evolution of the system according to the linguistic values of its principal characters which we call linguistic variables. Real values are transformed into linguistic values or fuzzy values by an operation called fuzzification, and then fuzzy reasoning is applied in the form of if-then rules. A final crisp value is obtained by defuzzification, which does the opposite of fuzzification. Therefore, recyclability comparisons can be made over different kinds of materials.

Fuzzy evaluation of material recyclability is a new scheme that uses fuzzy logic. The following two basic features justify the use of the fuzzy logic reasoning: (a) Fuzzy logic has the ability to deal with complex and polymorphous concepts, which are not amenable to a straightforward quantification and contain ambiguities. In addition, reasoning with such ambiguous concepts may not be clear and obvious, but rather fuzzy. (b) Fuzzy logic provides the mathematical tools to handle ambiguous concepts and reasoning, and finally gives concrete answers ('crisp' as they are called) to problems fraught with subjectivity (Phillis and Andriantiatsaholiniaina, 2001). Recyclability is, indeed, quite subjective. What appears unrecyclable for an economist or a physicist may be recyclable for an environmentalist, and the ingredients signifying recyclability may differ for these specialists.

To accomplish this task it is important to take into account the ideas people have about the quantification of the observable parameters of the notion. On the other hand, by using human expertise concerning the combination of the recyclability parameters, we achieve a knowledge-based measurement that overcomes these problems. The key idea is to model human inference, or equivalently, to imitate the mental procedure through which experts arrive at a value of recyclability by reasoning from various sources of evidence. These experts could be managers, engineers, operators, researchers, or any other qualified individual. Experts are capable of estimating recyclability if they know the values of certain relevant parameters (Tsourveloudis and Phillis, 1998).

In addition, fuzzy logic uses linguistic variables, thus performing computation with words. In other words, verbal or linguistic values are frequently used to quantify recyclability. This provides an additional motivation for building a knowledge-based system for material recyclability. But knowledge is almost never accurate and is completely contrary to what mathematical models require. Knowledge is ordinarily inexact and vague. Fuzzy logic offers a methodological framework (Zadeh, 1983) to represent knowledge together with a reasoning procedure whereby the value of recyclability is deduced.

From a technical point of view, the fuzzy method has the following advantages.

(a) It overcomes the difficulty of assessing certain parameters or attributes of recyclability without precise quantitative criteria.

(b) The methodology is easy to use and interpret. Therefore, the model has the potential to become a practical tool to policy-makers whose decisions ought to contribute to improvement of recyclability of materials important to the economy or harmful to the environment and to scientists involved in the field of recyclability measurement.

(c) It is adjustable by the user. Within the context of fuzzy logic, one can define new variables, values, or even rules and reasoning procedures as reality changes. Also, the user is able to adjust the inputs of the method according to need and the data at hand. The method, therefore, provides a situation of specific measurement and it can be easily expanded.

1.2 A Brief Review of Material Recycling and Recyclability

1.2.1 Material Recycling

Economic development ordinarily requires the consumption of natural resources. But materials consumed do not physically disappear. They are merely transformed to less useful or even harmful forms.

Waste problems associated with materials abound. In some cases (such as fuels) they are considerably transformed after reacting with atmospheric oxygen. In other cases (such as solvents and packaging materials) they are discarded in more or less the same form as they are used. Enormous quantities of metal ores are extracted from the earth's crust and soon become waste. Many kinds of materials are chemically degraded or they physically dissipate. Today dissipative use and waste is virtually the norm, not only for cheap materials like paper and plastics, but also even for silver, gold and platinum. For instance, copper chemicals are used in wood preservatives and fungicides (especially in vineyards). Zinc, normally contaminated by cadmium, is used in protective metal plating (galvanizing), batteries, paints and pigments, insecticides and tire manufacturing.

Recycling of materials can considerably reduce the need for energy in production and transport. Valuable materials may be recovered and the amount of material that ends up in landfills is reduced. Recycling is beneficial to the environment because it cuts down on waste and pollution. It reduces demand on non-renewable resources, and prevents pollution and waste disposal problems. Recycling also provides jobs. Other benefits include: (a) lower raw material costs from recycled sources; (b) reduced waste disposal costs; (c) less reliance on imports. The benefits of recycling depend on the materials and the form of recycling.

Material recycling is a process whereby a substance passes through a system that enables it to be reused. Recycling waste means that fewer new products and consumables need to be produced, which in turn saves raw materials and reduces energy consumption. Waste recycling has three phases: (a) Collection, sorting and transportation to a processing center; (b) Processing; (c) Development of markets for recycled products. Materials are separated either to be recycled or to avoid contamination with other materials (Thormark, 2001).

Recycling is generally done in three ways. The most effective one is to reuse an original product for about the same purpose as initially. Reuse might require upgrading or reprocessing. Another method is to remanufacture a product into its original form, like glass into glass and newspapers into newsprint. Both methods use solid waste to recover material that is destined for identical or similar use to the original. A third method of recycling is that of remanufacturing a product into another, such as using old plastic bottles to make carpeting, park benches, or plastic lumber. Recycled materials may be reprocessed into 100 percent recycled products of lower quality, but most are blended with virgin material in various proportions to manufacture high quality products.

Recycling in general and metal recycling in particular, many believe, enjoy a very bright future (Tilton, 1999). The production of one metric ton of primary (new) metal consumes more energy than production of one metric ton of secondary (recycled) metal. As resource depletion, environmental concerns, and other factors drive primary production costs up, recycling will inevitably go up the list of priorities, for two reasons.

One is the quick and increasing shortage of landfill sites for solid waste in the most industrialized regions. This forces governments to tax and regulate waste disposal and to introduce measures forcing original equipment manufacturers (OEMs) to take back old equipment for ultimate disposal or reuse. Some used materials can be remanufactured for further use. Remanufactured refrigerators, A/C units, kitchen appliances, cars (or engines), tires, and PCs can offer a good low-priced alternative to new equipment for low income workers in rich countries, or they could be sold in some developing countries. Increasingly, municipalities and private reuse-collection organizations are requiring those who generate solid waste to classify it. Special trucks pick up and cart recyclable items to transfer stations or directly to recycling facilities, thus lessening the load at incinerators and landfills.

A second reason for expecting growth in this area is that primary material processing activities are inherently quite dirty and energy-intensive. Although the mining sector has been largely exempted from intensive environmental regulation, this relative immunity from regulation cannot continue indefinitely. Other sectors have already experienced such a regulation. Most large-scale mining and metallurgical firms are already being forced to apply similar standards to their operations in developing countries. Small and medium sized operations will eventually have to follow suit. This trend will internalize the environmental costs of primary metallurgical operations, and then improve the relative economic attractiveness of secondary activities.

However, recycling is not without problems. Certain materials are dispersed into the environment at such low concentrations that make recovery for recycling impracticable, but that nevertheless constitute a health threat to humans and other species. Another obstacle to recycling has been the fact that economies of scale still favor large primary mining and smelting complexes over smaller and less centralized recyclers. But this advantage is declining over time as the inventory of potentially recyclable material grows to the point that efficient collection and logistic systems, as well as efficient markets, justify significant investments in recycling. Increasing energy and other resource costs, together with increasing costs of waste treatment and disposal, favor this shift. Government policies, driven by unemployment and environmental concerns, taken together, may accelerate the shift by gradually reducing taxes on labor and increasing taxes on extractive resource use (Ayres, 1997).

Efficiency and rate of recycling are two important factors related to material recycling. Recycling rate is the recovered content of material in recycled old scrap expressed as a percentage of apparent consumption of material. Recycling efficiency is the recovered content of material in recycled old scrap expressed as a percentage of old scrap generated (and thus potentially available for recycling). Old scrap is derived from manufactured items that have been discarded after serving a useful purpose (Sibley, Butterman, and Staff, 1995). New scrap is the counterpart of old scrap and it results in the course of producing new goods. Examples include waste gas, wastewater, toxic materials, scrap and sludge. Old paper, discarded consumer and producer durables, and construction debris are examples of old scrap. Since new scrap is easy to collect and identify, and normally of high quality, its recycling costs are low, and almost all new scrap is recycled. While the price for new scrap goes up and down with the market price of material, these fluctuations have little or no effect on the amount of new scrap recycled. Since the supply of secondary material produced from new scrap is inelastic, we shall be concerned with old scrap in this study.

There are several methods dealing with recycling in the literature. An explicit accounting method for recycling in life cycle inventory is presented in Newell and Field, 1998. A multiple criteria decision support system for environmental assessment of recycling measures in the steel industry is given in (Spengler et al., 1998). A cost-benefit analysis of resource material recycling with emphasis in a recycling program in Taiwan is presented in (Leu and Lin, 1998). A time series intervention model is proposed which analyzes recycling impact on solid waste generation (Chang and Lin, 1997).

All these methods examine specific aspects of recycling or are limited to a special industry or area. No general consideration on recycling exists. However, all these references may be used to evaluate material recyclability in this thesis.

1.2.2 Material Recyclability

Material recycling is carried out mainly due to three reasons: (a) hidden economic value of solid waste, (b) market requirements and (c) governmental regulations. The main purpose of material recycling is to minimize the amount of disposal and maximize the amount of materials returned into the production cycle.

Loosely speaking, recyclability is the ability of an element to be recycled. Two factors influence recyclability heavily, cost and physical and technological constraints. Despite the importance of recyclability, there is a lack of comprehensive assessment mechanisms in the literature.

Craig (2001) suggests that recyclability can be conceptualized in three ways: (a) chunk size, (b) concentration, and (c) bonding. This multiple characteristic makes a unique ranking impossible. However, his classification schema for recycling is only based on chemical bonding and thermodynamic considerations. Riess et al. (2000) analyze a number of samples in order to investigate the recyclability of flame retarded plastics that often contain brominated flame retardants and conclude that flame retarded polymers can be recycled under certain experimental conditions. Steenkamer and Sullivan (1998) investigate the recyclability of a new thermoplastic composite material, and consider its physical and mechanical characteristics. Ayres (1997) examines the economic and environmental implications of metals recycling. His paper gives a comprehensive analysis of recycling from both economic and environmental perspectives, but concentrates only on metals. Meanwhile, he suggests that an obstacle to recycling has been the fact that economies of scale still favor large primary mining and smelting complexes over smaller and less centralized recyclers.

The above papers examine the recyclability of specific materials, but the following papers narrow their research down to one or two aspects of recycling. None of them, however, provides a definition or measurement of recyclability. McLaren et al. (2000) develop a methodological framework for the environmental assessment of materials recycling systems and attempt to illustrate how dynamic, nonlinear modeling can be used to model the complexities of material recycling systems. Nakamura (1999) presents an interindustry approach to analyzing economic and environmental effects of recycling waste. Sibley et al. (1995) select twenty-two metals and rank them according to rate and efficiency of recycling as well as availability of recycled metal. Steward and Ritzert (1995) concentrate on waste minimization and recovery technologies.

Other papers examine only one material from a particular aspect of recycling. They will be cited later on in this dissertation. None of these measures gives a general scheme, which is suitable to all materials and encompasses all influencing factors of recyclability. Although one paper in the literature defines recyclability and provides a mathematical method to estimate it (Villalba et al., 2002), the measurement does not include all the influencing factors of recyclability and only reflects the physics of a material to be recycled. Liu et al. (2002) also provide a recyclability assessment based on artificial neural network, but this method focuses on a product and its starting point is design for recycling. They point out that whether recyclability is easy or difficult depends on the product design.

1.3 Fuzzy Logic Approach Used in the Dissertation

1.3.1 Description of Fuzzy Evaluation

The word “fuzzy” presents the continuum of logical values between 0 (completely false) and 1 (completely true). Fuzzy logic and classical logic differ in the sense that the former can handle both symbolic and numerical manipulations, while the latter only symbolic. Zadeh (1965) states that “Fuzzy logic’s primary aim is to provide a formal, computationally-oriented system of concepts and techniques for dealing with modes of reasoning which are approximate rather than exact.” Thus, in fuzzy logic, exact (crisp) reasoning is considered to be the limiting case of approximate reasoning. In fuzzy logic everything is a matter of degree. Fuzzy sets may be represented by a mathematical formulation known as the membership function. Fuzzy evaluation systems are rule-based systems.

The framework of evaluating material recyclability can be regarded as a fuzzy logic evaluator. To highlight the issues involved, Figure 1-1 shows the block diagram of a fuzzy logic evaluator, which comprises four principal components: a fuzzification interface, a knowledge base, an inference engine and a defuzzification interface.

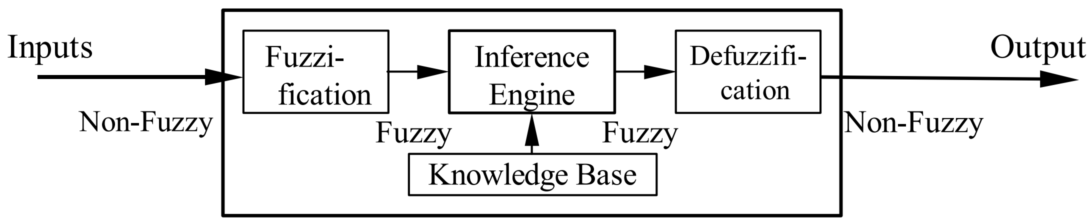


Figure 1-1 Block diagram of fuzzy logic evaluator

The functions of fuzzification interface are (a) to measure the values of input variables, (b) to perform a scale mapping that transfers the range of values of input variables into a corresponding universes of discourse, (c) to perform the function of fuzzification that converts the input data into suitable linguistic values which may be viewed as labels of fuzzy sets.

A fuzzification operator can transform crisp data into fuzzy sets expressed as

$$x = \text{fuzzifier}(x_0) \tag{1-1}$$

where x_0 is a crisp input value, x is a fuzzy set and the fuzzifier represents a fuzzification operator.

The knowledge base provides necessary definitions, which are used to define linguistic fuzzy rules and fuzzy data manipulation. It includes two kinds of knowledge: (a) choice of membership functions and (b) choice of scaling factors. A scaling factor may change a physical domain into its normalized counterpart.

The inference engine is the key of a fuzzy logic evaluator. It has the capability of simulating human experts based on fuzzy concepts and of employing fuzzy implication and the rules of inference. The inference engine mainly comprises a fuzzy rule base and some necessary knowledge about inference.

A fuzzy rule is a conditional statement that relates the observations concerning the influencing parameters of recyclability (IF-part) with the value of recyclability (THEN-part). Basically, the fuzzy rules provide a convenient way for an evaluation process. A fuzzy rule, such as "if (x is A_i and y is B_i) then (z is C_i)," is implemented by a fuzzy implication (fuzzy relation) R_i, and is defined as follows:

$$\mu_{R_i} \triangleq \mu_{(A_i \text{ and } B_i \to C_i)}(u,v,w) = [\mu_{A_i}(u) \text{ and } \mu_{B_i}(v)] \to \mu_{C_i}(w) \tag{1-2}$$

where A_i and B_i are fuzzy sets whose mathematical meaning is represented by appropriate membership functions; $R_i \triangleq A_i$ and $B_i \to C_i$ is a fuzzy implication (relation) in $U \times V \times W$; and $\to$ denotes a fuzzy implication function. There are many ways in which a fuzzy implication may be defined (e.g. Driankov et al., 1993). Implications bear the names of their inventors such as Kleene-Dienes, Lukasiewicz, Zadeh, Goguen, Sharp, Mamdani implication etc, or the name of their basic feature, such as Stochastic implication.

Fuzzy rules are an efficient way to map input spaces to output spaces, especially when the relationship between these spaces is too complicated to be expressed by mathematical functions. The impact of influencing factors on recyclability is difficult to be analytically measured, so accumulated human expertise is needed to devise fuzzy rules.

The defuzzification interface performs the following functions (a) a scale mapping, which converts the range of values of the output variables into corresponding universes of discourse, and (b) defuzzification, which yields a crisp value of recyclability from an inferred fuzzy evaluation process.

In the literature, there are many defuzzification methods, e.g. Center-of-Area/Gravity, Center-of-Sums, Center-of-Largest-Area, First-of-Maxima, Middle-of Maxima and Height defuzzification.

According to the above discussion, the principal design steps for the overall evaluation of recyclability are the following:

(a) Analyze and determine all influencing factors, fuzzification strategies, discretization/normalization of universes of discourse, and the corresponding membership functions.

(b) Devise fuzzy rules which express qualitatively the knowledge and key features of the overall system. They should satisfy certain conditions such as consistency, interaction, and completeness.

(c) Choose the fuzzy implication and compositional operator.

(d) Select and apply an approximate reasoning method, associating the observations with the available knowledge and computing the value of recyclability via a defuzzification strategy.

1.3.2 Fuzzy Reasoning

We measure the value of material recyclability using fuzzy reasoning. Specifically, based on the current knowledge of recycling, an inference engine equipped with a fuzzy rule base (together with other necessary components discussed in Section 1.3.1) may generate an evaluation of material recyclability.

1. Fuzzy Sets and Fuzzy Operations

Let U be a collection of objects denoted generally by {u}, which could be discrete or continuous. U is called the universe of discourse and u represents the generic elements of U. A fuzzy set F in a universe of discourse U is characterized by a membership function μ_F which takes values in the interval [0,1] namely, $\mu_F: U \rightarrow [0,1]$.

A fuzzy set may be viewed as a generalization of the concept of a classical set whose membership function only takes two values {0,1}. Thus a fuzzy set F in U may be represented by a set of ordered pairs of a generic element u and its grade of membership function: $F=\{(u,\mu_F(u))|u\in U\}$. When U is continuous, a fuzzy set F can be written concisely as $F=\int_U \mu_F(u)/u$. When U is discrete, a fuzzy set F is represented by

$$F=\sum_{i=1}^{n}\mu_F(u_i)/u_i \tag{1-3}$$

Let A and B be two fuzzy sets in U with membership functions μ_A and μ_B, respectively. The basic operations of union, intersection and complement etc. for fuzzy sets are defined via their membership functions as follows.

Union: The membership function $\mu_{A\cup B}$ of the union $A\cup B$ is pointwise defined for all $u\in U$ by

$$\mu_{A\cup B}=\max\{\mu_A(u),\ \mu_B(u)\} \tag{1-4}$$

Intersection: The membership function $\mu_{A\cap B}$ of the intersection $A\cap B$ is pointwise defined for all $u\in U$ by

$$\mu_{A\cap B}=\min\{\mu_A(u),\ \mu_B(u)\} \tag{1-5}$$

Complement: The membership function $\mu_{\overline{A}}$ of the complement of a fuzzy set A is pointwise defined for all $u\in U$ by

$$\mu_{\overline{A}}=1-\mu_A(u) \tag{1-6}$$

Fuzzy Relations: An n-ary fuzzy relation is a fuzzy set in $U_1\times\ldots\times U_n$ and is expressed as

$$R_{U1\times\ldots\times Un}=\{((u_1,\ldots,u_n),\mu_R(u_1,\ldots,u_n))\mid(u_1,\ldots,u_n)\in U_1\times\ldots\times U_n\} \tag{1-7}$$

Sup-star Composition: If R and S are fuzzy relations in U×V and V×W, respectively, the composition of R and S is a fuzzy relation denoted by R ∘ S and is defined by

$$R \circ S=\{[(u,w),\ \sup_v(\mu_R(u,v)*\mu_S(v,w))],\ u\in U,\ v\in V,\ w\in W\} \qquad (1\text{-}8)$$

where ∗ could be any operator in the class of triangular norms, namely, minimum, algebraic product, bounded product or drastic product. For more details, see (Lee 1990).

2. Linguistic Variables and Approximate Reasoning

A linguistic variable is a variable whose values are words or sentences in a natural or artificial language. For example, Weight is a linguistic variable if its values are linguistic rather than numerical, i.e., light, medium, and heavy, rather than 40, 41, 42, …. Practical values are transformed into linguistic values by fuzzification, and then fuzzy reasoning is applied in the form of if-then rules. A linguistic variable is defined by the name of the variable, linguistic values, membership functions, and physical domain over which the variable takes its quantitative values.

In this dissertation, the universes of discourse for all fuzzy sets are continuous, because it is believed that continuous universes of discourse are advantageous in stability over the discrete counterparts.

