中國環境工程學刊 第十卷 第四期 (民國八十九年)
Journal of the Chinese Institute of Environmental Engineering, Vol. 10, No. 4, pp. 323-335 (2000)

A PRELIMINARY COMPARISON AND INTEGRATION OF LIFECYCLE IMPACT ASSESSMENT MODELS

Yuh-Ming Lee* and Jimmy C.-M. Shan

Institute of Natural Resource Management
National Taipei University
Taipei, Taiwan, R.O.C.

Key Words : Lifecycle impact assessment, streamlines inventory analysis, fuzzy analytical hierarchy process

ABSTRACT

According to the framework outlined in ISO-14040, a complete practice of lifecycle assessment consists commonly of four phases: goal and scope definition, inventory analysis, impact assessment, and interpretation. This study intends to compare and then integrate the methods and computer models for lifecycle impact assessment. Methods such as critical volume, effect-oriented assessment, and eco-points are reviewed. Three commercial software packages: Eco-Pro, SimaPro, and GaBi are implemented for impact assessment. A set of production data of corrugated paperboard is collected and used for inventory analysis. The set of data will also be incorporated as the inputs into the above three models for comparison. The content of the paper, therefore, includes the lifecycle assessment framework, a comparison of the computer models, an integrated impact assessment procedure, and a case study. In the proposed application framework, we apply fuzzy analytical hierarchy process (FAHP) to the valuation of lifecycle impact. Lifecycle stages of material acquisition, transportation, production, and disposal are considered in the case study. The relative ranking of environmental concerns from the valuation of FAHP emerges to be similar to that directly from questionnaire survey. That is, the production stage poses the most significant impacts to the environment during the lifecycle of corrugated paperboard production. Moreover, SimaPro appears to be one of the most suitable software for common purpose applications.

INTRODUCTION

Life-cycle assessment (LCA) is a technique for evaluating the environmental effects associated with any "cradle-to-grave" production activities. These activities of product life cycle can range from the initial gathering of raw material from the earth until the point at which all residuals are returned to the earth. According to the ISO 14040 standard (International Organization for Standardization [1]), life cycle assessment shall include phases of goal and scope definition, inventory analysis (LCI), impact assessment (LCIA), and interpretation of results. The phases and applications of ISO 14040: Environmental Management - Life Cycle Assessment can be further illustrated as Fig. 1. The goal definition stage defines the purpose, scope, and boundaries of the study, the functional unit, key assumption to be made and likely limitation of the work [2]. The inventory analysis constitutes a detailed compilation of all of the environmental inputs and outputs to each stage of the life cycle. Usually, the inventory includes raw material and energy consumed, emissions to air and water, and solid waste produced. Life cycle impact assessment is a process whereby environmental impacts from the inventory are assessed, and generally the overall environmental performance of the product is determined [3]. Impact assessment commonly incorporates three stages: classification, characterization and weighting [4]. The last component of an LCA is to find the ways to improve or to redesign the production processes, or to reduce the costs and the materials used. Several relevant aspects, such as environmental, financial, convenience, and safety, are usually incorporated for improvement assessment or interpretation [5]. Generally speaking, life-cycle assessment's characteristics that provide its important advantages are the following [6]:

* To whom all correspondence should be addressed.