Membership functions interpret quantitatively the meaning of linguistic values. In this dissertation, the membership functions for the fuzzy sets are chosen to be trapezoidal, i.e. they are usually Γ shape, while some may be Λ shape. We make this choice because the parametric, functional descriptions of triangular membership functions are the most economic ones (Driankov et al., 1993). This explains the predominant use of this type of membership functions. In addition, it is proved (Pedrycz, 1994) that such membership functions can approximate any kind of membership functions. In the above references one can find a rather detailed exposition on membership functions.

Approximate reasoning is the best known form of fuzzy logic and covers a variety of inference rules whose premises contain fuzzy propositions. Inference in approximate reasoning is computation with fuzzy sets that represent the meaning of a certain set of fuzzy propositions. For example, let μ_A and μ_B be two membership functions, representing the meaning of a fuzzy proposition “X is A” and the conditional “if X is A then Y is B.” We then can compute the membership function representing the meaning of the conclusion “Y is B.”

To fire the evaluation value, Mamdani implication is used to present the meaning of if-then rules. This implication is the most popular one in the fuzzy logic field, because it is precise and fits various system applications (Nakanishi et al., 1993). Wang (1994) also shows that this implication is computationally simple. Its definition is based on the intersection operation, $p \rightarrow q \equiv p \wedge q$ which is associated with the min-operation. For simplicity, instead of a theoretical explanation, the following example illustrates the main ideas of Mamdani implication. Assume that there are two fuzzy rules

R_1: if x is A_1 and y is B_1 then z is C_1

R_2: if x is A_2 and y is B_2 then z is C_2

According to Mamdani implication, the membership function μ_c of the inferred consequence C is pointwise given by

$$\mu_c(z)=[\alpha_1 \wedge \mu_{C1}(z)] \vee [\alpha_2 \wedge \mu_{C2}(z)] \quad (1\text{-}9)$$

where $x \wedge y=\min\{x,y\}$, $x \vee y=\max\{x,y\}$, $\alpha_1=[\mu_{A1}(x_0) \wedge \mu_{B1}(y_0)]$, $\alpha_2=[\mu_{A2}(x_0) \wedge \mu_{B2}(y_0)]$, x_0,y_0=inputs and z=output.

In the evaluation of recyclability, to present the fuzzy rules, we usually use VB, B, M, G, VG; VL, L, AV, H, VH to indicate linguistic values of “Very Bad”, “Bad”, “Medium”, “Good”, “Very Good”; “Very Low”, “Low”, “Average”, “High”, “Very High” respectively, unless otherwise explained.

To change the fuzzy output into a usable crisp one (defuzzification), we use the Height method of defuzzification. Let $c^{(k)}$ and f_k be the peak value and height, respectively, of the kth fuzzy set of the fuzzy output. Then by the Height method, the defuzzified crisp output u* is given (see Figure 1-2)

$$u^*=\frac{\sum_{k=1}^{n} c^{(k)} f_k}{\sum_{k=1}^{n} f_k} \tag{1-10}$$

where n is the total number of rules in the rule base.

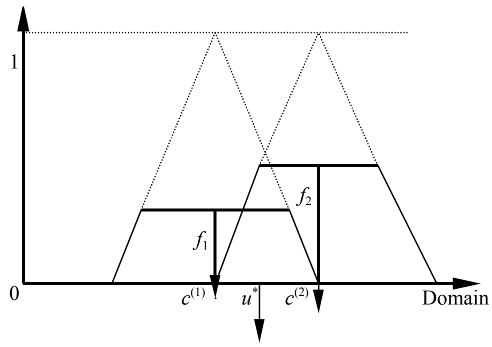


Figure 1-2 A graphical representation of the Height defuzzification method

1.4 Contribution and Organization of the Dissertation

1.4.1 Contribution of the Dissertation

This dissertation proposes an approach using fuzzy logic to evaluate the recyclability of materials. To do so, material recycling is analyzed from a global perspective, the notion of recyclability for any kind of materials is well defined and the principal influencing parameters are analyzed. The approach is based on fuzzy logic. To our knowledge, this is the first work in the literature that provides a scheme to evaluate material recyclability and examines various aspects of it. This work aims at building a simple evaluation mechanism by aggregating several factors, thus giving future users the possibility of modifying and adapting the model to specific cases. It is open to new indicators as reality and experience change, and it weighs all indicators according to their importance.

This general framework may become a useful aid to researchers as well as policy and decision-makers faced with resource depletion and environment pollution problems. It provides a theoretical base to decide which material is worth to be recycled. Resource economists could set priorities for critical indicators to increase the recyclability of material. In addition, it can identify, develop and exploit new technologies that can bolster productivity and save resources, especially non-renewable resources (including energy), while no harm is done to the environment. The contributions of the dissertation lie in defining material recyclability via fuzzy logic, analyzing influencing factors, and application to certain typical materials.

1.4.2 Organization of the Dissertation

The introductory chapter outlines why this work is done and gives brief surveys on existing technologies concerning material recycling and recyclability. In chapter 2 a conceptual introduction to material recyclability is given. An analysis of material recyclability is also conducted and a comprehensive definition of recyclability is then obtained. Factors that influence recyclability are analyzed in detail and their implications presented. Chapter 3 devises the fuzzy evaluator of material recyclability by selecting fuzzy parameters, designing fuzzy rules and training membership functions. To design the fuzzy evaluator, correlations among all factors are examined. To illustrate the proposed model, six numerical applications of metals and non-metals are presented in chapters 4 and 5, respectively. The fuzzy evaluator is used to assess recyclability and a ranking is provided. Suggestions about improving recyclability are given. To examine the robustness of the method, we conduct a sensitivity analysis and compute the rate of change of recyclability with respect to indicators and membership functions. The concluding chapter presents a comprehensive summary of this work, gives technical remarks on issues arising in the text and proposes suggestions for future study. An appendix contains a relevant rule base and summarizes all the data and results used in the case studies.

2. Analysis of Material Recyclability

2.1 Definition of Material Recyclability

2.1.1 Some Observations

Recyclability is an important characteristic of materials which, doubtlessly will aid the recycling industry to plan, design, and implement recycling work. A definition of recyclability should incorporate as many factors as possible in a precise manner. For the moment no such definition exists in the literature due mainly to the complexity of the term. Recyclability affects all metal industries (Henstock, 1996). In fact, we should say that it affects all material industries.

There are papers in the literature discussing the concept of recyclability from specific points of view.

Villalba et al. (2002) define recyclability as the ability of a material to reacquire the same properties it originally had. The degree of recyclability or recycling index of a material can be estimated by its devaluation (how much the material devalues during its first use), which is evaluated by its loss of monetary value. This measurement reflects only the ability of a material to reacquire its physical properties and does not consider other influencing factors. Craig (2001) presents a classification schema for recycling based on chemical bonding and thermodynamic considerations. He points out that multiple considerations and multiple objectives are necessarily involved, and also provides insights concerning recyclability which depends on (a) chunk size, (b) concentration, and (c) bonding. However, these three indicators fall within the scope of physics, which is only one of the aspects influencing recyclability.

Papers that examine the economic effects of recycling were introduced in chapter 1. The environment is another important facet of recycling. Recycling of waste reduces the demand for virgin materials, the amount of waste to be incinerated and/or landfilled, and emissions but it generates waste and emissions of its own (Nakamura, 1999). This paper introduces a static interindustry model for analyzing economic and environmental effects of recycling waste, based on three parameters: the proportion of recycled goods in the total input, the efficiency of recycling technology, and the efficiency of collection. The efficiency of collection is related to cost and savings in terms of reduced environmental impact. McLaren et al. (2000) develop a methodological framework for the environmental assessment of materials recycling systems. This paper explains that recycling exhibits both dynamic and nonlinear behavior and discusses structural properties of recycling systems. Weckenmann and Schwan (2001) apply the concept of fuzzy sets to deal with variability and uncertainty of data contained in commercial databases. González et al. (2002) propose a fuzzy logic approach for the impact assessment in LCA (life cycle assessment). This method avoids the need for in-depth environmental knowledge and extremely accurate data to carry out the assessment, and is more applicable to small and medium sized enterprises.

Di Vita (2001) presents a model of endogenous growth with an exhaustible resource in which waste recycling increases the growth rate of the total input. It is showed that technological change plays a central role in increasing the quantity of secondary materials produced. Similar papers exist which examine particular technologies for recycling materials. Spengler et al. (1998) suggest that economic factors should be considered simultaneously with ecological and technical criteria of recycling processes in an overall evaluation system.

According to the above analyses, the main factors involved in material recyclability are physics, technology, economics, and environment. One may observe that other factors such as politics may affect recyclability. However, the four aspects mentioned above are the principal factors governing material recyclability. Institutional considerations such as public support, legislative issues, and administrative instruments may affect recyclability but they can be included in the economic aspect, since they affect directly the costs and profits of recycling. For example, public support may result in an efficient collection of recyclable materials which renders recycling profitable. Demand for recycled materials affects recyclability directly. The four basic components of recyclability are sufficient to incorporate all aspects of interest.

2.1.2 Definition of Recyclability

As discussed above, material recyclability depends on the physics of the substance, technology of recovery, economics of the recycling process and environmental effects. Henceforth in this dissertation these factors will be called variables whose synthesis will provide an evaluation of material recyclability. Each variable will be decided by different indicators of its own. A pictorial representation of the model is shown in Figure 2-1.

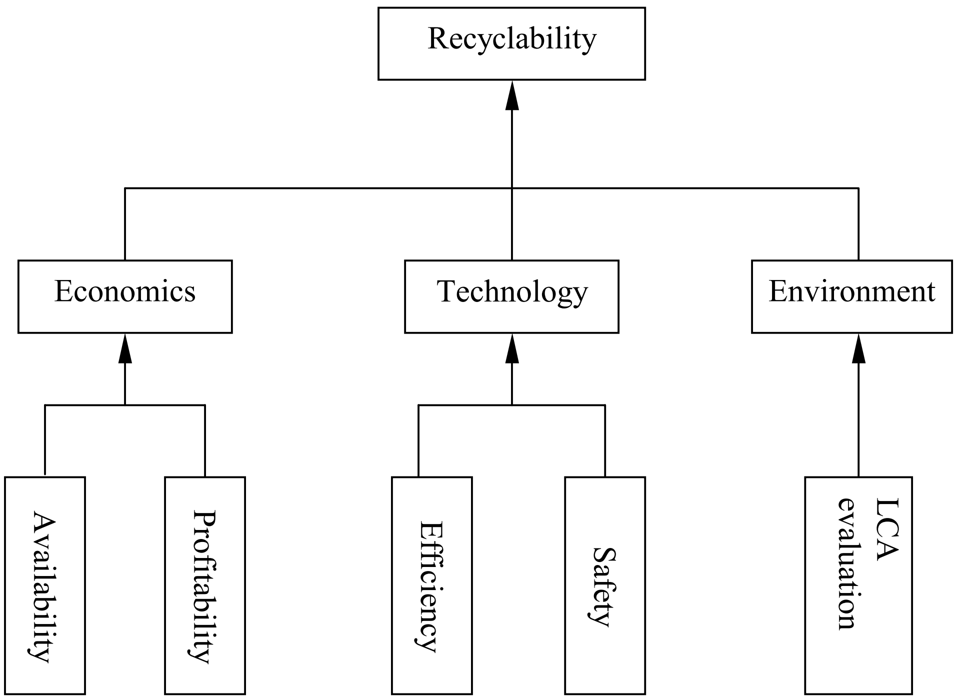


Figure 2-1 Diagram of Recyclability

Loosely speaking material recyclability is the capability of a given material to be finally recycled as a function of physics, economics, technology, and environment. It represents the degree that the material might be recycled. Some of these four aspects are controllable while others are not. For example, we can promote technical innovation but we cannot change the physics of waste. The effects of uncontrollable aspects ought to be analyzed to be able to understand their effects on recyclability. It is important to note that this dissertation studies recyclability in terms of materials such as metals, paper, glass, and not in terms of products such as computers, bulbs, cars, etc.

An important factor is the recycling rate. It has been mentioned in chapter 1, and is a characteristic of each metal. Recycling rate is the recycled content of material expressed as a percentage of recyclable material. Recyclable material is material in the form of waste for which a manufacturing technology exists which uses this material as raw input. It is assumed that twelve factors influence recycling rates, i.e., unit value, availability, capacity, disposal cost, environmental impact, purity, ease of collection, organization of infrastructure, marketability, sortability, public support, and legislative support (Sibley et al., 1995). It is further pointed out that the most influential ones are profitability, public support, organization of infrastructure, sortability, legislative support, and scrap purity.

Recycling rate and recyclability are important characteristics of material recycling, however, the recycling rate is easily expressed by a number while recyclability is complicated. In the following sections all variables involved in the definition of recyclability are discussed.

2.2 Physics

Physics plays an important role in recycling. The physical factors influencing recyclability are chunk size, concentration, and bonding (Craig, 2001), shown in Figure 2-2.

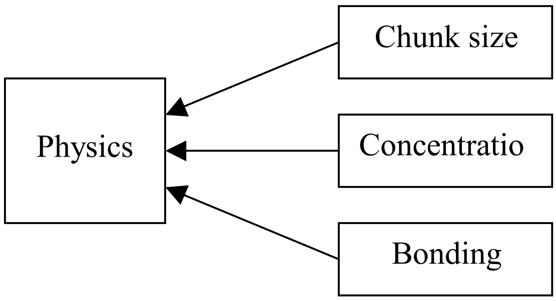


Figure 2-2 Indicators of Physics

Concentrated materials require less energy and are easier to recycle than dilute materials. It is a good strategy to separate materials and not allow them to mix and become dilute. Ordered systems are easier to recycle than disordered systems. The energy associated with chemical bonds can, in principle, be recovered through reversible (non-entropy-creating) processes. Disorder places limits on reversibility. Increasing order requires inputs of energy (more precisely, available energy) in order to decrease entropy. The key to recycling is to use to the maximum degree order existing in anything being recycled.

1. Chunk size

Chunk size is the size of reusable or relatively independent material in recycling waste, measured by the natural units of size depending on the materials, e.g., length, area and volume. In order to minimize the work and the cost the design of a recycling system should focus on handling the largest possible reusable "chunks" but not too large for the recycling equipment.

Ordered systems are easier to be recycled than disordered ones. However, ordered systems are usually embedded within disordered ones. For example, the wiring is mostly copper in a motor vehicle. Under old practices, entire vehicles were melted down and copper was mixed with steel, thereby degrading the quality of steel and rendering copper inaccessible. Modern practice uses removable wiring assemblies. Copper and steel can be recycled with minimal contamination. The wire harness constitutes a macroscopic 'chunk'. Steel scrap mixed with other waste (e.g. aluminum cans) can be magnetically separated at low energy expense. Aluminum can be separated with eddy current or flotation techniques. The 'chunks' in this case are tightly bound pieces of steel or aluminum, loosely coupled to each other. Macroscopic separation is generally preferable to microscopic separation, because there is less mixing of subclasses of materials, thereby reducing the need for separation at the atomic or molecular level.

Chunk size is related to concentration. The former focuses on volume while the latter on content.

2. Concentration

Concentration is defined as the amount of a specified substance in a unit of recycling waste, expressed as a percentage. In order to minimize the work and cost of recycling, the design of the recycling system should ensure that the highest possible concentrations in all feedstock are maintained.

In practice, low concentrations require moving large amounts of host material, thereby costing energy due to viscous forces, etc (Craig, 2001). Dumping of materials into waterways decreases concentration and complicates recycling. For example, when substances are released into large pools such as the atmosphere, lakes, or oceans, they acquire low concentrations and are difficult to recover. As concentrations increase, harm often occurs as with pesticide water contamination but higher concentrations may allow for easier removal or reprocessing. The general guideline is: when possible, do not dilute.

Furthermore, it is only practical to transport concentrated liquid wastes or sludge to a centralized facility. Dilute liquid waste is far too voluminous to economically transport. To overcome this problem, one approach is to use technologies such as ion exchange or membranes to extract and concentrate the targeted materials from the dilute liquid waste. Such processes concentrate materials to the point where they can be economically transported over relatively long distances. Once again, source segregation is highly desirable if minimum environmental impact is to be achieved in an economic fashion (Steward and Ritzert, 1995), especially when contaminants are present in the recycled waste.

Recycling is easier from a physical perspective if concentrations of desirable substances can be maintained at a high level because the energy per atom required for separation increases as the system becomes more and more dilute. In other words, the higher the concentration, the easier the recycling.

3. Bonding

All matter consists of atoms bound by chemical or nuclear forces. The meaning of "bound" is that energy is required to take things apart (to break chemical or physical bonds). Bonding affects recycling because the heart of recycling lies in the separation of components. How easy it is to recycle an item depends on the degree of separation which in turn is related to bonding. Tight bonding internally results in easier separation and recycling. Bonding in this thesis is defined as the degree of a recyclable material to be internally combined, and measured by a percentage. If we express this percentage by A/B mathematically, then A is the energy needed to separate the material from the wastes, and B is the energy needed to separate the unitary material.

Indeed an ordered item is tightly bound internally and, therefore, it is distinguishable from its environment. A goal of recycling is to separate ordered items. The motor vehicle wiring harness is bonded to the vehicle loosely, except for connections and hold-downs. These tight bonds are designed so that they can be easily broken in the recycling process.

The relationships between recyclability and its influencing factors are summarized as follows. When chunk size is medium and concentration is high, as well as bonding is tight, recyclability is high.

Physics is an important factor of recycling. It indirectly affects the economics of recycling via availability and profitability. In practice, chunk size, concentration, and bonding cannot be measured precisely. More importantly, they vary by batch, location, and society. Thus, although the importance of the components of physics cannot be overemphasized, their measurement as global attributes that express average characteristics of a given recyclable material is next to impossible. To overcome this difficulty, since the economics of the material reflects the aggregate influence of physics (good economics results from good physics, although physics is not the sole factor), we assume that physics is incorporated in economics.

2.3 Economics

Reuse of products and materials may be economically attractive compared to disposal. Metal scrap, waste paper, and soft drink bottles are examples of reusable materials. Through an economic analysis, Koh et al. (2002) conclude that recovery of certain used products is economically more attractive than disposal.

Analysis of recyclability is a multidisciplinary study where economics plays an important role. Economics is affected by the availability of used material and profitability of the recycling process (see Figure 2-1).

2.3.1 Availability of Used Material

Schemes for recycling waste material are likely to be economically successful only if a consistent and reliable supply of what might be called their “raw material”, that is scrap of a particular description, can be guaranteed. The economics of recycling does not depend solely upon the resale value of the reclaimed material but also on the availability of a constant intake of scrap to ensure continuous high output from the machinery and equipment employed. If the intake of material should periodically fall short, for seasonal or other reasons, the plant cannot be operated as economically as when a high consistent output can be maintained.

Availability is the quantity of used material potentially available for recycling. In this study, we define used or waste materials as those goods originally produced which have become waste with the passing of time, such as old paper or discarded consumer durables.

From the viewpoint of economics, used materials will be recycled if they can be collected and processed inexpensively. Their availability depends on the level of material consumption, changes in production technologies, and shifts in consumer preferences that alter the allocation of materials among their end uses. It is difficult to anticipate how the contribution of used materials recycling to total material supply will evolve. Material supplies from recycling of used material vary with the outcome of an economic competition between primary and secondary producers.

The inventory of recyclable materials in our industrial society has now reached a critical level and efficient markets for secondary materials have evolved, which means that economies of scale are becoming receptive to the recycling industries. However, in the past they were unfavorable to recyclers, because the stock level of used materials was low and prices were high.

When the availability of a used material is high, its recyclability is also high, because it is technologically easier and economically profitable to recycle.

2.3.2 Profitability of Recycling

Profitability of a recycling process is defined as the ability of profiting from it. Profit is equal to revenue minus cost. Revenue is the value of the recycled material while the cost is due to collection, transportation and processing.

The costs of recycling used material vary greatly. Some used material is easy to collect, easy to identify, and of high quality. Its recycling costs are low, and it is largely recycled regardless of price within bounds. Other used material is prohibitively expensive to recycle because it is widely dispersed and collection costs are high, or quality is poor. Little of this used material is recycled. In between these two extremes, one finds large quantities of used material that are economical to recycle.

The economics of the recycling process is highly vulnerable to fluctuations in market prices for raw materials. As the price of recycled material rises, firms find it profitable to collect and process more and more used materials, making the supply of secondary material produced from used items more responsive or elastic to price changes. In other words, a sharp rise in material prices could cause the share of total material supply coming from secondary producers to rise. Ultimately, of course, the supply of secondary material from used material is constrained by the availability of the latter.