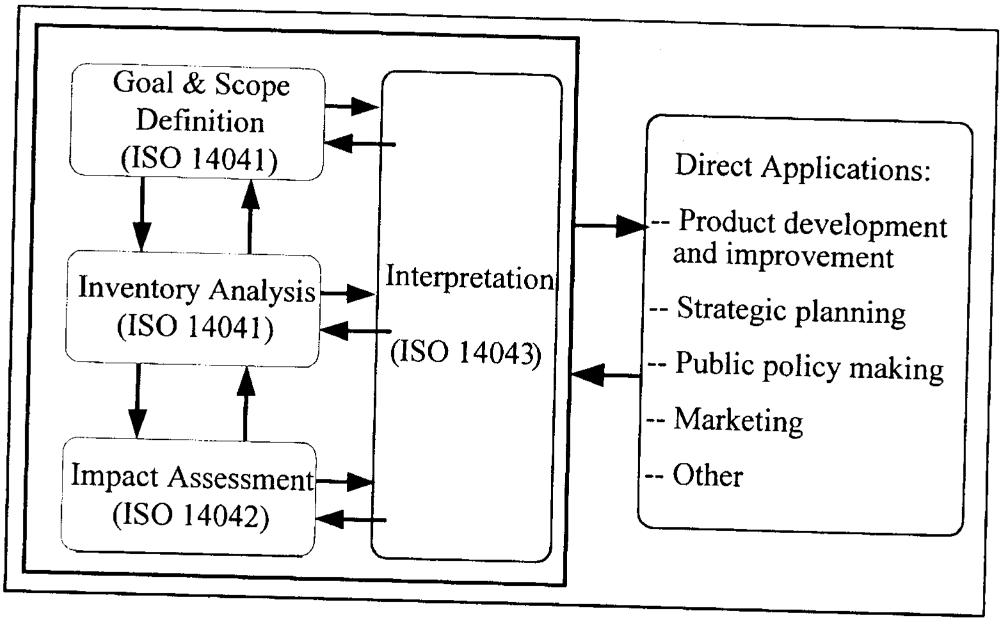

Fig. 1. Phases of a life cycle assessment and its applications.

- a system-wide or "cradle-to-grave" perspective, implying coverage of the multiple operations and activities throughout a life cycle,
- a multimedia perspective, implying coverage of resource use and emissions to different environmental media, *e.g.*, air, water, and soil, and
- a functional unit accounting system that normalizes energy carriers, material resources, emissions, and wastes across the system and across media after unit process allocation procedures.

The empirical practices of LCA, however, seem to be still at the stage of preliminary development. The study, thus, intends to develop an application framework on the basis of streamlined life cycle assessment. Moreover, the study focuses on the comparison and integration of life cycle impact assessment methods and computer models. The paper, in addition to the section of introduction, consists mainly of four parts. A general description of life cycle impact assessment is presented first, followed by the comparison of LCIA methods and software. The third part of this paper illustrates the application results and discussion. Some summarized remarks and suggestions conclude the paper.

LIFE CYCLE IMPACT ASSESSMENT

Life cycle impact assessment is the third phase in a life cycle assessment. According to Heijungs and Hofstetter [7], the impact assessment can be expressed as a "quantitative and/or qualitative process to characterise and assess the effects of the environmental interventions identified in the inventory table." The framework for life cycle impact assessment is, therefore, defined as [4]: "The life cycle impact assessment framework and its procedure should be transparent and provide the flexibility and practicality for this wide range of application. A large range in the levels of effort and intensity of the analysis are possible with life cycle assessment for different applications. In addition, impact assessment should be effective in terms of cost and resources used. Life cycle impact assessment is composed of several individual elements. These are category definition, classification, characterization, and weighting." The following describes the mentioned impact assessment elements individually.

1. Category Definition and Classification

Category definition is a follow-up stage of the goal and scope definition phase. Based on the information collected in the inventory phase the boundaries defined in the goal and scoping may be redefined. Numerous environmental categories have been proposed for life cycle impact assessment. In general, the selection of impact categories should consider the factors of [8]: completeness, practicality, independence, and relation to the characterization step (*i.e.*, the chosen impact categories should be related to available characterization methods). Classification is a qualitative step based on scientific analysis of relevant environmental processes. The stage has to assign the inventory input and output data to potential environmental impact categories. Three different space groups: global impacts, regional impacts and local impacts are usually used to place the impact categories further. The time aspect is also important when considering certain impact categories *e. g.*, global warming and stratospheric ozone depletion with time horizons of 20 to 500 years. The impact categories commonly considered, therefore, include (ISO preliminary list [4]):

- Local environmental concern - Land use.
- Global concerns - Depletion of abiotic and biotic resources, global warming, and stratospheric ozone depletion.
- Impact to both regional and local environment - Acidification (acidic deposition), eutrophication, and photochemical oxidant formation.
- General concerns - Human toxicological impacts and toxicity to eco-systems

2. Characterization

As stated in ISO [4], "the aim of characterization is to model categories in terms of indicators, and, if possible, to provide a basis for the aggregation of the inventory input and output within the category." Therefore, indicators representing overall changes or loading to the categories are introduced and evaluated. Each category should have a specific model for the relationship between the inventory and the indicator. In short, characterization is mainly a quantitative step based on scientific analysis of the relevant environmental processes. The characterization is to assign the relative contribution of each input/output (inventory) to the selected impact categories. The potential contribution of each input/output to the environmental impacts is estimated.