In order to find a balance between the resources invested in a recycling process and value gained from the recycled materials, an analysis of profitability should be carried out. The objective is to continue the recycling process as long as profitability is maintained.

The following is an example of recycling profit in the United Kingdom in 1993 (www.akf.dk/eng/waste5.htm).

Table 2-1 Recycling Profit in the United Kingdom

Materials	Euros/ton
Ferrous metal	-146
Aluminum	502
Glass	-24
Paper & board	-29
Plastic film	-12
Rigid plastic	-12

From Table 2-1 we see that recycling aluminum is quite profitable whilst recycling ferrous metal is costly. This is also true for glass, paper & board and plastics but the situation is not as bad as with ferrous metal. The costs in Table 2-1 are figures of 1993, a time when paper recycling was unprofitable. The profitability of recycling in certain cases is volatile. For example, after the German packaging ordinance was implemented in the beginning of the 1990s, there was a glut of secondary fiber on the world market, and the price for recycled paper plummeted, rendering paper recycling unprofitable in most countries. However, increasing demand for recycled paper in the Asian markets raised prices again, making paper recycling profitable in 1994-95. However, in the last quarter of 1995 prices for certain types of secondary paper fell by up to 40 percent again.

Let M_i be all materials commercially recycled today, i=1, 2, …, k. Let P_i=total profit=total revenue-cost for each material. Then the value of profitability (PROF) is given by

$$PROF_i = \frac{P_i - \min_i(P_i)}{\max_i(P_i) - \min_i(P_i)} \quad (2\text{-}1)$$

which is in [0, 1]. Equation (2-1) gives PROF=0 when P_i=min(P_i) which may appear unreasonable. This, however, is not the case since in practice recycling of certain materials operates at a net loss as we shall see.

High profitability gives people an incentive to recycle. If profitability is high, economics is also high. High profitability is related to high recyclability. In the above example, aluminum has high recyclability, whereas plastic film and rigid plastic have low recyclability.

Economics is influenced by two factors. Profitability is the more important one than availability. When availability is high, economics is affected positively. We summarize these ideas in Table 2-2.

Table 2-2 Influencing Factors

Economics	Very Good	Average	Very Bad
Availability	High	Medium	Low
Profitability	High	Medium	Low

2.4 Technology

Technology plays an important role in recycling since it is related to the scientific methods used to achieve a commercial or industrial objective in the recycling process. A technology should generate as little waste as possible and be safe, effective, energy conserving, resource saving, and accident preventing. A good technology operates at low cost, good recyclability, and small material usage. Technology may be influenced by efficiency and safety (see Figure 2-1).

Today, recyclable materials are recovered from municipal refuse by a number of methods including shredding, magnetic separation of metals, air classification that separates light and heavy fractions, screening, washing, and wet pulping. For example, recycling of scrap from demolition waste, discarded motor vehicles or other equipment involves manual removal of valuable metals such as steel and copper as well as non-metals using shredding, mechanical sorting and gravity, centrifugal or magnetic separation. The next step is either remelting in a reverberatory furnace for recasting, or return to a blast furnace feed for further purification.

2.4.1 Efficiency of Recycling Technology

Efficiency is an important index measuring the level of technology. Efficiency in this thesis is the amount of recycled material that can be obtained from a unit of waste material by using a specific recycling technology. It is expressed as the ratio of the quantity of recycled material to the total waste using a specific technology in any recycling system. High efficiency results in a decrease in the amount of waste that is not recycled. When the efficiency of recycling technology declines, a greater amount of waste is needed to produce the same amount of output. Clearly high efficiency of a technology for a given material is connected with high recyclability and vice versa.

2.4.2 Safety

Safety is the state of being certain that adverse effects will not be caused by some technology under defined conditions. Safety can be measured by lost-time injury rate (LTIR) and lost-time injury severity rate (LTISR) because they are the most common safety performance indicators in industry. A lost time injury is an injury serious enough that the employee either misses a day of work or is restricted from performing normal work duties. We define

- LTIR is measured as number of lost-time injuries per million hours worked. The bigger the value of LTIR is, the less safe this recycling technology is.
- LTISR indicates the severity of the lost-time injuries, calculated as number of lost workdays due to injuries per million hours worked.
- LTISR/LTIR gives the average number of days lost per injury.

A recycling technology with high level of safety may guarantee normal operation by reducing unwanted loss. When LTIR is low, then safety is high and recyclability with this technology is high.

2.5 Environment

Several decades ago, the environment was largely perceived as a free good. As a result, firms had little incentive to reduce the environmental costs associated with their production. Sulfur dioxide, particulates, and other pollutants were pumped into the air, and waste was dumped on land or into nearby streams. In the last decades this situation has changed greatly and environmental concern has become an important societal issue. Governments around the world have imposed regulations and other controls on mineral producers. Environmental regulations are often a motivating factor for innovation and waste recycling plays an important role on environmental improvement.

An increased awareness that landfills and incineration contribute to groundwater and air pollution has led societies to recognizing the significance of waste recycling (McClain, 1995). Recycling reduces the amount of waste to be incinerated and landfilled, but its activities are not free of waste generation either. In this dissertation, the cost for preventing new pollution during the recycling of waste has been taken into account in the profitability component of economics.

The impact of waste on the environment affects our decision to recycle, so it indirectly decides material recyclability. If a used material or its primary production pollutes the environment heavily, we must recycle it even if it is not economical to do so. For example, it is important to recycle rechargeable batteries because they contain toxic and erosive materials. Batteries are being recycled, although this process is of little economic value.

Existing environmental impact studies of recycling are generally limited to energy saving, amount of waste to landfill and conservation of natural resources (Thormark, 2001). This mentality, however, is changing. Pollution problems are being addressed in an integrated manner. The OECD (Organization for Economic Cooperation and Development) recognizes that such integration can be pursued by legislation. Fragmented pollution prevention is often ineffective. For instance, reduction of air pollution at the expense of water or land pollution by the generation of sludge that contaminates soil and groundwater is undesirable. To view recyclability globally one has to take into account the environmental impact of recycling on air, water, and land.

Air, water, and land pollution in the context of recycling is the contamination of the corresponding medium resulted by primary production, used material and recycling. Recycling is geared towards reducing pollution but environmental benefits may not always be obvious. As a rule, the more a waste material pollutes the higher the societal incentive to recycle becomes.

Let M_i be all materials commercially recycled today, i=1, 2, …, k. Let EB_i=external benefit for each material=external cost of waste disposal-external cost of recycling. Then the value of environment (ENVI) is computed by

$$ENVI_i = \frac{\max_i(EB_i) - EB_i}{\max_i(EB_i) - \min_i(EB_i)} \tag{2-2}$$

which is in [0, 1].

3. A Fuzzy Logic Approach to the Evaluation of Material Recyclability

3.1 Evaluation of Material Recyclability

Material recycling efficiency is closely connected with recyclability. The analyses in previous chapters provide a basis for its evaluation. Recyclability will thus be assessed quantitatively.

As already stressed, a reliable measure of recyclability should be the result of integrating physical, technological, economic and environmental variables. Recyclability evaluation will then acquire a global perspective. This is not easy due to lack of accurate data and methodological problems. An additional difficulty is the disparate nature of the variables involved. Physical properties of materials are given in physical units, technical characteristic might be described verbally such as the safety of a technology, while economic criteria are mostly expressed in monetary units or percentages.

The decision maker should weigh appropriately ‘physics’, ‘technology’, ‘economy’ and ‘environment’, so that their importance may be differentiated. This is usually done subjectively. A direct algebraic approach to assess recyclability is impossible because the parameters involved are not amenable to numerical evaluation. As already discussed well-defined parameters, linguistic variables, and subjective judgment are all involved in the measurement of recyclability. Fuzzy logic is capable of handling disparate elements such as the above, combining them logically, and providing a single aggregate or crisp value. Another advantage of fuzzy logic is its ability to utilize expert knowledge and emulate human decision makers.

The fuzzy logic approach uses parameters represented by linguistic variables and the overall recyclability is given by their synthesis. The proposed system uses expert knowledge to assess material recyclability. This is the first effort in the literature to assess recyclability using fuzzy logic. Papers dealing with the evaluation of a multifaceted entity using fuzzy logic have appeared in the literature. Tsourveloudis and Phillis (1998) present a fuzzy logic methodology for the measurement of manufacturing flexibility. They measure nine different flexibility types and give the overall flexibility as the combined effect of these types. Phillis and Andriantiatsaholiniaina (2001) use fuzzy logic to assess sustainability.

The model we develop herein serves a dual purpose, it provides a flexible framework defining recyclability as a function of a number of variables (any but given) and at the same time it gives the mathematical machinery to compute numerical values of recyclability. Although the end result of the computation is a numerical value for recyclability, it is clear from Fig. 2-1 that a whole battery of recyclability values can be derived for each of its four components.

This chapter provides a framework for determining and measuring material recyclability in terms of a list of quantitatively defined parameters using a fuzzy logic approach. The proposed measurement framework is systematic and knowledge-based. In order to calculate the overall recyclability of material, a set of well defined parameters are proposed.

Recyclability assessment should satisfy a number of requirements:

(a) The model should be user friendly.

(b) The measurement should allow recyclability comparisons among different materials.

(c) The method should be suitable for all materials.

(d) Human knowledge should be used in the evaluation.

3.2 Fuzzy Evaluation of Material Economics

3.2.1 Evaluator Description

Economics is an important aspect influencing material recyclability. The constituent indicators of economics are availability (AVAI) and profitability (PROF) of the recycling process. A fuzzy combination of these indicators provides a measurement of economics (ECON). ECON is an intermediate fuzzy variable, which represents the direct effects of economics on material recyclability. The Fuzzy Evaluator for Economics is shown in Figure 3-1. It uses fuzzy if-then rules operating on rule bases derived from expert knowledge. By its nature, this kind of reasoning is highly nonlinear.

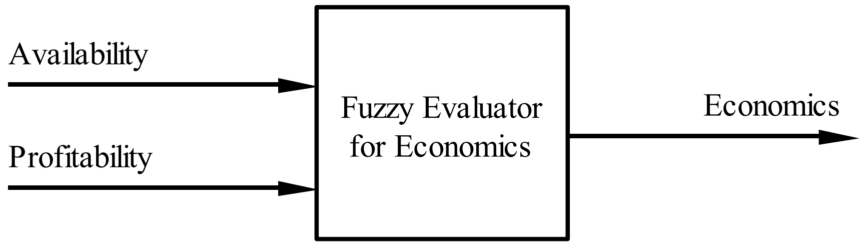


Figure 3-1 Fuzzy Evaluator for Economics

Both indicators take three linguistic values low (L), medium (M), and high (H), while the linguistic values for ECON are very bad (VB), bad (B), average (AV), good (G), and very good (VG).

These linguistic values may be real or fuzzy numbers over a physical domain which is normalized with the aid of scaling factors. The use of normalized domains (universes of discourse) requires a scale transformation which maps the physical values of indicators into a normalized domain. Profitability is the ability or rate of yielding profit, so it is expressed as a percentage. The physical domains of AVAI and PROF, however, are unbounded. Thus a scaling mechanism should be devised whereby this domain will be mapped into [0, 1]. This procedure will be explained in chapters 4 and 5.

3.2.2 Membership Functions

The membership functions for the fuzzy indicators PROF and AVAI are shown in Figures 3-2 (a) and (b), respectively. Triangular membership functions are selected. The reason is explained in chapter 1. Their membership functions in X are denoted by μ_T:

X→[0, 1], where T is the set of linguistic values of concern and T={L, M, H}. For simplicity and without loss of generality, the horizontal axis of each membership function ranges over [0, 1], whereas the vertical axis expresses membership grades ranging again over [0, 1]. This is valid for all membership functions in this dissertation.

The membership functions for PROF are unbounded from above (see Figure 3-2 (a)). The effect of AVAI becomes smaller when it exceeds a certain value. Take recycling aluminum cans as an example. If the number of available waste cans is in the tens of thousands, it may be too small to recycle economically and availability is L. When the number is larger in the M range, availability does not have a proportional effect on economics. When the number reaches hundreds of thousands, the effect of availability on economics changes slowly and its value is H. Therefore, the effect of AVAI changes faster when its value is small. We devise the membership functions for AVAI as in Figure 3-2 (b).

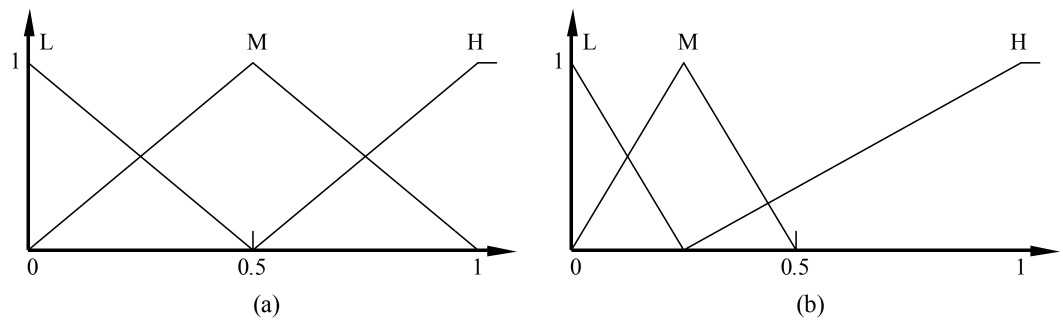


Figure 3-2 Membership Functions: (a) PROF and (b) AVAI

The membership functions for ECON are shown graphically in Figure 3-3.

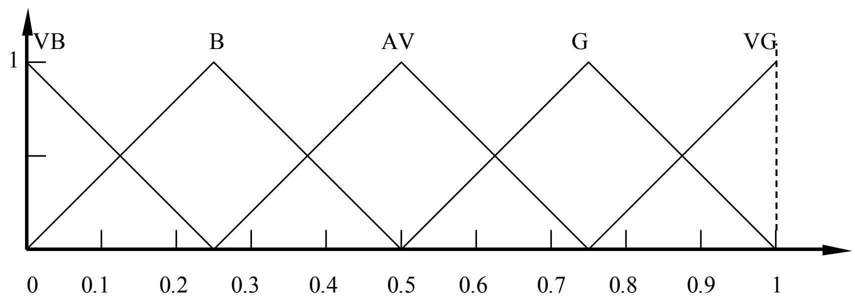


Figure 3-3 Membership Functions for ECON, TECH, and ENVI

As discussed in Chapter 2, the fuzzy evaluation of material recyclability has two stages. ECON is an intermediate fuzzy variable, in the sense that it is an output of the first stage and one indicator of the second and final stage. To obtain a finer result we choose five linguistic values for ECON T_{ECON}={VB, B, AV, G, VG}. The same values are chosen for the remaining intermediate fuzzy variables TECH and ENVI.

In the following, we develop the fuzzy rules and explain the fuzzy formalism that is used toward evaluation.

3.2.3 Rule Base for ECON

Table 3-1 Rule Base for ECON

Fuzzy Indicators		Fuzzy Output
AVAI	PROF	ECON
H	H	VG
H	M	G
H	L	B
M	H	G
M	M	AV
M	L	VB
L	H	VB
L	M	VB
L	L	VB

The rule base for the intermediate variable ECON is presented in Table 3-1. Because either of the two indicators takes three linguistic values, the rule base has $3^2=9$ rules. The rule base is not difficult to be understood. High availability and profitability make recycling attractive and the economics for recycling better. Arguments are given in Chapter 2 and summarized in Table 2-2. Whenever AVAI is low, ECON is very bad. Profitability is the more important indicator and thus emphasis is given on PROF when the rule base is devised.

3.3 Fuzzy Evaluation of Recycling Technology

3.3.1 Evaluator Description

As discussed previously, material recyclability is influenced by the level of recycling technology. Recyclability improves with improving technology, all other things being equal. Specifically, the recycling technology is governed by efficiency (EFF) and safety (SAFE). A combination of these indicators provides an evaluation of technology, the intermediate fuzzy variable TECH as shown in Figure 3-4.

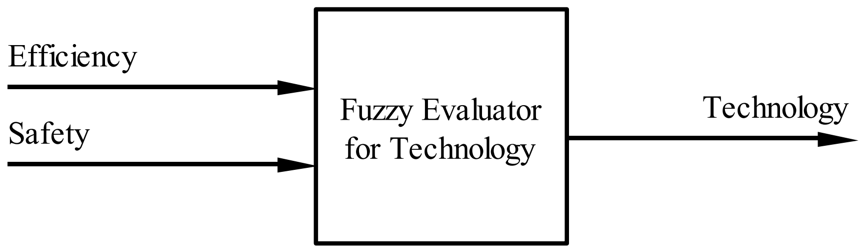


Figure 3-4 Fuzzy Evaluator for Technology

Both indicator and TECH take three and five linguistic values, respectively. The physical domain of EFF is bounded by its upper limit of 100%. SAFE reaches its upper limit when a recycling technology is risk free to operators, firms, and the environment. The physical domain of EFF and SAFE is [0, 1].

3.3.2 Construction of the Fuzzy Evaluator for TECH

The technology is with high safety when the normalized value of SAFE is very big, and the membership functions for SAFE are presented in Figure 3-5 (a). The membership functions of the fuzzy indicators EFF are those of Figure 3-5 (b), because EFF has uniform effects on recycling technology and affect RECY positively. The membership functions of TECH are shown in Figure 3-3.

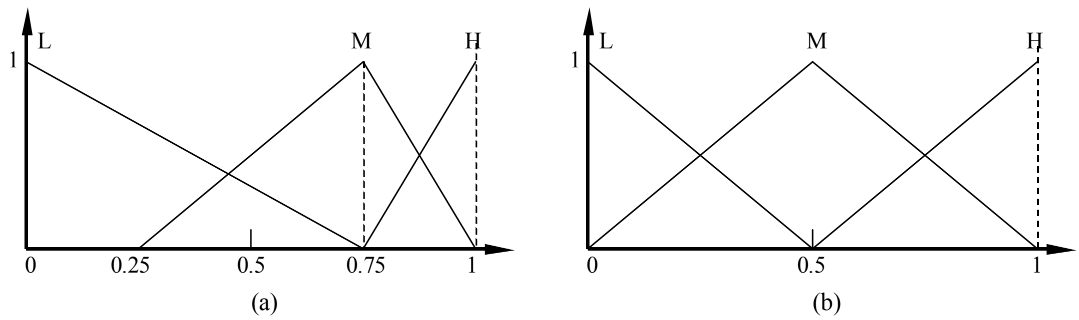


Figure 3-5 Membership Functions for (a) SAFE, (b) EFF

Table 3-2 Rule Base for TECH

Fuzzy Indicators		Fuzzy Output
EFF	SAFE	TECH

H	H	VG
H	M	G
H	L	B
M	H	G
M	M	AV
M	L	VB
L	H	VB
L	M	VB
L	L	VB

The rule base for TECH has 3^2=9 rules which are shown in Table 3-2. Its logic is straightforward. According to the analysis in Chapter 2, when the efficiency or safety is high, recyclability is high and technology is better. The rules are expressions of the role of interdependencies among the factors of TECH. Furthermore, efficiency is a decisive indicator for technology as compared to safety. No matter how much the values of SAFE take, if EFF is L then TECH takes VB.

3.4 Evaluation of Environment

Any industrial activity or product has environmental impacts. These impacts may be local, regional, and global in nature. They include effects on ecosystems, effects on human health, emission loadings, residual hazardous wastes, and the depletion in natural resources. Most importantly, these impact categories are common to virtually all industrial processes, and therefore provide a uniform basis for evaluating and comparing products to one another. In this thesis, Life Cycle Assessment (LCA) combined with economic valuation is applied to evaluate the environmental impacts.

3.4.1 Description of LCA

LCA is an analytic method for identifying and evaluating the environmental flows (to and from the environment, including air emissions, water effluents, solid waste, and the consumption/depletion of energy and other resources), over the entire life cycle of a product, process or activity. It is commonly referred to as a “cradle-to-grave” analysis and aims to increase resource-use efficiency and decreasing liabilities. The life cycle includes production and extraction of raw materials, intermediate products manufacturing, transportation, distribution, use, re-use, maintenance, and recycling (or incineration, landfilling).

An LCA involves four main phases: goal definition, inventory analysis, impact assessment and improvement assessment. The goal definition phase identifies the purpose, and determines scope and boundaries of the study, the functional unit, (based on a fixed quantity of products as supplied to their end use, for example), key assumptions to be made and likely limitations of the work.

Inventory analysis is the phase of the LCA involving the identification and quantification of inputs and outputs such as energy and materials used and wastes released to the environment, for a given product system throughout its life cycle. This phase includes data collection and the final inventory calculation. The compiled flows result in an inventory which is classified into five main categories: raw material consumption, energy consumption, air emissions, water effluents and solid waste. Generally, however, the inventory is restricted in scope to quantitative environmental emissions. It includes also a measure of social factors by recording the number of kilometers involved in transportation.

The Life cycle impact assessment aims at understanding and quantifying the energy and raw material inputs, wastes generated and environmental releases associated with each stage of a product system. It assesses the potential environmental and human health impacts associated with a given product system based on the life cycle inventory results. It incorporates three stages: classification, characterization and valuation. In the first stage, the data are classified according to an environmental problem, scale, and media. Characterization quantifies the relative contribution of each input or output to each environmental problem.

Improvement assessment is to identify and evaluate opportunities available for reducing energy and material inputs, or environmental impacts at each stage of the product life cycle.

3.4.2 Lifecycle Inventory

We compare the relative environmental impacts of a recycling system (the recovery of materials and their subsequent use in new products) with a waste disposal system (the landfill disposal of the waste and use of primary materials). The life cycle stages of both systems include primary production, distribution, use, waste generation, and collection. Environmental burdens of these stages are not quantified because of the comparative nature. There remain important differences between the transport and landfill or processing stages of each system. Environmental inputs and outputs are associated with energy use and process emissions at these stages.

Transport stages make a large contribution to the environmental and social impacts of recycling schemes. Their effects include gaseous emissions, road accident casualties and road congestion. Environmental impacts from landfill include landfill gas generation, leachate and disamenity. The principal gaseous emissions from the anaerobic decomposition of waste in landfill sites are methane and carbon dioxide. Both are greenhouse gases, but methane has a far greater radiative forcing potential than carbon dioxide. In the processing stage, problem is the scarcity of data. However, there are energy savings (and thus the associated emissions of generation) by using secondary materials rather than primary materials.

The data for recycling system include vehicle distances travelled to collect the recyclables, the quantity of different materials collected, the energy used in sorting operations and the distance to manufacturers. The environmental emissions comprise transport emissions and those from energy generation. In the waste disposal system, the data associated with transport, the atmospheric methane emissions from landfill disposal, and the amount of energy recovered from a tonne of each waste component are needed.

3.4.3 Lifecycle Impact Assessment

In the phase of impact assessment, we use the traditional classification and characterization, and make a comparison between the two waste management options. We choose three indicators: global warming, acidification and nutrification (also known as eutrophication) of surface water. The inventory results for each material are classified as contributing to each indicator. Global warming potentials (GWPs) are a measure of the possible warming effect on the atmosphere from the emission of each gas, relative to carbon dioxide (CO_2). They account for effects over the whole globe and for changes in concentration over time. We use the GWPs on a 100-year basis to measure the carbon dioxide equivalent of emissions of CO_2, CH_4 and N_2O produced by the recycling and waste disposal systems for each material. The waste disposal systems generally make a larger contribution to global warming than the recycling systems.

Acid gas emissions (SO_2, NO_x, HF and HCl) result in acid deposition when atmospheric waste vapor condenses and precipitation occurs. It results in decreased pH levels in soils and water and increases the mobility of toxins in the soil, which have a detrimental impact to aquatic life and forests. The aggregate effects of acid gases can be evaluated by the mass of hydrogen ion equivalents. Nutrification of surface water is the addition of nutrients to water, which results in enhanced primary productivity.

3.4.4 Economic Valuation

In order to compare environmental impacts which have been quantified in heterogeneous units, some method of weighting these impacts is desirable. Economic valuation methodologies can be used to value environmental and social costs and benefits, as well as assign weights to environmental and social impacts. They include dose-response relationships, contingent valuation, the hedonic property price approach and stated preferences. Craighill and Powell (1996) supplement the impact assessment stage with economic valuation of environmental and social impacts. This method particularly gives its potential to combine external costs with private costs.

An economic valuation of the inventory results uses monetary estimates for the damage done by specific gaseous emissions, casualties from road traffic accidents, and road congestion. Evaluation of the external environmental costs is based upon estimates of the social costs such as damage to crops and forests, lost productivity, medical costs, a statistical life and willingness to pay to avoid symptoms. Included in these costs are the estimated health effects related to ozone, particulate, and other conventional or "criteria pollutants" (Lave et al., 1999). Thus, environmental impacts are transformed into external (environmental) costs. We need to derive the external cost of managing 1 tonne of each material by each of the two systems. The valuation procedure is to multiply the relevant economic value by the physical parameter. This technique allows impacts to be expressed in homogenous units.

Total external costs include external costs of gaseous emissions, external costs of casualties from road traffic accidents, and external costs of road congestion. The physical impacts of gaseous emissions are derived from dose-response functions of damage to crops and forests. The damage value of human health is computed from the value of lost productivity, medical costs, the value of a statistical life and willingness to pay to avoid symptoms (Craighill and Powell, 1996). In order to derive the external cost of casualties per kilometer, the number of expected casualties from road traffic accidents is calculated from the number of incidents and distances travelled annually.

Estimates of congestion costs are presented by the opportunity cost of productive time wasted due to congestion. By summing all the above various external costs in all lifecycle stages, we arrive at the total external cost of each system.

Table 3-3 Economic Valuation of External Costs in the UK

Material	Waste disposal (Euros/ton)	Recycling (Euros/ton)	Net benefit from recycling (Euros/ton)
Steel	387.64	45.53	342.11
Aluminum	2705.52	160.31	2545.21
Glass	366.60	96.69	269.91
Paper	431.45	106.18	325.27
HDPE	13.65	17.37	-3.72
PET	20.12	30.58	-10.46
PVC	10.73	16.62	-5.89

Environmental benefit concerns the improvement of the environment from recycling. When the total external costs for the complete recycling of a material are less than those for the complete waste disposal system, we say that there is a net environmental benefit from recycling this material. The larger the external benefit, the more this material should be recycled since its environmental impact is heavy without recycling. Thus the recyclability of this material is high. Craighill and Powell (1996) combine LCA with economic valuations to make estimates of such external costs for the United Kingdom (Table 3-3). From the table one can compare the environmental effects of recycling five materials.

Table 3-3 gives a net benefit from recycling for all materials except plastics. It illustrates that there is substantial external benefit associated with the recycling of aluminum. There are also some environmental benefits for recycling steel, paper and glass, but the benefit is only in the range of 10-14 percent of that from aluminum. Recycling of plastics results in environmental costs. The results imply that it is preferable to recycle aluminum, glass, paper and steel, but that recycling is not the environmentally optimal solution for plastics. However, the uncertainties involved in estimating environmental costs and benefits of recycling, weaken the case for encouraging recycling of steel, paper and glass.

While LCA methodology has been standardized by the Industrial Standards Organization (ISO 14000), the underlying physical data are not generally available in published sources for mines and minerals processing industries (Ayres et al., 2002). The mining, concentration and smelting/refining processes in use are quite diverse, partly due to significant differences in the grade and concentration of ores being exploited in different locations and partly due to local factors such as energy costs and environmental regulations. In any case the relevant data are mostly considered proprietary. In addition, there are some social and environmental impacts which are not easily quantified in either physical or monetary terms, but which may determine the success or failure of a particular recycling scheme. However, this is an evolving area of research.

Environmental considerations are important when recycling is decided. Environment (ENVI) is an intermediate fuzzy parameter influencing recyclability. As previously, the variable ENVI takes five linguistic values, and its membership functions are shown in Figure 3-3.

3.5 Architecture of the Fuzzy Evaluator of Material Recyclability

3.5.1 Description

As illustrated in Figure 2-1, material recyclability (RECY) is evaluated by the three intermediate variables ECON, TECH, and ENVI. The output RECY is the recyclability of the material under examination in the form of a percentage (%).

The fuzzy evaluator for material recyclability is shown in Figure 3-6. It uses if-then rules operating on rule bases. The fuzzy rules describe relationships between the four intermediate parameters and the fuzzy output (recyclability). For example,

"if ECON is T_1 and TECH is T_2 and ENVI is T_3 then RECY is T_4"

is a symbolic expression of such a rule. ECON, TECH, ENVI, and RECY are fuzzy sets and their meaning is represented by appropriate membership functions.

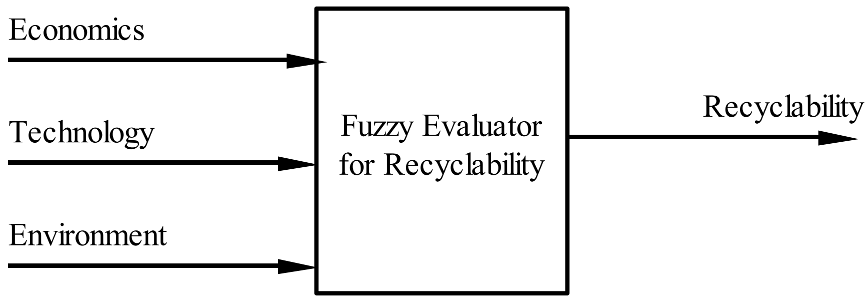


Figure 3-6 Fuzzy Evaluator for Recyclability

In order to define rules with a greater capacity of discrimination, the linguistic variable RECY takes five values, very low (VL), low (L), average (AV), high (H), and very high (VH). The four input indicators are the outputs of previous evaluators, and their values have been assessed. Their membership functions are used to obtain crisp values, which provide information about their contribution in the overall assessment.

3.5.2 Construction of the Fuzzy Evaluator for the Output

The membership functions for the output are shown in Figure 3-7.

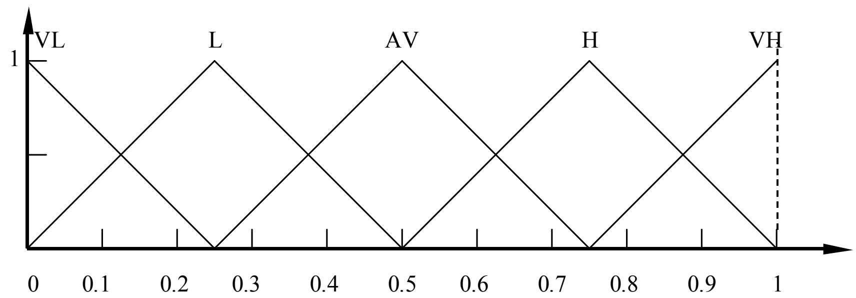


Figure 3-7 Membership Functions for RECY

To determine material recyclability RECY, the rule base needs 5^3=125 rules because there are three variables and each takes five linguistic values. Its logic is straightforward. The full rule base is shown in Table A-1 in the Appendix.

As a rule of thumb when ECON or TECH is good, material recyclability is high, while bad ENVI may result in high recyclability. When either ECON or TECH is very bad, material recyclability is very low regardless of the value of the other inputs. If, however, both ECON and TECH are not very bad, material recyclability is determined by all three inputs.

In the next two chapters, we assess recyclability by applying the fuzzy methodology through case studies. Six typical materials are examined, aluminum, copper, nickel, paper, plastic, and glass. These case studies illustrate the method in detail.

4. Fuzzy Evaluation of Metal Recyclability

4.1 Aluminum

4.1.1 Problem Description

Metals are fundamental chemical elements in the environment and the economy. Humans extract and use them for a multitude of purposes. Aluminum is a widely used metal of high economic importance. Its recycling is also of importance because extraction and processing of aluminum are highly polluting and require large amounts of energy.

Secondary production of copper from old scrap in the United States declined between 1970-98 but it is increasing for aluminum and lead (Tilton, 1999). The increase of aluminum production is attributed to two reasons. First, inventories of recyclable aluminum in use have accumulated over time while technologies and markets for this metal have developed. Second, mining and smelting of primary metal ore is inherently dirty and energy-intensive.

It is estimated that the metal content of household waste ranges between 5 and 10%. It is mainly made up of aluminum and tin-plated steel cans. Aluminum is an expensive metal and its recycling can be profitable. Anything made of aluminum can be recycled repeatedly. Cans, aluminum foil, plates and pie molds, window frames, garden furniture and automotive components are melted down and used to make the same products again. The recycling rate for aluminum cans is above 70% in some countries.

At the end of its useful life, a product's aluminum content is endlessly recyclable without quality loss, saving energy and raw materials. Most of the energy used to produce primary aluminum is electrical energy for the smelting process, which, in effect is an environmental investment. The energy is embedded in the metal and therefore available to use over and over again. Recycling one kilogram of aluminum may save about 8 kilograms of bauxite, 4 kilograms of chemical products and 14 kilowatt hours of electricity. Important issues about aluminum can be found in the site http://www.c-a-b.org.uk/public/alumin.htm. Remelting aluminum saves up to 95% of the energy needed to produce the primary product from ore, as well as 95% of the greenhouse gases associated with primary production (http://www.alcan.com). It is the most cost-effective material to recycle. The overall market for used aluminum is steadily growing, so the more aluminum there is in a product, the more chance it has of being recycled. The recycling rate of used aluminum products in buildings is over 80 percent, while it is over 95 percent in transportation and 30 percent in packaging. In Europe 30 percent of the 1.9 million tons of aluminum used in 1997 came from recycling.

Sibley et al. (1995) examine the recycling of twenty-two metals and estimate that the recycling efficiency is 36% and availability is 69% for aluminum. Ayres (1997) calculates that the net world production of aluminum was 19.8 million metric tons (MMT) in 1993. He also states that environmental problems associated with end use consumption and disposal of iron steel and aluminum are primarily due to a wide variety of ‘small’ uses. Scrap from demolished structures, pipelines, worn-out rails and rolling stock, obsolete machinery, junk cars and the like is easily collected and recycled in electric furnaces. It is a lot more difficult to recover metal economically from cans, bottle caps, wire products, aluminum foil, and so forth. These tend to be mixed with other kinds of waste (household refuse) or to be scattered over the landscape as litter. In this context, aluminum cans and bottle caps constitute by far the most serious visible pollution since aluminum is highly corrosion resistant, whereas small iron or carbon steel objects eventually rust away.

Scrap at all stages is meticulously collected and sorted by aluminum companies and customer organizations. Unlike other metals, scrap aluminum has significant value and commands good market prices. Gas collected from burning off the volatile substances in beverage can coatings provides heat for the recycling process. Every last bit of energy is used. Used beverage cans are normally back on supermarket shelves as new beverage cans in 6-8 weeks.

Because aluminum lying in our landfills will still be around in 200 or more years, recycling cans and scrap aluminum makes sense. It eliminates waste, saves energy, conserves natural resources, reduces use of city landfills and provides added revenue to recyclers, charities and local town governments. The aluminum can is 100% recyclable; there are no labels or covers to be removed. In fact, nearly 55 percent of a new aluminum can is made from recycled aluminum. Today's aluminum can requires about 40% less metal than 25 years ago. Cans made from aluminum are worth 6 to 20 times more than any other used packaging material. Aluminum is the only packaging material that more than covers the cost of its own collection and processing at recycling centers.

Pilot projects are in effect in several countries for recycling aluminum foil from packaging materials. Automobile makers make cars with aluminum components which are easily dismantled and the scrap is sorted and reused for identical new parts. In most other recycling schemes scrap material is rarely reused for the same application, and it has to be downgraded to an application requiring lesser metallic properties.

4.1.2 Evaluation of the Intermediate Parameters

Aluminum has become the leading recoverable material. Used aluminum beverage cans remain the most recycled item, but other types of aluminum, such as siding, gutters, storm window frames and lawn furniture, can also be recycled. Aluminum has a high market value and continues to provide an economic incentive to recycle. We now derive the fuzzy indicators for the intermediate evaluators as follows.

1. Economics

Availability (AVAI) for used aluminum is 69% (see Table A-2). From the membership functions for AVAI shown in Figure 3-2 (b), this value is fuzzified into H with membership grade 0.587. Profitability (PROF) of recycling is decided by the following model.

Recycling aluminum gives the highest profit (502 euros/ton) but recycling ferrous metal gives the lowest one (-146 euros/ton) among all materials (see Table 2-1). The recycling profit (P_i) is 502 euros/ton, thus the value PROF for aluminum is then computed as 1.0 by (2-1). Its fuzzy value is H with membership grade 1.0 (see Figure 3-2 (a)).

According to the fuzzy rule base for ECON (Table 3-1), and Mamdani implication (Driankov et al., 1993), the fuzzy evaluation of ECON is formulated as follows.

— If AVAI is H with grade 0.587 and PROF is H with grade 1.0 then ECON is VG with grade 0.587.

The fuzzy output of ECON is VG with membership grade 0.587. From the membership functions for ECON (Figure 3-3), the defuzzified value of ECON is 0.9.

2. Technology

The aluminum industry's sustainable development report by International Aluminum Institute shows that global lost time injury rates for primary smelters were: 7.0 for 1997, 6.0 for 1998, 7.2 for 1999, 5.0 for 2000, rates given per million hours worked.

The company HYDRO deals, among others, with aluminum. Its lost time injury rate for 1997 was 5, the same as for the previous year. It is lower than that for primary smelters. LTISR/LTIR is computed as 14 for aluminum production in 1997. Hence, Al production has an index of 14 compared to the company average 15. This shows that Al production is more or less average in safety. About Al, we could grade 14 on a scale from 0 to 40, assuming that HYDRO has a wide spectrum of activities and is representative for safety. Then the value of SAFE is 0.65 on the interval of 0 and 1, and fuzzified into L with membership grade 0.133 and M with membership grade 0.80 according to Figure 3-5.

Recycling efficiency is the recovered content of metal in recycled old scrap expressed as a percentage of old scrap generated (Sibley et al., 1995). Hence, the value of EFF is 36%, and it can be fuzzified at L with membership grade 0.28 and M with membership grade 0.72.

According to Table 3-2, and Mamdani implication (Driankov et al., 1993), TECH is evaluated as follows.

— If EFF is L with grade 0.28 and SAFE is L with grade 0.133 then TECH is VB with grade 0.133.

— If EFF is L with grade 0.28 and SAFE is M with grade 0.80 then TECH is VB with grade 0.28.

— If EFF is M with grade 0.72 and SAFE is L with grade 0.133 then TECH is VB with grade 0.133.

— If EFF is M with grade 0.72 and SAFE is M with grade 0.80 then TECH is AV with grade 0.72.

The fuzzy value for TECH is VB with membership grade 0.28 and AV with grade 0.72.When $e^{(1)}= e^{(2)}= e^{(3)}=0$, $e^{(4)}=0.5$, and $f_1=f_3=0.133$, $f_2=0.28$, $f_4=0.72$, the crisp value of TECH is obtained by

$$\text{TECH*}=\frac{\sum_{x=1}^{4} e^{(x)} f_x}{\sum_{x=1}^{4} f_x}=0.284 \qquad (4\text{-}1)$$

3. Environment

The value of ENVI can be deduced using an external benefit analysis. Used aluminum does relatively little direct damage to the environment, although as Ayres (1997) writes, “aluminum cans and bottle caps constitute by far the most serious eyesore since aluminum is highly corrosion resistant”. Primary production from bauxite ore is highly polluting. Production of aluminum from bauxite and subsequent aluminum purification results in a caustic waste called ‘red mud’ (Ayres, 1997) and emissions of CO, CO_2 and toxic fluorides.

Recycling aluminum waste prevents pollution and saves energy, thus it benefits the environment highly. The net benefit from recycling aluminum is 2545.21 euros/ton (see Table 3-3). The large net benefit means that this waste material has heavy environmental impact with disposal and its value of ENVI is low. The value of ENVI is computed using (2-2).

The value of ENVI for aluminum is thus obtained as 0 by (2-2) where $EB_i = \max_i(EB_i)$=2545.21 euros/ton and $\min_i(EB_i)$=-10.46 euros/ton. The fuzzy value of ENVI is VB with membership grade 1.0, which means that waste aluminum has very bad effect on the environment.

Lave et al. (1999) also represent a rough estimate of the external environmental costs of production for four commodities. Their calculations find that avoiding primary aluminum production has the greatest environmental benefit.