3. Valuation/Weighting

Weighting has previously been referred to as valuation. In the LCA community, the two terms are still interchangeable. ISO [4] states that "weighting aims to rank, weight, or, possible, aggregate the results of different life cycle impact assessment categories in order to arrive at the relative importance of these different results." Therefore, weighting is a qualitative or quantitative step not necessarily based on natural science but often on political or ethical values. Weighting methods have been developed by different institutions based on different principles. For example, SETAC [3] proposes methods of the decision analysis using multi-attribute utility theory, analytic hierarchy process, and impact analysis matrix approach. Lindeijer [9] further introduces the following methods: proxy approach, technology abatement approach, monetarisation, authorized goals or standards (distance to target), and authoritative panels (societal approach).

LIFECYCLE IMPACT ASSESSMENT METHODS AND MODELS

LICA, as described previously, often involves evaluation methods not necessarily based on natural science but on political or ethical values. The implementation of LCIA methodologies therefore may be obscured by the issues of "cross-media" and "subjective aggregation" [3]. In general, LCIA focuses on relative comparisons of whole systems with respect to resource use and emission loadings. All-in-one methods for LCIA still remain as a discussion topic in LCA community though an applicable framework consisting of classification, characterization, and weighting has been proposed for LCIA implementation. Lindeijer [9] compiles six assessment methodologies (of the Authorized Targets / Standards category of the weighting methods): abatement cost / the Tellus system, "molar" method, critical volume method, critical surface time method, "eco-scarcity" method, "Eco-Indicator" method, and "effect category" (or effect-oriented) method. Among them, we find that the effect-oriented method, the eco-scarcity method, and the critical volume method are the three ones commonly applied. This study therefore focuses on the discussions of the three methods. Furthermore, due to that large amounts of data have to be stored and processed, computers and hence software are the natural tools for LCA. Menke *et al.* [10] profiled 37 software tools for LCA and reviewed 5 in-depth. In the study we propose to compare the LCIA methodologies through the implementation of LCA software. With the considerations of software popularity and financial affordability, we implement EcoPro, GaBi, and SimaPro for comparison. A brief description of the implemented software packages can be found in Lee and Shan [11]. The generalized description of the mentioned LCA methodologies and a preliminary comparison of LCA software are presented as follows.

1. Methods for Life Cycle Impact Assessment

- Effect-oriented method: The assessment method is first developed by the CML (Center for Environmental Sciences), Leiden University in the Netherlands [12]. The method assesses impacts of environment concerns based on their effects on the environment (normally, including human health, ecological systems, resource depletion, and social welfare). Issues such as global warming, ozone layer depletion, acid deposition, eutrophication, formation of photochemical pollutants, toxicity to human and eco-systems, and abiotic resource depletion are the eight "effects" most considered. An "equivalence factor" should be introduced when dealing with several stressors contributing to the same effect. For example, the emission of CO_2, CH_4, and N_2O causes the effect of global warming. If the GWP (global warming potential, based on per unit of CO_2 emitted) is used to quantify their impacts, then the equivalence factors of 11 for CH_4 and 270 for N_2O should be applied to express their associated effects on global warming.

- The eco-scarcity method: The definition of eco-scarcity is frequently interchangeable with eco-point. The eco-point of a particular "flow" introduced into the environment can be defined as [13]:

$$Eco\text{-}Point = \frac{1}{F_C} \times \frac{F}{F_C} \times C \qquad (1)$$

where F_C: the critical flow which is the maximum loading at which the perspective ecosystem dose not show the adverse effect.

F: the actual flow that the environment currently undertaken.

$\frac{F}{F_C}$: Eco-scarcity, the resource is said to be over used if the current loading is greater than the critical flow ($F/F_C > 1$).

C: a dimensionless factor to avoid large negative exponent values.

Since all of the impacts are expressed as eco-points, the life cycle impact can be easily aggregated. That is, air, water, and soil emissions, resource consumption, and some non-chemical stressors (*e. g.*, radiation loadings) can be aggregated as a single life cycle index.

- The critical volume method: With some pre-defined limits or thresholds, the critical volume of the stressors in the same physical phase (usually water or air) can be defined as [13]:

$$\text{Critical Volume} = \frac{\text{Atmospheric Emsision or Waterborne Wastes}}{\text{Ambient Standards or Environmental Thresholds}} \qquad (2)$$

The assessment results expressed in volumes, similar to those from the method of eco-point, can be easily aggregated into a single index. However, the method is not suitable for the classes of landfill and energy consumption because of the lack of ambient standards.