4.1.3 Evaluation of Aluminum Recyclability

We have obtained the values VG with membership grade 0.587 for ECON; VB with membership grade 0.28 and AV with membership grade 0.72 for TECH; and VB with membership grade 1.0 for ENVI.

According to the fuzzy rule base in Table A-1 (see Appendix), and Mamdani implication, the fuzzy evaluation of RECY is formulated as follows.

— If ECON is VG with grade 0.587 and TECH is VB with grade 0.28 and ENVI is VB with grade 1.0 then RECY is VL with grade 0.28.
— If ECON is VG with grade 0.587 and TECH is AV with grade 0.72 and ENVI is VB with grade 1.0 then RECY is VH with grade 0.587.

From the membership functions for RECY (Figure 3-6), the peak values and heights of the fuzzy parameter RECY are $e^{(1)}$=0, $e^{(2)}$=1.0, and f_1=0.28, f_2=0.587. By the height method of defuzzification, the crisp output RECY is given by

$$\text{RECY}^* = \frac{\sum_{x=1}^{2} e^{(x)} f_x}{\sum_{x=1}^{2} f_x} = 0.677 \qquad (4\text{-}2)$$

or the recyclability of aluminum is 67.7%. This result shows that aluminum does not have a very high recyclability, although its recycling has very good economic characteristics as well as benefits environment very much.

4.2 Copper

4.2.1 Problem Description

Copper is an example of material that is of interest to both resource economists and environmental scientists. It is a widely used industrial metal, which, in certain forms and concentrations, is moderately biotoxic (Graedel et al., 2002). It also could be supply-limited and one of the most thoroughly recycled among what we might call structural metals. Copper conducts heat and electricity very well; it is malleable and can be drawn into thin wires; it resists corrosion. Waste processing of copper is environmental friendly, it consumes less energy than primary copper production and conserves the primary raw materials. Copper is recovered mainly through pyrometallurgical processes and to a lesser extent through hydrometallurgy.

Recycling of copper is as old as the usage of the metal itself. Since 1965, copper recovered from scrap, as a percent of total world copper produced, has ranged between 31% in 1998 and 1999 to 38% in 1995. Refineries buy recycled metal and convert it to pure copper. This process results in a tremendous energy saving since the work ordinarily needed to mine, crush and smelt ore doesn't have to be done again. This in turn creates less emissions of harmful gases into the atmosphere. Environmental considerations favor recycling. More importantly, refined copper from recycling is of the same quality as new metal. Obviously, recycling copper is a win-win situation.

Copper is used in products either as pure metal or as an alloy. The widespread use of copper in concentrated amounts indicates the high potential for recycling of the metal (Spatari et al., 2002). In contrast to other metals such as zinc and cadmium, copper tends to disperse less in the environment. Metals that disperse usually pose environmental risks. Copper alloys are readily recycled. Unlike other metals, copper is exceedingly slowly corroded in natural environments. Copper uses tend to have long residence times; thus, we expect that most of the copper processed during the last decades is still in use.

The majority of copper in finished products is contained in pure form (70%) and the remainder in alloy form. About 36% of the copper in old scrap comes from pure copper products, and the rest from alloy products. New scrap and old scrap differ greatly in their quality. Because of its high purity, most of the new scrap can be directly re-melted, while a good deal of old scrap has to return to the refinery and smelter stage. Today almost 100% of copper production waste (new scrap) is recycled because of its high purity and economic value (Bertram et al., 2002), and nearly 100% of copper-bearing alloys are returned to the semi-product stage, not only because of economic benefits but also because of environmental regulations limiting emission of heavy metals in refineries. Only galvanic sludge, chemical, and electrolysis residues, whose recycling is not yet economical, are disposed of as part of hazardous wastes. In Europe about 60% of copper from waste is recycled (Spatari et al., 2002).

If scrap contains pure copper and has not been contaminated by other substances, a high quality product can be made from it. Thus high recyclability results from high bonding. If scrap consists only of a single alloy, it is easy to remelt and produce a good quality product, although composition may change. If scrap is mixed or contaminated by other materials such as solder then, when remelted, it will be difficult to produce a composition within specifications. If scrap has been contaminated beyond acceptable limits, it is necessary to re-refine it to pure copper using conventional secondary metal refining techniques that provide a useful supplement to supplies of primary copper.

Copper is used mainly in buildings, machinery, vehicles and infrastructure. Waste originates in municipal solid refuse, construction and demolition, end-of-life vehicles, and electrical and electronic equipment (Bertram et al. 2002).

It is estimated that recycling efficiency for copper is 30% and availability for used copper is 73% (Sibley et al., 1995). Emissions of copper to the environment from incinerators and landfills account for under 5,000 ton/y but several new sources of emissions have not yet been quantified (Bertram et al., 2002). In 1999, the National Electrical Manufacturers Association (NEMA) in USA petitioned the EPA (Environmental Protection Agency) to delist copper from its Toxic Release Inventory (TRI) because it felt that recycling prevents most copper from entering the environment. There also was growing evidence that copper was not detrimental to the environment.

4.2.2 Evaluation of the Intermediate Parameters

We now evaluate the indicators and the four intermediate parameters.

1. Economics

We know that availability (AVAI) for used copper is 73%. From the membership functions for AVAI (Figure 3-2 (b)), it is fuzzified into H with membership grade 0.64.

Surplus world copper production, lower copper prices and increasing environmental compliance costs result in a decline in secondary copper-base scrap collection and processing capacity. Recovery from old scrap resource has suffered in recent years, owing to the unfavorable economic conditions and loss of essential processing capacity. According to International Copper Study Group, the profit of recycling copper is estimated as 246 euros/ton. Using (2-1), PROF is computed as 0.605, which is fuzzified into M with membership grade 0.79 and H with membership grade 0.21.

ECON is evaluated as follows, based on the corresponding rule base and Mamdani implication.

— If AVAI is H with grade 0.64 and PROF is M with grade 0.79 then ECON is G with grade 0.64.
— If AVAI is H with grade 0.64 and PROF is H with grade 0.21 then ECON is VG with grade 0.21.

The fuzzy value for ECON is G with membership grade 0.64 and VG with membership grade 0.21.When $e^{(1)}$=0.75, $e^{(2)}$=1.0, and f_1=0.64, f_2=0.21, the crisp output of ECON is given by

$$\text{ECON*}=\frac{\sum_{x=1}^{2} e^{(x)} f_x}{\sum_{x=1}^{2} f_x}=0.812 \qquad (4\text{-}3)$$

2. Technology

Recycling efficiency for copper is estimated as 30% (Sibley et al., 1995). EFF is then fuzzified into L with membership grade 0.4 and M with membership grade 0.6 from Figure 3-5 (b).

In the report of Bureau of Labor Statistics, presented in the site www.bls.gov, the highest lost time injury rate in the U.S. metal industries was 16.5 and LTIR was 9.8 for copper production in 2002, per 100 full-time workers. The normalized value of SAFE is obtained as 0.406. According to Figure 3-5 (a), it is fuzzified into L with membership grade 0.459 and M with membership grade 0.312.

TECH is formulated as follows.

— If EFF is L with grade 0.4 and SAFE is L with grade 0.459 then TECH is VB with grade 0.4.
— If EFF is L with grade 0.4 and SAFE is M with grade 0.312 then TECH is VB with grade 0.312.
— If EFF is M with grade 0.6 and SAFE is L with grade 0.459 then TECH is VB with grade 0.459.
— If EFF is M with grade 0.6 and SAFE is M with grade 0.312 then TECH is AV with grade 0.312.

The fuzzy value of TECH is VB with grade 0.459, AV with grade 0.312. When $e^{(1)}=e^{(2)}=e^{(3)}=0$, $e^{(4)}=0.5$, and $f_1=0.4$, $f_2=f_4=0.312$, $f_3=0.459$, the crisp value of TECH is

$$\text{TECH}^*=\frac{\sum_{x=1}^{4} e^{(x)} f_x}{\sum_{x=1}^{4} f_x}=0.105 \tag{4-4}$$

3. Environment

Used copper itself doesn't pollute the environment much. Moderate excess quantities of copper are not known to cause problems. However, the environmental impact of copper from primary production is serious.

Copper refineries emit large quantities of sulfur oxides causing severe damage to forests. In the US, copper mining accounts for the largest mine waste among all metals extracted. To produce a ton of pure copper, on average, it is necessary to process 110 tons of copper ore. Ore must be extracted, concentrated, and finally smelted. Domestic copper mining in the US generated 316 million metric tons of gangue (plus 600 million tons of overburden) and yielded 2 million tons of copper in 1994 (Ayres, 1997). In addition, copper mining and refining produces toxic byproducts such as lead, mercury, arsenic, bismuth, cadmium, thallium, cobalt, selenium, silver and tellurium which are being dispersed into the environment at very low concentrations that make later recovery for recycling impracticable. These metals constitute a threat to the health of humans and other species.

Fortunately, recycling copper waste prevents a lot of pollution, because it avoids mining and further refining. According to the study of Ayres et al. (2002), the external benefit of recycling copper is 2496.47 euros/ton. Therefore, ENVI for copper is given as 0.0191 by (2-2), which is fuzzified into B with membership grade 0.076 and VB with membership grade 0.924 according to the membership functions of ENVI.

4.2.3 Evaluation of Copper Recyclability

The fuzzy values of the three intermediate parameters for copper are ECON is G with membership grade 0.64 and VG with membership grade 0.21; TECH is VB with membership grade 0.459 and AV with membership grade 0.312; ENVI is VB with membership grade 0.924 and B with membership grade 0.076. RECY is evaluated as follows

— If ECON is G with grade 0.64 and TECH is VB with grade 0.459 and ENVI is B with grade 0.076 then RECY is VL with grade 0.076.

— If ECON is G with grade 0.64 and TECH is VB with grade 0.459 and ENVI is VB with grade 0.924 then RECY is VL with grade 0.459.

— If ECON is G with grade 0.64 and TECH is AV with grade 0.312 and ENVI is B with grade 0.076 then RECY is H with grade 0.076.

……

— If ECON is VG with grade 0.21 and TECH is AV with grade 0.312 and ENVI is VB with grade 0.924 then RECY is VH with grade 0.028.

The peak values and heights of the fuzzy parameter RECY are $e^{(1)}= e^{(2)} = e^{(5)} = e^{(6)} =0$, $e^{(3)}= e^{(4)}= e^{(7)}=0.75$, $e^{(8)}=1.0$, and $f_1= f_3= f_5= f_7=0.076$, $f_2=0.459$, $f_4=0.312$, $f_6= f_8=0.21$. The crisp output RECY is

$$\text{RECY*}=\frac{\sum_{x=1}^{8} e^{(x)} f_x}{\sum_{x=1}^{8} f_x}=0.3732 \tag{4-5}$$

Thus recyclability for copper is 37.32%. Recycling waste copper is environmentally friendly because of energy, primary raw materials and pollution savings. Environmental considerations strongly favor copper recycling.

4.3 Nickel

4.3.1 Problem Description

Nickel is a lustrous, silvery-white metal discovered in 1751. It is widely used in over 300, 000 products for consumer, industrial, military, transport/aerospace, marine, power production and architectural applications. Nickel is primarily sold for first use as refined metal (cathode, powder, briquet, etc.) or ferronickel, and it is essential to the economics of a number of businesses and thus contributes to employment.

Unlike other non-ferrous metals, nickel is rarely used by itself but is commonly mixed with other metals to produce alloys. There are thousands of different alloys containing nickel — each developed to offer a particular combination of technical properties (corrosion resistance, mechanical properties and service life) relevant to particular conditions of use. About 65 percent of nickel is used to manufacture stainless steels, and 20 percent in other steel and non-ferrous (including "super") alloys, often for highly specialized industrial, aerospace and military applications. Turbine blades, discs and other critical parts of jet engines are fabricated from superalloys. Nickel-base superalloys are also used in land-based combustion turbines, such as those found in electric power stations. About 9 percent of nickel is used in plating and 6 percent in coins and a variety of nickel chemicals such as carbonate (NiCO3), chloride (NiCl2), divalent oxide (NiO), and sulfate (NiSO4). The public may recognize nickel in coins, as it is used for this purpose in pure or alloy forms by many countries, or as bright and durable electrolytically-applied coatings on steel (nickel plating).

It is usual practice for special alloys to be recycled as the same special alloy wherever possible: they will have their own closed loops. The motivation is commercial — maintaining the identity of the alloy during fabrication, use and recycling allows the alloy producer to use (and value) all the alloy components in the recycled alloy, not just the nickel. It also allows the producer to achieve high quality product specifications without incurring extra refining or qualification costs. It follows that the environmental impacts are also minimized as a result.

Nickel occurs in nature principally in the form of oxides, sulphides and silicates. Ores of nickel are mined in about 20 countries on all continents, and are smelted or refined in about 25 countries. Primary nickel is produced and used in the form of ferro-nickel, nickel oxides and other chemicals, and as more or less pure nickel metal. Nickel is also readily recycled in many of its applications, and large tonnages of secondary or "scrap" nickel are used to supplement newly mined metal. The International Nickel Study Group estimates that nickel bearing scrap totaling 4.4-4.6 million tons per year is collected and recycled (http://www.insg.org). This scrap is estimated to contain almost 350,000t of nickel (or one-quarter of the total demand) annually which is mainly used by the stainless steel industry. Most of the scrap is stainless steel scrap, resulting from the demolition of obsolete factories, machinery and equipment, and consumer goods.

Only about 1 million tons of new or primary nickel are produced and consumed annually in the world, compared with over 10 million tons of copper and nearly 800 million tons of steel. Nickel is technically a finite resource: it makes up a fixed percentage of the earth's composition (fifth most common element after iron, oxygen, silicon and magnesium although only approximately 0.01% of the earth's crust). What is recoverable from nature will vary with technology but is also ultimately finite.

However, nickel is used but not "consumed". Nickel taken from the inventory of nature (deposits) is available for use and re-use without degradation: it does not deteriorate or lose any of its intrinsic properties. There is always the same amount of nickel existing at the end of a particular product cycle as at the beginning. Although nickel can be "lost" (emissions to air, water and soil at levels or in amounts too small to be economically recovered), the basic supply of nickel for present and future generations is not in question.

Nickel has its own unique attributes: corrosion resistance, durability, excellent strength and toughness at elevated temperatures, the ability to act as a catalyst. Nickel is a reclaimable product. Its recycling can be profitable to the recycler and the purchaser. No public subsidy is involved. Nickel is highly recycled although rarely as nickel; it is mostly recycled as part of an alloy. Recycling efficiency for nickel is estimated very high (95%) but availability for used nickel is relatively low (17%) (Sibley et al., 1995).

Recycling of nickel benefits the environment because of reduced consumption of environmental resources; reduced emissions because of high efficiency of recycling; longevity, since nickel alloys and related products survive long. The high price of nickel also encourages commercial users to use nickel very efficiently in the first use. The white paper written by the International Nickel Study Group states that any nickel-containing material can be recycled profitably, thus ensuring that little nickel is knowingly sent to landfills or incinerators. Recycling of nickel alloys permits the recovery of other metals as well. Because nickel does not deteriorate, the finite but large amounts of nickel available do not significantly decline over time. The nickel industry and those involved in nickel recycling are committed to reducing the amount of nickel that is lost due to fugitive emissions, emissions to different media, committed to landfill, or dissipative uses.

The quantities of solid mining and milling waste is typically much greater than the quantity of processed metal, therefore, recycling can significantly reduce this waste. Nickel content in ore averages 2%. Nickel smelting yields tailing slag, flue ash and dust, or sludge rich in byproduct metals (Ayres, 1997). Significant quantities of metals are discarded or lost in refinery operations, mainly as smoke, dust and slag.

All metals and metal compounds have a certain level of toxicity and may harm living organisms. Nickel in certain forms and under particular circumstances, may have detrimental environmental effects. It appears to be extremely difficult to make a general assessment on the environmental consequences of nickel.

4.3.2 Evaluation of the Intermediate Parameters

1. Economics

Nickel has high resistance to general corrosion. This basic feature in use means that, at end-of-life, most nickel-containing articles are still intact and easily identifiable (e.g., a kitchen sink made of stainless steel). This greatly facilitates the initial collection and sorting of nickel-containing end-of-life products. Nickel is one of the most recycled materials in today’s global economy.

Nickel recycling is encouraged by the high value of most nickel-containing products at the end of their life. Nickel is worth too much for people to just throw it away. The market price per ton of nickel fluctuates but is usually about two to three times more than aluminium and more than ten times more than steel. Recyclers and industrial users recognize this value.

Availability (AVAI) for used nickel is 17% (see Table A-2) and this is fuzzified into L with membership grade 0.32 and M with membership grade 0.68.

We know that any nickel-containing material can be recycled; most nickel-containing material can be recycled profitably; no public subsidy is involved. Lower operating costs are the result of higher operating efficiencies, durability and reliability. In the site http://www.nidi.org, profit of recycling nickel is 347 euros/ton. The value of profitability (PROF) for nickel is then obtained as 0.761 by (2-1), which is fuzzified into M with membership grade 0.478 and H with membership grade 0.522.

According to the fuzzy rule base (Table 3-1) and Mamdani implication, the fuzzy evaluation of ECON is

— If AVAI is L with grade 0.32 and PROF is M with grade 0.478 then ECON is VB with grade 0.32.
— If AVAI is L with grade 0.32 and PROF is H with grade 0.522 then ECON is VB with grade 0.32.
— If AVAI is M with grade 0.68 and PROF is M with grade 0.478 then ECON is AV with grade 0.478.
— If AVAI is M with grade 0.68 and PROF is H with grade 0.522 then ECON is G with grade 0.522.

The fuzzy value for ECON is VB with membership grade 0.32 and AV with membership grade 0.478 and G with membership grade 0.522. From the membership functions of ECON (Figure 3-3), the peak values and heights are $e^{(1)}=e^{(2)}=0$, $e^{(3)}=0.5$, $e^{(4)}=0.75$ and $f_1=0.32$, $f_2=0.32$, $f_3=0.478$, $f_4=0.522$. Using the height method of defuzzification, the crisp output of ECON is given by

$$\text{ECON*}=\frac{\sum_{x=1}^{4} e^{(x)} f_x}{\sum_{x=1}^{4} f_x}=0.384 \qquad (4\text{-}6)$$

2. Technology

Recycling efficiency for nickel is very high (95%). Hence, the crisp value of EFF is 0.95, which is fuzzified to obtain the fuzzy values M with membership grade 0.1 and H with membership grade 0.9.

The Operations Performance Report for 2002 for the nickel production industry in the U.S. shows that the lost time injury frequency rate is 3.9 for 2002, measured as per 100 full time workers. We know that the highest lost time injury rate for the U.S. metal industries in 2002 was 16.6. Therefore, the normalized value of SAFE is 0.765, and fuzzified as M with grade 0.94 and H with grade 0.06.

TECH is then evaluated as follows.

— If EFF is M with grade 0.1 and SAFE is M with grade 0.94 then TECH is AV with grade 0.1.
— If EFF is M with grade 0.1 and SAFE is H with grade 0.06 then TECH is G with grade 0.06.
— If EFF is H with grade 0.9 and SAFE is M with grade 0.94 then TECH is G with grade 0.9.
— If EFF is H with grade 0.9 and SAFE is H with grade 0.06 then TECH is VG with grade 0.06.

The fuzzy value of TECH is AV with grade 0.1, G with grade 0.9, and VG with grade 0.06. When $e^{(1)}$=0.5, $e^{(2)}$= $e^{(3)}$=0.75, $e^{(4)}$=1.0 and f_1=0.1, f_2=0.06, f_3=0.9, f_4=0.06, the crisp value of TECH is computed by

$$\text{TECH*}=\frac{\sum_{x=1}^{4} e^{(x)} f_x}{\sum_{x=1}^{4} f_x}=0.741 \tag{4-7}$$

3. Environment

Nickel alloys have high melting point (1453° C) and good mechanical strength, which mean that waste nickel has a relatively small environmental impact. However, nickel in certain forms and under particular circumstances, may generate detrimental environmental (including health and safety) effects. Also, nickel mining and refining are polluting activities. Recycled nickel metal requires 75% less primary energy, compared with extraction and refining of virgin metal (Rydh and Karlström, 2002). The external benefit from recycling nickel is shown as 1962.52 euros/ton by Ecobalance Inc. (2000). The value of ENVI is then given as 0.228 by (2-2), which is fuzzified as B with membership grade 0.912 and VB with membership grade 0.088.