2. Preliminary Comparison of the LCA Software

As stated above, computers and hence software are the natural tools for LCA due to large amounts of data storage and processing. For preliminary evaluation of the implemented software, the study adopts the criteria developed by Menke *et al*. [10] and Yano [14]. In general, criteria of such as, data volume and update frequency, interface, transparency, and price are commonly considered while selecting LCA software. A preliminary comparison of the three software packages (EcoPro, GaBi, and SimaPro) is thereby carried out and summarized as Table 1.

Table 1. A preliminary comparison of the implemented LCA software

Criteria	SimaPro 4.0	EcoPro 1.5	GaBi 3.0
Volume of Data	Fair	Poor	Good
Update Frequency	Fair to Good	Fair	Fair to Good
User Interface	Windows	Windows	Windows
Network Operation	Supported	N/A	N/A (Lean Ver.)
Transparency of the Assessment Procedure	Fair	Poor	Fair
Sensitivity Analysis	N/A	N/A	Supported
Inputs/Outputs Visualization	Fair	Good	Excellent
Operating Applicability	Excellent	Good	Fair
Self-Teaching Simplicity	Excellent	Excellent	Fair
Documentation	Simplified Manual	Simplified Manual	More Illustrative Manual
Approximated Price (NTD, Educational)	45,000	35,000	240,000

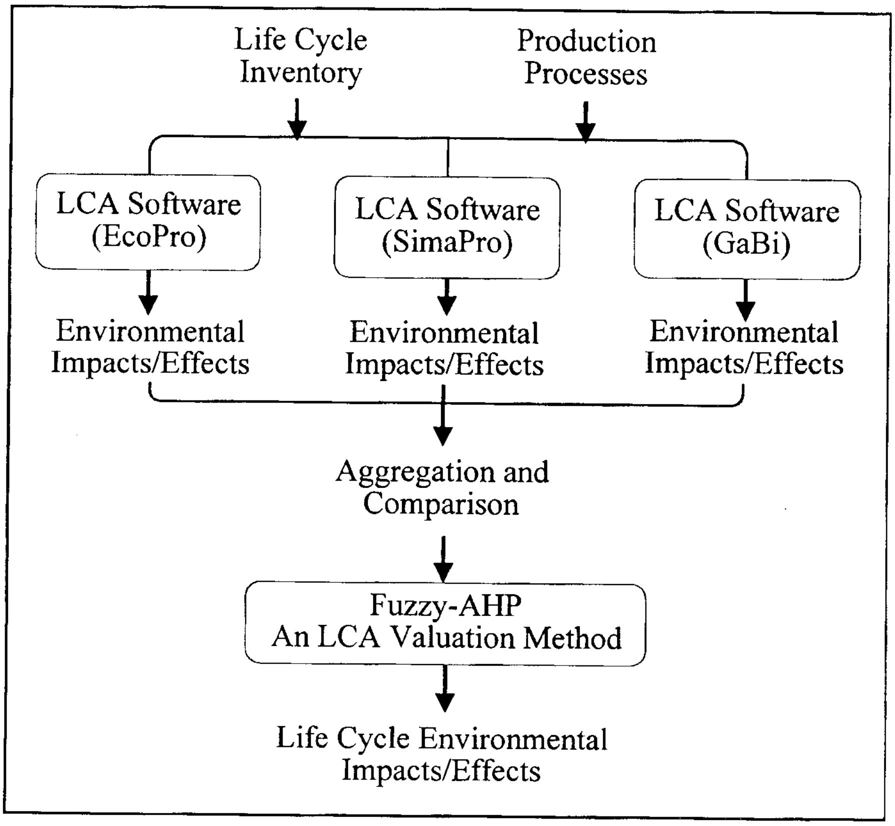

Fig. 2. The LCA framework proposed and implemented in the study.

Table 2. The production and composition of corrugated paperboard at the Ta-Yuan paper mill

Source/Identification	Component	Kraft Linerboard			Corrugating Medium		
		A-200	B_2-175	B_4-130	FP-120	R-180	SA215
Virgin Pulp	NUKP	0.22	0.22	0	0	0	0
Domestic Recycled Paper	TOCC	0.61	0.78	0.85	1.00	0.70	0.60
Imported Recycled Paper	AOCC	0.17	0	0	0	0	0
	KLB	0	0	0.15	0	0	0
	GOCC	0	0	0	0	0.30	0.40
Physical Characteristics	unit weights (g/m^2)	200	175	130	120	215	180
	shear strength (kgf/cm^2)	6.20	4.20	2.10	N/A	N/A	N/A