4.3.3 Evaluation of Nickel Recyclability

The three intermediate parameters have been assessed: ECON is VB with membership grade 0.32 and AV with membership grade 0. 478 and G with membership grade 0.522; TECH is AV with membership grade 0.1, G with membership grade 0.9, and VG with membership grade 0.06; ENVI is VB with membership grade 0.088 and B with membership grade 0.912.

The recyclability of nickel is

— If ECON is VB with grade 0.32 and TECH is AV with grade 0.1 and ENVI is B with grade 0.912 then RECY is VL with grade 0.1.

— If ECON is VB with grade 0.32 and TECH is AV with grade 0.1 and ENVI is VB with grade 0.088 then RECY is VL with grade 0.088.

— If ECON is VB with grade 0.32 and TECH is G with grade 0.9 and ENVI is B with grade 0.912 then RECY is VL with grade 0.32.

……

— If ECON is G with grade 0.522 and TECH is VG with grade 0.06 and ENVI is VB with grade 0.088 then RECY is VH with grade 0.06.

Here $e^{(1)}= e^{(2)}= e^{(3)}= e^{(4)}= e^{(5)}= e^{(6)}=0$, $e^{(7)}= e^{(8)}= e^{(9)}= e^{(10)}= e^{(11)}= e^{(13)}= e^{(14)}= e^{(15)}=0.75$, $e^{(12)}= e^{(16)}= e^{(17)}= e^{(18)}=1.0$, and $f_1=f_7=f_{13}=0.1$, $f_2=f_4=f_8=f_{10}=f_{14}=f_{16}=0.088$, $f_3=0.32$, $f_5=f_6=f_{11}=f_{12}=f_{17}=f_{18}=0.06$, $f_9=0.478$, $f_{15}=0.522$. The crisp output of RECY is

$$\text{RECY*}=\frac{\sum_{x=1}^{18} e^{(x)} f_x}{\sum_{x=1}^{18} f_x}=0.5626=56.26\% \tag{4-8}$$

4.4 Sensitivity Analysis of RECY

We have provided a fuzzy model to evaluate recyclability and applied it to the case of three metals. All the data used for the evaluation and results are shown in Tables A-2, A-3 and A-4 (see Appendix). Improvements in metal recycling from waste reservoirs will be an important future activity. Analyzing all the influencing factors can help to set priorities for the improvement of material recyclability.

To examine the robustness and sensitivity of the model, we conduct a sensitivity analysis and compute the rate of change in RECY with respect to indicators and membership functions. In the following, aluminum is chosen as an example.

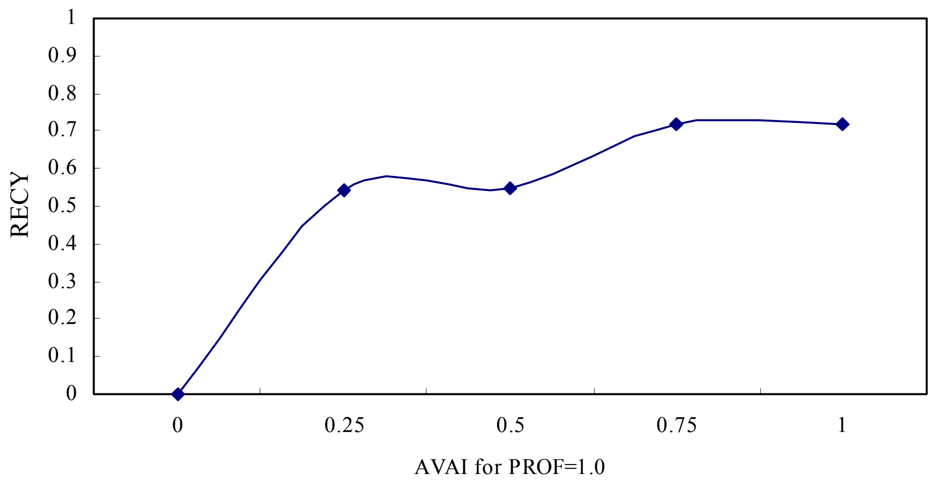
4.4.1 Changing the Values of Indicators

We change the values of two indicators of ECON in turn, and obtain the results of ECON and RECY shown in Table 4-1. The second row shows the reference values, and indicators change as follows in the other rows. One indicator is assigned one of five values (0, 0.25, 0.5, 0.75, 1.0) at a time while the other remains unchanged. For example, when AVAI takes one of five values from the third row to the seventh row in the table, PROF does not change. We then obtain five values of RECY associated with different values of AVAI. Their functional relation is obvious. RECY is plotted as a function of AVAI and PROF in Figure 4-1. The gradient at each point of these curves is a direct reflection of the sensitivity of this point.

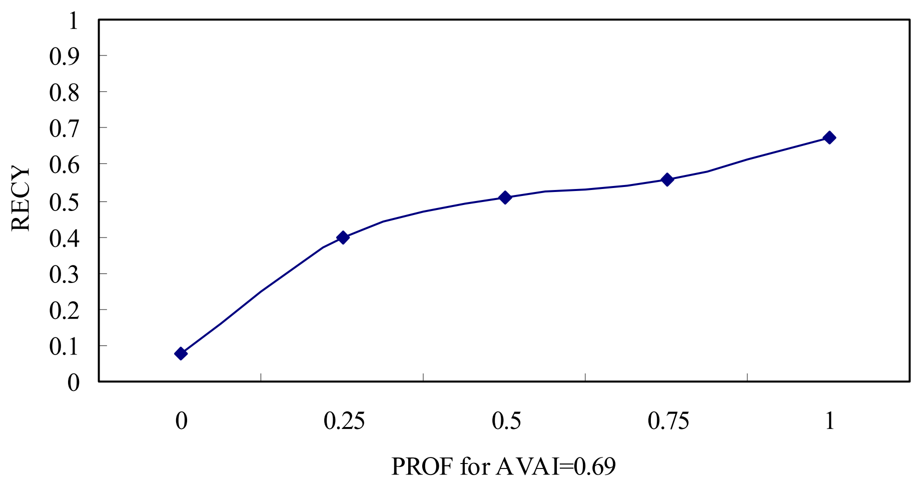
Table 4-1 Changes of RECY Related to Either Indicator of ECON

AVAI	PROF	ECON	RECY
0.69	1.0	0.9	0.677
0	1.0	0	0
0.25	1.0	0.75	0.54
0.5	1.0	0.833	0.543
0.75	1.0	0.932	0.72
1.0	1.0	1.0	0.72
0.69	0	0.25	0.081
0.69	0.25	0.5	0.401
0.69	0.5	0.75	0.508
0.69	0.75	0.875	0.561
0.69	1.0	0.9	0.677

Figure 4-1 shows that AVAI influences RECY significantly during its whole domain, and both indicators of ECON affect RECY positively.



(a)



(b)

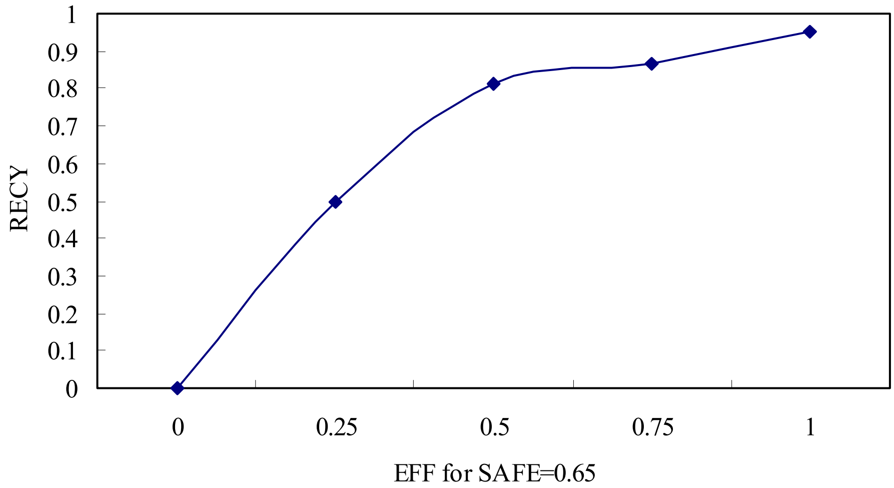
Figure 4-1 Relations between RECY and AVAI (a), PROF (b)

The following Table 4-2 presents the relations of TECH with its indicators. The corresponding curves are shown in Figures 4-2. The changing pattern of each indicator is the same as that of Table 4-1.

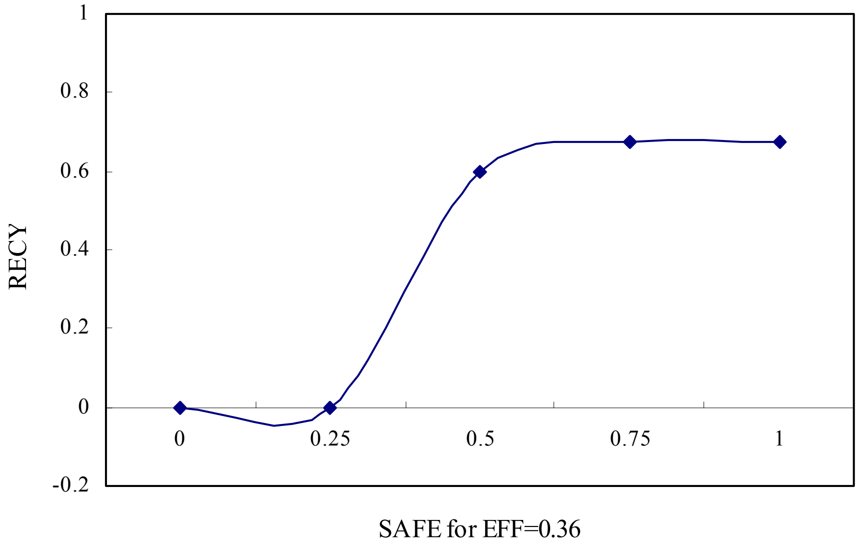
Recycling technology plays an important role in the determination of RECY. From Figure 4-2, RECY is very sensitive to changes in EFF or SAFE when their values are less than 0.5, and RECY can reach its maximum when EFF is equal to 1.0.

Table 4-2 Changes of RECY Related to either EFF or SAFE

EFF	SAFE	TECH	RECY
0.36	0.65	0.284	0.677
0	0.65	0	0
0.25	0.65	0.197	0.5
0.5	0.65	0.429	0.815
0.75	0.65	0.520	0.869
1.0	0.65	0.679	0.954
0.36	0	0	0
0.36	0.25	0	0
0.36	0.5	0.180	0.600
0.36	0.75	0.36	0.677
0.36	1.0	0.54	0.677



(a)



(b)

Figure 4-2 Relations between RECY and EFF (a), and SAFE (b)

To compute the quantitative effect of each indicator on RECY at a certain point, let ∇RE be the gradient of a tangent. Then

$$\nabla\text{RE}=\frac{\Delta RECY}{\Delta VI}=\frac{RECY_{final}-RECY_{initial}}{VI_{final}-VI_{initial}} \quad (4\text{-}9)$$

where $RECY_{final}$ is the value of RECY after changing a given indicator's value, $RECY_{initial}$ the value of RECY without change, VI_{final} the changed value of a given indicator, and $VI_{initial}$ its initial value. Initial is the value used or computed in the aluminum case such that $RECY_{initial}$ =0.6770. VI_{final} is always equal to $VI_{initial} \pm 0.01$. ∇RE is calculated in the last column of Table 4-3. It measures how much change of RECY in percentage resulted by 1% change of the corresponding indicator.

Table 4-3 Sensitivity Analysis of Recyclability for Aluminum

Indicator	$VI_{initial}$	VI_{final}	$RECY_{initial}$	$RECY_{final}$	∇RE
AVAI	0.69	0.70	0.6770	0.6818	0.48
PROF	1.0	0.99	0.6770	0.6637	1.33
EFF	0.36	0.37	0.6770	0.6930	1.6
SAFE	0.65	0.66	0.6770	0.6770	0

According to Table 4-3, RECY is sensitive to AVAI, PROF and EFF. EFF affects RECY most, thus increasing its value can improve RECY significantly. When PROF becomes less than 1.0, the recyclability for aluminum will decrease significantly. One percent decrease in PROF will result in 1.33% decrease in RECY. The other two cases can be analyzed in the same way in order to find which indicator affects recyclability most, and the results are presented in Tables 4-4 and 4-5.

Table 4-4 Sensitivity Analysis of Recyclability for Copper

Indicator	$VI_{initial}$	VI_{final}	$RECY_{initial}$	$RECY_{final}$	∇RE
AVAI	0.73	0.74	0.3732	0.3732	0
PROF	0.605	0.615	0.3732	0.3765	0.33
EFF	0.3	0.31	0.3732	0.3732	0
SAFE	0.406	0.416	0.3732	0.3817	0.85

From Table 4-4, it is known that RECY is sensitive with the change of PROF and SAFE. Increasing SAFE is effective to improve RECY because 1% increase of it can increase RECY by 0.85%. Recyclability for copper can also be improved by raising the value of PROF.

Table 4-5 shows that RECY is sensitive to AVAI, EFF, or SAFE, but AVAI influences RECY the most. We may heighten recyclability for nickel by increasing the value of AVAI or SAFE, or enhancing the level of recycling efficiency although it is already high. Because AVAI is very low, there is much space to improve recyclability for nickel.

Table 4-5 Sensitivity Analysis of Recyclability for Nickel

Indicator	$VI_{initial}$	VI_{final}	$RECY_{initial}$	$RECY_{final}$	∇RE
AVAI	0.17	0.18	0.5626	0.5717	0.91
PROF	0.761	0.771	0.5626	0.5626	0
EFF	0.95	0.96	0.5626	0.5648	0.22
SAFE	0.765	0.775	0.5626	0.5667	0.41

4.4.2 Changing the Shape of Membership Functions

We change the shapes of membership functions to observe the change of the values of RECY. Uniform shape is changed into non-uniform and vice versa. For example, the membership functions for AVAI are changed into those of EFF, and those for PROF are changed into those of AVAI, etc. Despite such changes the values of all indicators remain constant. The results are presented in Table 4-6. $RECY_{final}$ is the value of RECY after changing the shape of membership functions of a certain indicator, and $RECY_{initial}$ is equal to 0.6770 which is the value of RECY for aluminum. The last column gives the values of $\Delta RECY/RECY_{initial}$ where $\Delta RECY = RECY_{final} - RECY_{initial}$.

Table 4-6 Variation of RECY Related to the Shape of Membership Functions

Indicator in changed shape	$RECY_{initial}$	$RECY_{final}$	Rate of change in RECY
AVAI	0.6770	0.5417	-19.99%
PROF	0.6770	0.6770	0
EFF	0.6770	0.8291	22.47%
SAFE	0.6770	0.7601	12.27%
ECON	0.6770	0.6770	0
TECH	0.6770	0.6770	0
ENVI	0.6770	0.6770	0
All the above variables	0.6770	0.9237	36.44%

When the shapes of membership functions for each of four variables such as PROF are different, the values of RECY remain the same. But if the shapes for AVAI, EFF, and SAFE are changed, RECY will be affected. Their shape must be carefully chosen in order to obtain reasonable results. Some change makes RECY decrease, for example, changing the shape of membership functions for AVAI. This is the case that non-symmetrical shape is changed into symmetrical one. The shape for EFF affects the value of RECY the most. When it is changed, the value of RECY increases by 22.47%. When we change the shapes of membership functions of all the variables simultaneously (see the last row of Table 4-6), RECY is obtained as 0.9237.

5. Fuzzy Evaluation of Non-Metal Recyclability

5.1 Paper

5.1.1 Problem Description

After end-use, waste paper is recycled for production of paper and board or recovered for energy use. If recycled, the waste paper is recovered, sorted, baled and transported to paper mills to produce recycled pulp. Eventually, the collected paper is processed. If recovered for energy use, the waste paper is assumed to follow the normal waste-handling system. It then replaces oil or coal. The production value of waste paper depends on the price of fossil fuel and round timber. The higher the price of oil, the more waste paper is recovered for energy purposes.

The specific case of paper is of particular interest because of the significance of discarded paper in total waste, the complex problem of recyclability associated with it, and because of the possible contribution of the recycling of old paper to the preservation of woods, a vital factor of the ecosystem. Even though trees are renewable resources, the rapid increase in paper use in our information society, coupled with the demand for pulpwood worldwide, has created a situation in which pulp trees are used faster than they are being replaced. Waste management policy in a number of countries is characterized by a hierarchy of options in which waste minimization, reuse and recycling are all considered preferable to energy recovery (Byström and Lönnstedt, 1997). This is in turn considered superior to landfill.

Paper and paperboard account for more than 60% of all materials diverted from the municipal solid waste stream for recycling and composting. In the year 2000, 78% of recovered paper was recycled (Source: American Forest and Paper Association).

Paper is made of pulp. Pulp for paper production can be divided into two groups by its origin: virgin pulp made of log chips and logs (chemical and mechanical pulp) and secondary pulp made of old paper (Nakamura, 1999). The two groups of pulp can substitute for each other depending on the technology in use, and the quality of paper supplied and produced.

Waste paper pulping generally requires no virgin fiber inputs and saves 64 percent energy compared to pulping from virgin fiber. The average saving, however, does not include added energy costs of collection and transportation. In contrast to chemical pulping of wood from virgin sources, waste paper pulping provides no wood waste or dissolved chemicals. As a consequence, increased waste paper utilization reduces the availability of biomass energy and increases reliance on purchased energy (Byström and Lönnstedt, 2000).

Over the last decades increased use of waste paper to produce new paper made the industry to undergo significant changes in material and energy use. As paper is recycled, the length of fiber is reduced making paper weaker. Instead of piling up in a landfill, paper can be recycled seven to ten times before the fibers become too soft to hold together.

The American Forest and Paper Assn. (AF&PA) reported that the U.S. paper industry reached a paper recovery rate of 48% in 2000, up by 5.6% over 1999, representing some 49.4 million tons of recovered paper and paperboard. In 1988 when the industry first began keeping full records, the overall recovered paper rate was only 30%. According to the Confederation of European Paper Industries (CEPI), the recycling of paper in Western Europe rose during 2000. The overall recycling rate reached 49.8%, keeping the paper industry on track towards the voluntarily agreed rate of 56% by 2005. Although the report is broadly positive, CEPI notes that there are large differences among countries, and further increases will be required.

Paralleling the increase in paper recovery rates, recycling technologies have been progressively evolving during the past decade. Overall, recycling technologies have come a long way in recent years, and in most grades the business is currently booming. Synergistic, technological developments in recent years have dramatically improved recycled pulp quality and reduced overall production costs.

However, recycling of waste paper, particularly that collected from households, has in the past suffered from problems of financial viability owing to high costs of collection and sorting and low sales revenues. The situation may be changing as improvements in collection have brought down costs, while alternatives such as landfill and incineration are becoming too expensive. Increases in recycled paper prices during 1994 and 1995 made recycling schemes look particularly attractive. As prices have subsequently fallen again, it remains to be seen whether the financial viability of recycling can be sustained. The highly volatile price of recycled paper remains a complicating factor in ensuring the financial stability of collection schemes.

Paper in the household and commercial refuse system is often easily recycled. But when newspapers are thrown together with garbage, they become wet and contaminated and probably cannot economically be recycled. Furthermore, consumers still view recycled paper as “inferior” paper and choose not to buy recycled paper stock, which tends to drive production down and cost up. Policy measures to encourage recycling of waste paper are justified by environmental or social considerations not reflected in financial costs. Such policies should aim primarily to correct market failures associated with waste collection and disposal. They will be less effective at addressing failures occurring at other stages of the paper cycle.

An increase in recycling may increase the total emissions of CO_2 because of an increased need to transport waste to recycling centers. However, no net increase in CO_2 emissions results since recycling of old paper reduces the amount of waste and the total emissions of CO_2 (Nakamura, 1999).

The European Topic Center on Waste and Material Flows (ETCWMF) states that paper waste is a high volume waste with middle range environmental impact (http://waste.eionet.eu.int/activities/0000219.html). Studies show that paper recycling has substantial greenhouse gas benefits through the avoidance of land filling, because landfill results in high methane emissions associated with the decomposition of organic waste. Other benefits include water conservation, decreased energy use and process emissions, which are gained through bypassing the primary production process. Recycling reduces the risks of air and water pollution from manufacturing processes. The US EPA found that making paper from recycled materials results in 74% less air pollution and 35% less water pollution.