APPLICATIONS AND DISCUSSIONS

To fulfill the intent of comparing and integrating life cycle impact assessment methodologies, we propose and implement an LCA application framework. As shown in Fig. 2, the assessment results from the three mentioned packages are compared and aggregated firstly. The fuzzy analytical hierarchy process (FAHP) is applied at the stage of valuation. As a result, an integrated index of life cycle impacts can be obtained with a streamlined inventory data compiled from the case study. The Ta-Yuan paper mill of the Cheng-Loong Corp. provides the baseline production data for the case study. As illustrated in Table 2, the products analyzed include kraft linerboard and corrugating medium, which are the two components of corrugated paperboard. Three classes of linerboard (A-200, B_2-175, and B_4-130) and three types of medium (FP-120, R-180, and SA215) are studied. For reasons of applicability and simplicity, we "scope" the production lifecycle into four systems (or processes), namely, material acquisition, transportation, production, and waste disposal. Figure. 3 illustrates the production processes. Moreover, Table 3 summarizes the streamlined inventory data in which the production volume (in tons) in 24 hour at the mill is defined as the functional unit.

1. Life Cycle Impact Assessment - Comparison and Aggregation

For the comparison of LCIA methods, we implement the three software packages with the same streamlined inventory database (Table 3). The impact categories considered in the study and corresponding to the software used are listed as the following.