5.1.2 Evaluation of the Intermediate Parameters

1. Economics

Sibley et al. (1995) define the following three terms. Recycling rate is the recovered content of material in recycled waste material expressed as a percentage of apparent consumption. Recycling efficiency is the recovered content of material in recycled waste material expressed as a percentage of waste material generated (and thus potentially available for recycling). Availability is the quantity of waste material generated expressed as a percentage of apparent consumption. From their definitions, availability can be obtained by recycling rate divided by recycling efficiency. Direct data on AVAI are not available. The recycling rate is known to be 48% in US and 49.8% in Western Europe. The average value of recycling rate is then 48.9%. The recycling efficiency is 78%, thus AVAI is 0.627. It is fuzzified into H with membership grade 0.503.

From 2.3.2, the paper recycling profit is –29 euros/ton. The profitability (PROF) is computed by (2-1). When P_i=-29 euros/ton, PROF=0.181, which is fuzzified into L with membership grade 0.638 and M with membership grade 0.362.

ECON is evaluated as follows, based on the fuzzy rule base (Table 3-1) and Mamdani implication.

— If AVAI is H with grade 0.503 and PROF is L with grade 0.638 then ECON is B with grade 0.503.
— If AVAI is H with grade 0.503 and PROF is M with grade 0.362 then ECON is G with grade 0.362.

The fuzzy output of ECON is B with membership grade 0.503 and G with membership grade 0.362. By the height method of defuzzification, it is defuzzified into 0.459 when $e^{(1)}$=0.25, $e^{(2)}$=0.75, and f_1=0.503, f_2=0.362.

$$\text{ECON*}=\frac{\sum_{x=1}^{2} e^{(x)} f_x}{\sum_{x=1}^{2} f_x}=0.459 \tag{5-1}$$

2. Technology

Recycling plant workers spend day after day near conveyor belts and balers, which have caused a high percentage of the fatalities and severe injuries in the recycling industry. In the past dozen years, conveyors have been the cause of some 200 fatalities in North American, with seven of those occurring within the recycling industry. For recyclers in particular, balers are particularly dangerous. Since 1986, there have been 43 fatalities involving balers used in recycling applications. Of those, 29 have involved horizontal balers that were baling scrap paper. An additional hazard — resulting in 14 deaths in the past 12 years — involves completed bales in storage falling onto workers. Uneven stacks or heavier bales stacked on top of lighters ones can cause stacked bales to topple. Paper recyclers are particularly subject to both baler accidents and tipped bale accidents, in part because there is not the same “respect” for paper as there is for metal. Forklift drivers will drive carefully near stacked metal bales, in part because they don’t want to get cut by jagged metal or damage their vehicles.

The value of SAFE for paper can be obtained as follows. From the site www.bls.gov, we know that the highest lost time injury rate was 16.6 per 100 full-time workers in 2002. While it is reported in 2003 by Pulp and Paper Health and Safety Association (PPHSA) that average lost time injury frequency rate is 4.76 for 2002. The value of SAFE can be obtained by normalization as 0.713, and fuzzified into L with membership grade 0.049 and M with membership grade 0.926 according to Figure 3-5 (a).

Recycling efficiency is 78%, which reflects the level of technology efficiency. The crisp value of EFF is 0.78, which is fuzzified into M with membership grade 0.44 and H with membership grade 0.56.

TECH is then evaluated in the following.

— If EFF is M with grade 0.44 and SAFE is L with grade 0.049 then TECH is VB with grade 0.049.

— If EFF is M with grade 0.44 and SAFE is M with grade 0.926 then TECH is AV with grade 0.44.
— If EFF is H with grade 0.56 and SAFE is L with grade 0.049 then TECH is B with grade 0.049.
— If EFF is H with grade 0.56 and SAFE is M with grade 0.926 then TECH is G with grade 0.56.

TECH is VB with grade 0.049, B with grade 0.049, AV with grade 0.44, and G with grade 0.56. When $e^{(1)}$=0, $e^{(2)}$=0.5, $e^{(3)}$=0.25, $e^{(4)}$=0.75, and f_1= f_3=0.049, f_2=0.44, f_4=0.56, TECH is obtained by

$$\text{TECH*}=\frac{\sum_{x=1}^{4} e^{(x)} f_x}{\sum_{x=1}^{4} f_x}=0.594 \quad (5\text{-}2)$$

3. Environment

The volume of waste from paper recycling is no more than that created in mechanical pulping of roundwood (which produces bark and rejects) and much less than that from chemical pulping (which produces bark rejects, spent liquor, sludges, and requires effluent treatment). But because of the heterogeneous composition of sludges from recycled pulp, and rejects such as staples and glue, disposal is difficult. Cleaner raw materials, processes and products are still needed.

From Table 3-3, external benefit of recycling paper is 325.27 euros/ton. Using (2-2), ENVI is computed as 0.870, which is fuzzified into G with membership grade 0.52 and VG with membership grade 0.48 according to the membership functions of ENVI.

5.1.3 Evaluation of Paper Recyclability

In order to evaluate paper recyclability, we list the results of three intermediate parameters. ECON is B with membership grade 0.503 and G with membership grade 0.362; TECH is VB with grade 0.049, B with grade 0.049, AV with grade 0.44, and G with grade 0.56; ENVI is G with membership grade 0.52 and VG with membership grade 0.48.

According to the fuzzy rule base for RECY and Mamdani implication, the fuzzy evaluation of RECY is formulated as follows.

— If ECON is B with grade 0.503 and TECH is VB with grade 0.049 and ENVI is G with grade 0.52 then RECY is VL with grade 0.049.
— If ECON is B with grade 0.503 and TECH is VB with grade 0.049 and ENVI is VG with grade 0.48 then RECY is VL with grade 0.049.
— If ECON is B with grade 0.503 and TECH is B with grade 0.049 and ENVI is G with grade 0.52 then RECY is L with grade 0.049.
— If ECON is B with grade 0.503 and TECH is B with grade 0.049 and ENVI is VG with grade 0.48 then RECY is L with grade 0.049.

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For $e^{(1)}= e^{(2)}= e^{(9)}= e^{(10)}=0$, $e^{(3)}= e^{(4)}= e^{(5)}= e^{(6)}=0.25$, $e^{(7)}= e^{(8)}= e^{(11)}= e^{(12)}= e^{(13)}= e^{(14)}= e^{(16)}=0.5$, $e^{(15)}=0.75$, and $f_1= f_2= f_3= f_4= f_9= f_{10}= f_{11}= f_{12}=0.049$, $f_5= f_6=0.44$, $f_7=0.503$, $f_8=0.48$, $f_{13}=f_{14}=f_{15}=f_{16}=0.362$, the crisp value of recyclability for paper is computed by

$$\text{RECY}^*=\frac{\sum_{x=1}^{16} e^{(x)} f_x}{\sum_{x=1}^{16} f_x}=0.4319 \qquad (5\text{-}3)$$

or the recyclability of paper is 43.19%.

5.2 Plastic

5.2.1 Problem Description

Plastic is a versatile product in the modern society. Plastic can be flexible or rigid, transparent or opaque. It can look like steel, leather, wood, or silk, and can be made into toys or heart valves etc. Altogether there are more than 10,000 different kinds of plastics. The basic raw materials for plastic are petroleum and/or natural gas. These fossil fuels are sometimes combined with other elements, such as oxygen or chlorine, to make different types of plastic.

There are three disposal methods for waste plastics: landfilling, recycling and incineration. Recycling recovers the raw material, which can then be used to make new plastic products. Incineration recovers the chemical energy, which can be used to produce steam and electricity. Plastics not recycled can be converted to energy through controlled combustion. Landfilling plastics does neither of these things. The value of landfilled plastic is buried forever.

Most people view plastics as the most environmentally damaging material, both in its production and disposal, and believe that plastics are the most difficult of the materials to recycle among glass, metals, paper and plastics (McDonald and Ball, 1998). Recycling plastics has several advantages. Recycled plastics have nearly all the desirable properties of virgin plastics. Most plastics do not break down with recycling. The recycling process does not shorten the grains, strands or fibers within the material and consequently does not reduce its strength.

Recycling plastics has two stages, mechanical and chemical. Mechanical recycling refers exclusively to the reprocessing of waste material for any purposes except energy recovery or disposal, without changing the chemical structure of the processed material. Chemical recycling refers to the reprocessing, other than organic recycling, of waste material for any purposes except energy recovery or disposal, by changing the chemical structure of the processed material.

Nearly 9.5 percent by weight of trash in developed countries is plastics in numerous forms and this percentage is increasing. Containers made from recycled plastic save up to 60 percent of the energy required to make the same product from virgin material. With increased amounts of plastics being handled and a greater variety of plastics targeted for recycling, the business of collecting and processing post-consumer plastics continues to grow. New methods have been introduced for identifying certain individual plastics and efficiently separating them from other materials.

Plastics have different formulations and should be sorted before they are recycled to make new products. Mixed plastics can be recycled, but they are not as valuable as sorted plastics because the recycled plastic’s physical properties, such as strength, may vary with each batch. Commingled plastics that are not separated can be processed into mixed plastics products for a small but growing market. Additives improve the product properties, but contribute significantly to the cost.

Most plastics found in waste are packaging materials such as plastic bags and beverage bottles, which are usually contaminated. Plastic packaging offers advantages such as flexibility and lightweight. For example, the UK produces approximately 4.5 million tons of plastic waste per year and most of this waste arises from packaging. The cost of used plastic received at a processor's plant is the main contributor to the processor's total cost. Until better automatic machines are developed, the cost of manually removing extraneous matter is also significant. In addition, the cost of transporting plastics per unit weight is high and hence the profit margin of recycled plastics is usually low.

Other factors also contribute to the economic unattractiveness of recycled plastics. Virgin plastics have a relatively low cost whereas recycling requires collection, sorting, cleaning and reprocessing. Furthermore recycled plastics are not suitable in food packaging where the food comes into contact with the plastic for hygienic reasons. Mixtures of plastics require sorting into mono-polymer streams prior to recycling. Furthermore, people have not shown a willingness to clean and separate their discarded plastic. Schemes for recycling plastics are likely to be economically successful only if a consistent and reliable supply of scrap can be guaranteed. In fact, a study by the Plastics Recycling Foundation concludes that voluntary drop-off or buy-back centers will not bring in enough plastics to make nationwide recycling economically viable. In spite of these limitations, 20 percent of plastic soft drink bottles are now recycled (http://www.econlib.org/library/Enc/Recycling.html).

Because recycled plastic is more expensive than virgin plastic, people would be reluctant to buy it. Most people expect their plastic to be recycled, but they won’t pay a few extra cents to buy a bottle made of recycled plastic. Recycling plastics will not be profitable unless we create a demand for recycled plastics.

However, the business of plastics recycling holds a promise for profit opportunities although less expensive plastics economically unfit for recycling. Polyethylene (PE), polystyrene (PS), polyethylene terephthalate (PET), and HDPE (high density poly ethylene) are now being recycled in large volumes. PET is durable and useful. Soft drink and water bottles are made from this resin, as are many plastic jars and clamshell packages such as cookie containers or trays. PET is an expensive polymer, and the use of recycled PET offers bottle manufacturers economic advantages. PET bottles can be reprocessed for about $0.20 per pound less than the price of virgin PET pellets (http://pep.sric.sri.com/Public/Reports/Phase_94/RP199B/RP199B.html), while the return on investment is less than 25% for PE milk bottles or PS foam food-service containers at current prices.

Plastic recycling is still a relatively new and developing field of recycling. The plastic recycling rate is far below that of other materials and has remained at 10%. Presently, 20% of total generated plastic is recycled (http://msw.cecs.ucf.edu/recyclingefficiency.ppt).

The use of all kinds of plastics, however, has increased considerably. As an example of the growing popularity of plastics in automotive applications, an average American car contained10 percent plastic by weight in the year 2000. In other world markets, plastics account for 18 percent of the average car's weight. The percentage of plastic in a refrigerator or washing machine that was disposed of in 1980, was 16% by weight. Ten years later this had increased to 38%. Until now the recycling of plastics has been quite limited and the bulk of these plastic components were dumped as waste.

The environmental impact of plastics is at its greatest during the manufacturing process. Polyvinyl chloride (PVC) is the most polluting plastic to manufacture, while HDPE and LDPE (low density poly ethylene) are principally problematic only for their emissions of volatile organic compounds (VOCs) in manufacturing. However, the principal environmental impact of plastics is that they stay in landfills, emitting toxics to groundwater from their colorants, labels, inks, etc. When plastic waste is littered it becomes a virtually permanent part of the landscape, resisting degradation for years. Plastics deteriorate but never decompose completely. When incinerated, they produce toxic emissions of various kinds as well as toxics in their ash. Plastic waste in the marine environment poses a deadly threat to wildlife through entanglement and ingestion.

Plastics are being recovered due to environmental concerns. However, existing plastic recycling practices have significant hidden problems, including the creation of unrecyclable products. Therefore, strategies that reduce the environmental impact of plastics and lead to systematic improvements in consumption and disposal should reduce use (source reduction), reuse containers, require producers to take back resins, legislatively require recycled content, standardize labeling, and inform the public.

The low recycling rate for mixed plastic waste is largely due to the lack of a cost-effective recycling technology. Furthermore, contaminants such as paper and glue additives can potentially affect the physical properties of recycled polymers as well as their prospects for application (Cavalieri and Padella, 2002). The main drawbacks of mechanical recycling are related to the selection of waste into polymer types and to loss of properties during final reprocessing.

5.2.2 Evaluation of the Intermediate Parameters

1. Economics

Profit margin of recycling plastics is usually low because of high cost of collecting, sorting and transporting. Recycled plastic is more expensive than virgin plastic. Table 2-1 shows that plastic recycling profit is as low as –12 euros/ton. According to (2-1), PROF is obtained as 0.207 where P_i=-12 euros/ton. Thus the fuzzy value of PROF is L with membership grade 0.586 and M with membership grade 0.414.

The value of AVAI for plastics can be obtained by AVAI=recycling rate/recycling efficiency. Because the recycling rate for waste plastic is 10% and the recycling efficiency is 20%, AVAI=0.5, which is fuzzified into H with membership grade 0.333.

The fuzzy evaluation of ECON is then proceeded.

— If AVAI is H with grade 0.333 and PROF is L with grade 0.586 then ECON is B with grade 0.333.
— If AVAI is H with grade 0.333 and PROF is M with grade 0.414 then ECON is G with grade 0.333.

The fuzzy value of ECON is B with membership grade 0.333 and G with membership grade 0.333. For $e^{(1)}$=0.25, $e^{(2)}$=0.75, and f_1=0.333, f_2=0.333, the crisp value for ECON is

$$\text{ECON*}= \frac{\sum_{x=1}^{2} e^{(x)} f_x}{\sum_{x=1}^{2} f_x} = 0.5 \qquad (5\text{-}4)$$

2. Technology

Plastics have different formulations and each batch of plastics is of different physical properties, which make recycling technology complex. Beyond this, plastic recycling is still a relatively new and developing technology which is not necessarily cost effective. The present recycling efficiency for waste plastic is 20%, thus EFF is equal to 0.2 which is fuzzified into L with membership grade 0.6 and M with membership grade 0.4.

Plastics plants as a group appear to be run less safely than the average factory. Nationwide data from the U.S. Bureau of Labor Statistics (BLS) show that injury rate for plastics products is 9.1 per 100 full-time workers in 2002. The value of SAFE is normalized as 0.452, and fuzzified into L with grade 0.397 and M with grade 0.404. TECH is computed in the following.

- If EFF is L with grade 0.6 and SAFE is L with grade 0.397 then TECH is VB with grade 0.397.
- If EFF is L with grade 0.6 and SAFE is M with grade 0.404 then TECH is VB with grade 0.404.
- If EFF is M with grade 0.4 and SAFE is L with grade 0.397 then TECH is VB with grade 0.397.
- If EFF is M with grade 0.4 and SAFE is M with grade 0.404 then TECH is AV with grade 0.4.

The fuzzy value of TECH is VB with membership grade 0.404 and AV with membership grade 0.4. When $e^{(1)}= e^{(2)} =e^{(3)} =0$, $e^{(4)}=0.5$, and $f_1= f_3=0.397$, $f_2=0.404$, $f_4=0.4$, the crisp value for TECH is

$$\text{TECH*}=\frac{\sum_{x=1}^{4} e^{(x)} f_x}{\sum_{x=1}^{4} f_x}=0.125 \qquad (5\text{-}5)$$

3. Environment

A plastic is thought to be one of the most environmentally damaging materials, both in its production and disposal. From Table 3-3, external benefits for HDPE, PET and

PVC are –2.57euros/ton, -7.28 and –4.10 euros/ton, respectively. External benefits for plastic should take an average. Therefore, EB for plastic=-6.69 euros/ton, and ENVI is obtained as 1.0 by (2-2). It is fuzzified into VG with membership grade 1.0, which implies that recycling is not the environmentally optimal solution for plastics. However, emissions data are particularly scarce for the manufacture of products using secondary polymers and this hinders the search for a conclusive answer on the issue of plastics recycling (Craighill and Powell, 1996).

5.2.3 Evaluation of Plastic Recyclability

We have obtained values for all the components of RECY. Its computation follows the steps:

— If ECON is B with grade 0.333 and TECH is VB with grade 0.404 and ENVI is VG with grade 1.0 then RECY is VL with grade 0.333.

— If ECON is B with grade 0.333 and TECH is AV with grade 0.4 and ENVI is VG with grade 1.0 then RECY is L with grade 0.333.

— If ECON is G with grade 0.333 and TECH is VB with grade 0.404 and ENVI is VG with grade 1.0 then RECY is VL with grade 0.333.

— If ECON is G with grade 0.333 and TECH is AV with grade 0.4 and ENVI is VG with grade 1.0 then RECY is AV with grade 0.333.

Here $e^{(1)}= e^{(3)}=0$, $e^{(2)}=0.25$, $e^{(4)}=0.5$, and $f_1=f_2=f_3=f_4=0.333$ and, therefore

$$\text{RECY*}=\frac{\sum_{x=1}^{4} e^{(x)} f_x}{\sum_{x=1}^{4} f_x}=0.1875 \qquad (5\text{-}6)$$

Recyclability for plastic is 18.75%.

5.3 Glass

5.3.1 Problem Description

Glass is one of the most ancient and useful materials known to human societies. Nowadays glass is rather cheap and taken for granted as a packaging material. Glass containers are widely used to package a huge array of foods and drinks. Glass makes up about 8% of American municipal household waste by weight. According to the Glass Packaging Institute, each glass container produced in the United States contains on average, 30% recycled glass (http://www.green-networld.com/tips/glass.htm). About 75% of America's glass is used for packaging. In the UK, glass packaging makes up about 9% by weight of the average household waste but accounts for over 70% by weight of packaging recycled from the total household waste stream. New glass made from reclaimed scrap glass saves energy and raw materials.

Being non-metallic and inorganic, glass can be neither incinerated nor decomposed microbially (Su and Chen, 2002), thus recycling is the only possible solution for waste glass. Glass recycling cuts waste disposal costs, which are likely to rise due to landfill taxes. Recycling also saves about 32% of the energy needed to produce glass. Glass has a low melting point and energy use becomes more efficient as recycled batches become larger. Every glass bottle and jar can be crushed, melted and molded into a new container over and over again, making glass 100% recyclable. There are no waste by-products.

Conventional glass is brittle, easily broken by a small impact. This physical property has been used to crush waste glass to form desirable particles for mixing purposes. When waste glass is taken to a manufacturing or recycling plant, it is broken up into small pieces called cullet. The broken pieces are crushed, sorted, cleaned, and prepared to be mixed with other raw materials. New glass bottles may be made with up to 100% cullet. However, the actual percentage depends on the quality and quantity of cullet available.

Modern bottle manufacturing requires very clean and uniform feedstock. Jars, bottles, and other containers are some of the everyday objects made from glass that can be recycled. They are sorted manually by color at recycling depots into clear, amber and green glass. Containers of different colors are taken to a plant to upgrade the quality of the waste glass before reprocessing.

Not all glass is recyclable. Glass found in light bulbs, cookware, mirrors, crystal, and windowpanes contains ceramics. This type of glass is not recyclable because doing so would introduce impurities into the recycling process. Even for recyclable glass, much is not recycled. According to the Earthworks Group, about 28 billion bottles and jars are thrown away every year. The glass recycling rate in the U.S. has grown from 22% in 1988 to 38% in 1996 (http://www.illinoisrecycles.org/html/mfact.php). In 2000, the European average recycling efficiency of glass containers was 55%, with some countries recycling over 90% (http://www.wasteonline.org.uk/).

Glass has the least volatile pricing of all the post consumer recycling commodities. Bottle glass is made from readily available and inexpensive raw materials such as sand and potash. To be competitive, recycled glass must maintain a price that competes with these abundant raw materials. The price depends on the cleanliness and color of the recycled product. Clean flint cullet is usually the most desirable form of recycled glass scrap. Mixed color broken glass with ceramics or stones mixed in it is the least desirable grade of cullet bringing the lowest price. Most recyclers will color, sort out, break or crush, and screen bottles before selling their product.

Glass may be collected at the curb or at central collection centers and brought to the recycling center for processing. Because of collection and transportation costs, it has become widely recognized that glass recycling, like any other recycling, can't be offered as a free service. For recycling to be a sustainable operation, there has to be money set aside for the collection and recycling of glass and other recyclables.

Glass recycling is in a state of change. Many recycling operations are processing glass at a loss or very small income (http://www.andelaproducts.com/glasspro.html). However, it is possible to realize positive revenue by improving the technology. The basic difficulty in making glass recycling profitable is that glass itself does not have a high value as a material. The value of the materials from which glass is made represents only a small fraction of the value of a finished glass product (approximately 10 to 20 percent, and this percentage falls as the product becomes more complex). The cost of an item made of glass is determined largely by the complexity of processing that the item requires and by the volume of production.

Glass is nontoxic: discharging it to the environment poses no risk, save from cuts. For recycling of glass to be a sensible environmental policy, the energy, equipment, and labor associated with collection, separation, and recycling of glass should be smaller than the energy, equipment, and labor associated with producing the new glass.

Glass produced from recycled glass instead of raw materials reduces related air pollution by 20% and water pollution by 50% (http://www.reachoutmichigan.org/). We save over a ton of resources for every ton of glass recycled, i.e. 0.665 ton of sand, 0.216 ton of soda ash, 0.216 ton of limestone, and 0.075 ton of feldspar. Furthermore, a ton of glass produced from raw materials creates 0.192 ton of mining waste, which can be cut by about 75% using 50% recycled glass (http://www.green-networld.com/tips/glass.htm).

5.3.2 Evaluation of the Intermediate Parameters

1. Economics

From 2.3.2, recycling profit of glass is –24 euros/ton. Using (2-1), PROF is computed as 0.188 where P_i=-24 euros/ton. It is fuzzified into L with membership grade 0.624 and M with membership grade 0.376.

The recycling rate is 38% and the recycling efficiency is 55%; then AVAI is 38%/55%=0.691, which is fuzzified into H with membership grade 0.588. ECON is assessed as follows.

— If AVAI is H with grade 0.588 and PROF is L with grade 0.624 then ECON is B with grade 0.588.
— If AVAI is H with grade 0.588 and PROF is M with grade 0.376 then ECON is G with grade 0.376.

The fuzzy value of ECON is B with membership grade 0.588 and G with membership grade 0.376. For $e^{(1)}$=0.25, $e^{(2)}$=0.75, and f_1=0.588, f_2=0.376, ECON is

$$\text{ECON*}=\frac{\sum_{x=1}^{2} e^{(x)} f_x}{\sum_{x=1}^{2} f_x}=0.445 \qquad (5\text{-}7)$$

2. Technology

The recycling efficiency of glass is estimated at 55%, thus EFF is 0.55. The fuzzy value of EFF is M with membership grade 0.9 and H with membership grade 0.1 by fuzzification.

Based on the report published in the site of www.bls.gov, the injury rate for glass is 8.65 per 100 full-time workers in 2002. Comparing with the highest injury rate in 2002 which is 16.6, we get the normalized value of SAFE for glass is 0.479. Its fuzzified value is L with membership grade 0.361 and M with membership grade 0.458 according to the membership functions for SAFE. TECH is then formulated.

— If EFF is M with grade 0.9 and SAFE is L with grade 0.361 then TECH is VB with grade 0.361.
— If EFF is M with grade 0.9 and SAFE is M with grade 0.458 then TECH is AV with grade 0.458.
— If EFF is H with grade 0.1 and SAFE is L with grade 0.361 then TECH is B with grade 0.1.
— If EFF is H with grade 0.1 and SAFE is M with grade 0.458 then TECH is G with grade 0.1.

The fuzzy value of TECH is VB with membership grade 0.361, B with membership grade 0.1, AV with membership grade 0.458, and G with membership grade 0.1. For $e^{(1)}=0$, $e^{(2)}=0.5$, $e^{(3)}=0.25$, $e^{(4)}=0.75$, and $f_1=0.361$, $f_2=0.458$, $f_3=f_4=0.1$, the crisp value for TECH is

$$\text{TECH*}=\frac{\sum_{x=1}^{4} e^{(x)} f_x}{\sum_{x=1}^{4} f_x}=0.323 \tag{5-8}$$

3. Environment

We know that external benefit is 269.91 euros for recycling one ton of glass (see Table 3-3). ENVI is thus obtained as 0.891 by (2-2). It is fuzzified into G with membership grade 0.436 and VG with membership grade 0.564.

5.3.3 Evaluation of Glass Recyclability

We now proceed with the computation of RECY.

— If ECON is B with grade 0.588 and TECH is VB with grade 0.361 and ENVI is G with grade 0.436 then RECY is VL with grade 0.361.
— If ECON is B with grade 0.588 and TECH is VB with grade 0.361 and ENVI is VG with grade 0.564 then RECY is VL with grade 0.361.
— If ECON is B with grade 0.588 and TECH is B with grade 0.1 and ENVI is G with grade 0.436 then RECY is L with grade 0.1.

……

— If ECON is G with grade 0.376 and TECH is G with grade 0.1 and ENVI is VG with grade 0.564 then RECY is AV with grade 0.1.

Thus for $e^{(1)}= e^{(2)} = e^{(9)} = e^{(10)}=0$, $e^{(3)}= e^{(4)}= e^{(5)}= e^{(6)}=0.25$, $e^{(7)}= e^{(8)}= e^{(11)}= e^{(12)}= e^{(13)}= e^{(14)}= e^{(16)}=0.5$, $e^{(15)}=0.75$, and $f_1= f_2= f_9= f_{10}=0.361$, $f_3= f_4= f_7= f_8= f_{11}= f_{12}= f_{15}= f_{16}=0.1$, $f_5=0.436$, $f_6=0.458$, $f_{13}= f_{14}=0.376$,

$$\text{RECY*}=\frac{\sum_{x=1}^{16} e^{(x)} f_x}{\sum_{x=1}^{16} f_x}=0.2505 \tag{5-9}$$

or recyclability for glass is 25.05%.

5.4 Sensitivity Analysis of RECY

Recyclability for three non-metal materials is evaluated using fuzzy logic. Generally, recyclability of non-metals is lower than that of metals. Most recyclability components for metals are better than those of nonmetals.

The effect on the overall results, of small changes in the data, can be further investigated by using sensitivity analysis. Sensitivity analysis is similar to that in section 4.4. Here, we only compute the value of ∇RE to see how much each indicator influences RECY and find which indicator affects RECY most. Tables 5-1, 5-2, and 5-3 show the results. The variables used in the Tables are defined in section 4.4.1. Again, $VI_{final} = VI_{initial} \pm 0.01$.

Table 5-1 shows that RECY is sensitive to all the indicators. Improving any indicator can raise recyclability for paper. Recyclability for paper is 43.19% which is not very high because ECON is low, although TECH is higher. Recyclability has room for improvement since AVAI, PROF, EFF, and SAFE can be further improved.

The profitability of paper recycling is low because of high costs of collection and sorting and low sales revenues. The highly volatile price of waste paper is a factor disturbing the financial stability of collection schemes. Furthermore, consumers tend to avoid buying recycled paper, which drives production down and cost up, making recycled paper a cost prohibitive item. The public's understanding of the importance of recycling would drive the cost of collection and sorting down and improve the overall economics of recycling. Although profitability is low, most governments encourage paper recycling because of environmental and ecological considerations.

Table 5-1 Sensitivity Analysis of Recyclability for Paper

Indicator	$VI_{initial}$	VI_{final}	$RECY_{initial}$	$RECY_{final}$	∇RE
AVAI	0.627	0.637	0.4319	0.4322	0.03
PROF	0.181	0.191	0.4319	0.4347	0.28
EFF	0.78	0.79	0.4319	0.4339	0.2
SAFE	0.713	0.723	0.4319	0.4390	0.71

From Table 5-2, we see that RECY is only sensitive to the indicator SAFE, and 1% change in SAFE will result in 1.4% change in RECY. Increasing SAFE is the most effective way to improve RECY for plastic, thus SAFE is a decisive indicator among all the indicators of RECY for plastic. The values of EFF and SAFE are too low because the plastic recycling technology is complex and relatively new. It is hoped that the recycling technology for plastic will be improved in the future.

Waste plastic takes a small proportion of waste by weight and mixed plastics are of low value, which provide no incentive to recycle. Little change of any indicator will not change the value of RECY at the current recycling level. Recycling plastic will be economically successful only if a consistent and reliable supply of waste plastic can be guaranteed. Recyclability for plastic is 18.75%, which shows that plastic is the most difficult material to be recycled.

Table 5-2 Sensitivity Analysis of Recyclability for Plastic

Indicator	$VI_{initial}$	VI_{final}	$RECY_{initial}$	$RECY_{final}$	∇RE
AVAI	0.5	0.51	0.1875	0.1875	0
PROF	0.207	0.217	0.1875	0.1875	0
EFF	0.2	0.21	0.1875	0.1875	0
SAFE	0.452	0.462	0.1875	0.1875	0

From Table 5-3, it is shown that RECY is only insensitive to the indicator AVAI, which means that RECY does not change with a little change in AVAI. The value of RECY is as low as 25.05%. However, it can be improved by many ways, such as increasing PROF, EFF or SAFE.

Table 5-3 Sensitivity Analysis of Recyclability for Glass

Indicator	$VI_{initial}$	VI_{final}	$RECY_{initial}$	$RECY_{final}$	∇RE
AVAI	0.691	0.701	0.2505	0.2505	0
PROF	0.188	0.198	0.2505	0.2531	0.26
EFF	0.55	0.56	0.2505	0.2591	0.86
SAFE	0.479	0.489	0.2505	0.2539	0.34

Physics of waste glass plays an important role in improving its recyclability. It can be increased by regulations and collecting effectively. The economics of glass recycling is low because its profitability is also low and not all glass is recyclable. The level of recycling technology is low, thus there is still room for improvement.

A long term recyclability improvement can be reached in several ways. Sound marketing for recycled products has to be developed and appropriate recycling technologies should be judiciously selected. Local and national governments ought to support recycling. Proper container size may reduce worker numbers. Also on-route compaction, optimal location of recycling centers, and development of innovative products improve recyclability. Public education through different media may improve participation of citizens as well as the quality of waste put out for collection. Finally, compulsory recycling would be essential in many developing countries.

6. Conclusions

6.1 Summary

The term of recyclability is not new, but is not well defined due to its complexity. This dissertation provides a formal definition of material recyclability and introduces a new method to evaluate it using fuzzy logic. It is a general approach that can be applied to evaluate the recyclability of any kind of material. The necessary expertise is represented via fuzzy logic terminology, which allows for human-like knowledge representation and reasoning. Overall recyclability is computed based on three intermediate linguistic variables. The value of recyclability can serve as a property of the material and as such can be considered in the material selection process. Such a framework can be used to provide directions to increase the efficiency of waste utilization and provide information for the consideration of resource and environmental policy initiatives.

First, we explain why the fuzzy evaluation of material recyclability is important. Definitions and arguments are provided. This part is the theoretical basis of the dissertation. Second, we give short reviews concerning material recycling, material recyclability and fuzzy logic, which form the technical basis of the dissertation. A definition of recyclability is then presented, which synthesizes several influencing aspects. They are summarized as three intermediate parameters, which are then defined and analyzed. All the indicators of each intermediate parameter are also selected and examined in detail.

Based on the previous analyses, we devise a framework for evaluating material recyclability. The overal recyclability of a material depends on three factors: economics, technology, and the environment. Environmental factors are taken into account by using the method of life cycle assessment (LCA). Economics and technology as well as the overal recyclability are derived using basic indicators, fuzzy rule bases, and fuzzy inference.

The recyclability of three metals and three non-metals is computed and the fuzzy evaluation is illustrated in detail. These case studies show that fuzzy logic can treat non-fuzzy and fuzzy variables simultaneously within one model. Recyclability for non-metals is generally lower than that for metals. Metals should not be viewed as waste but rather as renewable resources that can be used again and again in new products, conserving scarce resources, saving energy and preventing pollution. Recycling is a priority over disposal.

In order to promote overall recyclability, develop strategies for recycling and optimize waste utilization, a prerequisite is the detection of critical indicators that affect the value of ECON, TECH, ENVI, and RECY. We do this by performing sensitivity analysis of RECY to various indicators.

The fuzzy method appears to be well suited to provide quantitative measurement of material recyclability. The method is adaptive in the sense that it admits new indicators depending on the system conditions and eliminates old ones if they have no effects on the results. Defining appropriate parameters, devising corresponding membership functions, collecting the relevant data, and constructing adequate fuzzy rules are indispensable steps to achieve a better assessment.

6.2 Suggestions for Future Study

The fuzzy framework for the evaluation of recyclability needs to be refined to become more practical and systematic. New ways to train and generalize fuzzy rules, especially when the rule bases are large, should be found. Neural networks and machine learning methods would be promising.

Data accuracy, confidentiality, availability and quality are common problems. Data and information are highly variable in availability and quality from one geographical region to another. Most data concern certain developed countries. In other cases, data and information are not available at all. Under such circumstances, methods have to be found to evaluate the intermediate parameters. The objective of this dissertation is to provide a general framework. However, more accurate data are needed in order to develop strategies for recycling and optimize waste utilization additional.

Utilization of existing data is a difficult task. Methods have to be devised to produce useful information from these numbers. Mining, accumulation and transformation of data are topics of future study.

In this dissertation, we only studied six materials. Many more materials are potential subjects of study. The ultimate goal is to use such studies to make decisions about recycling that will be beneficial to people and the environment.

Appendix

Table A-1 A Rule Base for RECY

Number	Fuzzy Inputs			Fuzzy Output
	ECON	TECH	ENVI	RECY
1	VG	VG	VG	H
2	VG	VG	G	H
3	VG	VG	AV	VH
4	VG	VG	B	VH
5	VG	VG	VB	VH
6	VG	G	VG	H
7	VG	G	G	H
8	VG	G	AV	H
9	VG	G	B	VH
10	VG	G	VB	VH
11	VG	AV	VG	AV
12	VG	AV	G	H
13	VG	AV	AV	H
14	VG	AV	B	H
15	VG	AV	VB	VH
16	VG	B	VG	AV
17	VG	B	G	AV
18	VG	B	AV	H
19	VG	B	B	H
20	VG	B	VB	H
21	VG	VB	VG	VL
22	VG	VB	G	VL

23	VG	VB	AV	VL
24	VG	VB	B	VL
25	VG	VB	VB	VL
26	G	VG	VG	H
27	G	VG	G	H
28	G	VG	AV	H
29	G	VG	B	VH
30	G	VG	VB	VH
31	G	G	VG	AV
32	G	G	G	H
33	G	G	AV	H
34	G	G	B	H
35	G	G	VB	VH
36	G	AV	VG	AV
37	G	AV	G	AV
38	G	AV	AV	H
39	G	AV	B	H
40	G	AV	VB	H
41	G	B	VG	AV
42	G	B	G	AV
43	G	B	AV	AV
44	G	B	B	H
45	G	B	VB	H
46	G	VB	VG	VL
47	G	VB	G	VL
48	G	VB	AV	VL
49	G	VB	B	VL
50	G	VB	VB	VL
51	AV	VG	VG	AV
52	AV	VG	G	H
53	AV	VG	AV	H
54	AV	VG	B	H
55	AV	VG	VB	VH
56	AV	G	VG	AV
57	AV	G	G	AV
58	AV	G	AV	H
59	AV	G	B	H
60	AV	G	VB	H
61	AV	AV	VG	AV
62	AV	AV	G	AV
63	AV	AV	AV	AV
64	AV	AV	B	H
65	AV	AV	VB	H
66	AV	B	VG	L
67	AV	B	G	AV
68	AV	B	AV	AV
69	AV	B	B	AV

70	AV	B	VB	H
71	AV	VB	VG	VL
72	AV	VB	G	VL
73	AV	VB	AV	VL
74	AV	VB	B	VL
75	AV	VB	VB	VL
76	B	VG	VG	AV
77	B	VG	G	AV
78	B	VG	AV	H
79	B	VG	B	H
80	B	VG	VB	H
81	B	G	VG	AV
82	B	G	G	AV
83	B	G	AV	AV
84	B	G	B	H
85	B	G	VB	H
86	B	AV	VG	L
87	B	AV	G	L
88	B	AV	AV	AV
89	B	AV	B	AV
90	B	AV	VB	AV
91	B	B	VG	L
92	B	B	G	L
93	B	B	AV	L
94	B	B	B	AV
95	B	B	VB	AV
96	B	VB	VG	VL
97	B	VB	G	VL
98	B	VB	AV	VL
99	B	VB	B	VL
100	B	VB	VB	VL
101	VB	VG	VG	VL
102	VB	VG	G	VL
103	VB	VG	AV	VL
104	VB	VG	B	VL
105	VB	VG	VB	VL
106	VB	G	VG	VL
107	VB	G	G	VL
108	VB	G	AV	VL
109	VB	G	B	VL
110	VB	G	VB	VL
111	VB	AV	VG	VL
112	VB	AV	G	VL
113	VB	AV	AV	VL
114	VB	AV	B	VL
115	VB	AV	VB	VL
116	VB	B	VG	VL

117	VB	B	G	VL
118	VB	B	AV	VL
119	VB	B	B	VL
120	VB	B	VB	VL
121	VB	VB	VG	VL
122	VB	VB	G	VL
123	VB	VB	AV	VL
124	VB	VB	B	VL
125	VB	VB	VB	VL

Table A-2 US Old Scrap Metals Recycling Performance, 1993, in percent

Commodity	Efficiency[1]	Availability[2]	Recycling rate
Aluminum	36	69	25
Copper	30	73	22
Nickel	95	17	16

Source: Sibley et al. (1995)

[1]Defined as old scrap consumed divided by old scrap generated plus net imports, or minus net exports.

[2]Defined as old scrap generated plus net imports, or minus net exports, divided by apparent consumption.

Table A-3 Statewide Composition Results (2000)

Material	Percent
Total plastics	9.70%
Rigid plastic containers	1.51%
Rigid packaging	0.91%
Rigid plastic products	1.74%
Plastic film packaging	2.8%
Plastic film products	1.51%
Mixed plastic	1.21%

Source: http://www.deq.state.or.us/wmc/solwaste/wcrep/wcrep2000table1.htm

Table A-4 Data and Results in the Case Studies

Variables		Metals			Nonmetals		
		Case 1: Aluminum	Case 2: Copper	Case 3: Nickel	Case 4: Paper	Case 5: Plastic	Case 6 Glass
Indicators	AVAI	0.69	0.73	0.17	0.627	0.5	0.691
	PROF	1.0	0.605	0.761	0.181	0.207	0.188
Intermediate Parameter 1	ECON	0.9	0.812	0.384	0.459	0.5	0.445
Indicators	EFF	0.36	0.3	0.95	0.78	0.2	0.55
	SAFE	0.65	0.406	0.765	0.713	0.452	0.479
Intermediate Parameter 2	TECH	0.369	0.105	0.741	0.594	0.125	0.323
Intermediate Parameter 3	ENVI	0	0.0191	0.228	0.870	1.0	0.891
Final Output	RECY	0.6770	0.3732	0.5626	0.4319	0.1875	0.2505

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