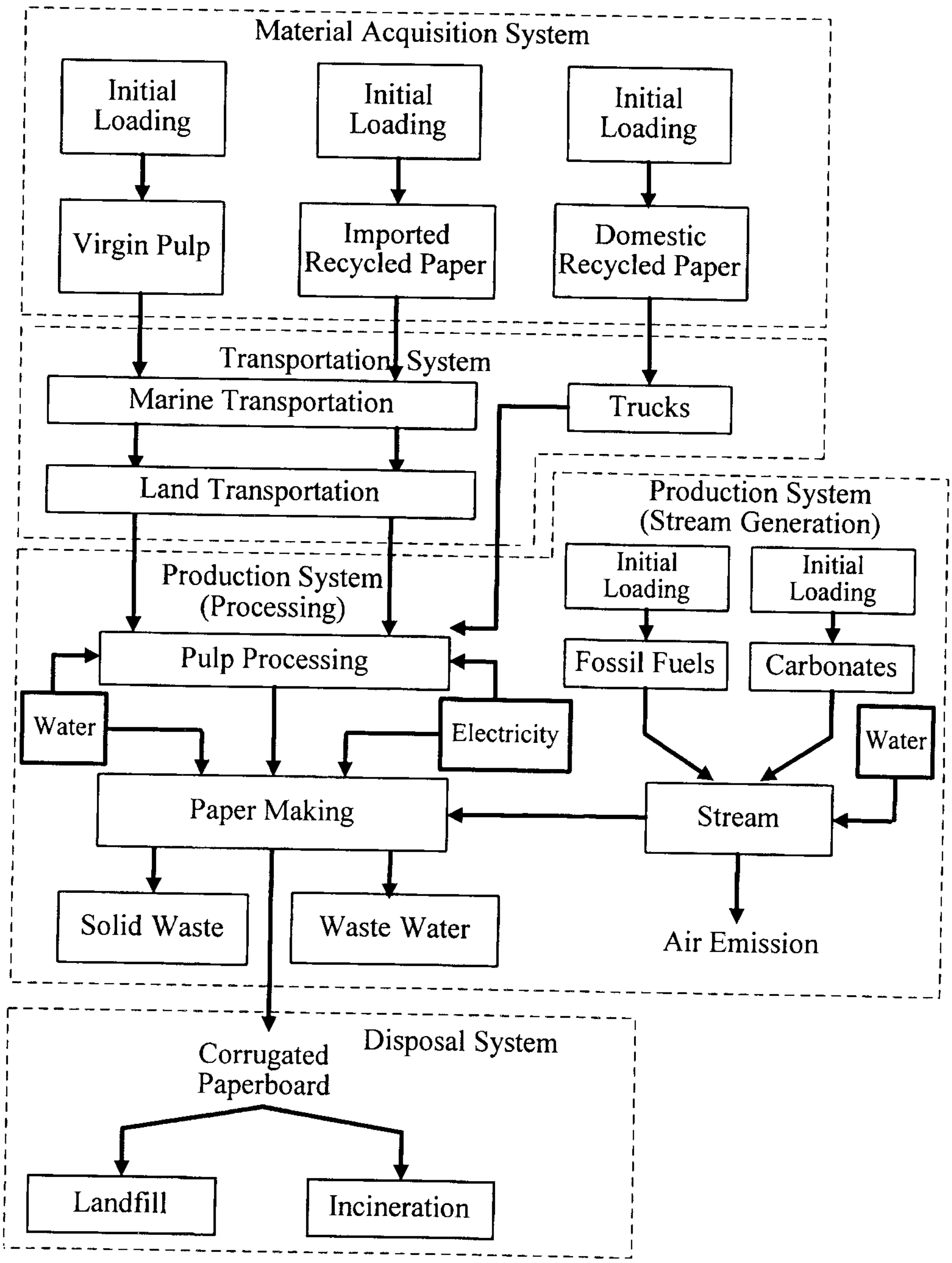

Fig. 3. Production processes and the "scoping" of the case study.

Table 3. The streamlined inventory data used in the case study

	System 1: Material Acquisition						
Material	NUKP(tons)	TOCC(tons)	AOCC(tons)	KLB(tons)	GOCC(tons)		
Quantity	5,878	27,015	2,673	911	4,306		
Product	Components of corrugated paperboard 40,783 tons						
	System 2: Transportation						
Entry	Types, distance and vehicles of transportation						
Inventory	Imported from the U.S. (Marine Cargo Vessels): 15,000 km Imported from the Canada (Marine Cargo Vessels): 16,000 km Imported from the Germany (Marine Cargo Vessels): 25,000 km Port (Keelung harbor) to the mill (Ta-Yuan) (40-ton Trailers): 60 km Total distance for domestic paper recycling (28-ton Trucks): 150 km						
	System 3-1: Production - Stream Generation						
Entry	Water(m^3)	Coal(tons)	Oil(liter)	Stream generated (tons)			
Quantity	60,990	6,650	67,000	57,000			
Output	Electricity 6,480,000 kw						
	System 3-2: Production - Paper Making						
Entry	Water (tons)	Stream (tons)	Electricity (kw)	Waste Water (m^3)	COD (ppm)	SS (ppm)	Solid Waste (tons)
Quantity	329,265	51,000	12,960,000	326,139	2,270	128	4,198
Production	Corrugated Paperboard 36,585 tons						

- EcoPro and GaBi: global warming, eutrophication, acid deposition, stratospheric ozone depletion, photochemical pollutants, eco-toxicity to both terrain and aquatic eco-systems, human toxicity, and abiotic resource depletion.
- SimaPro: global warming, eutrophication, acid deposition, stratospheric ozone depletion, heavy metals, carcinogens, winter and summer smog, and energy consumption.

Based on the same set of data input, the compassion of assessment results can be summarized as the following.

- Assessment of environmental impact indices: A general comparison of the assessment results from the application of the three packages depicts that EcoPro is the most "conservative" one. The impact indices evaluated by EcoPro are much higher than the other two. For example, the impact of greenhouse gas emission - global warming potential (GWP) assessed by EcoPro is 50 times of that evaluated by SimaPro and GaBi. Similarly, the impact index of eutrophication (NP) is 80 times higher. It may due to the attribute of the developers. EcoPro, to some extent, is developed by an environmental protection institution. The other two seem to be developed mainly for commercial uses. Furthermore, the database of SimaPro and GaBi are built principally based on BUWAL250. They also yield similar impact indices. We, thus, adopt the impact categories used in the two packages as more as possible.
- Relative ranking of environmental impacts: In the perspective of relative impact ranking, all of the three packages yield similar assessment results on global warming, acid deposition, and photochemical pollutants with the six paperboard components compared. The assessment results from EcoPro and GaBi on stratospheric ozone depletion, eutrophication, and human toxicity further depict their similarity of relative ranking of environmental concerns.

Conclusively, the assessment results from SimaPro and GaBi are relatively more applicable based on the comparison listed above. The study, therefore, aggregates the categories considered in the two packages and proposes a life cycle impact assessment hierarchy for the proceeding analyses. As illustrated in Fig. 4, the 11 categories are further classified as impacts on human health, ecosystems, and resource depletion. Moreover, lifecycle stages are also integrated into the hierarchy for the application of FAHP.

2. Valuation of Life Cycle Impacts - Fuzzy Analytical Hierarchy Process

In order to obtain an integrated life cycle impact index, the FAHP method is applied at the procedure of valuation. The FAHP, introduced by

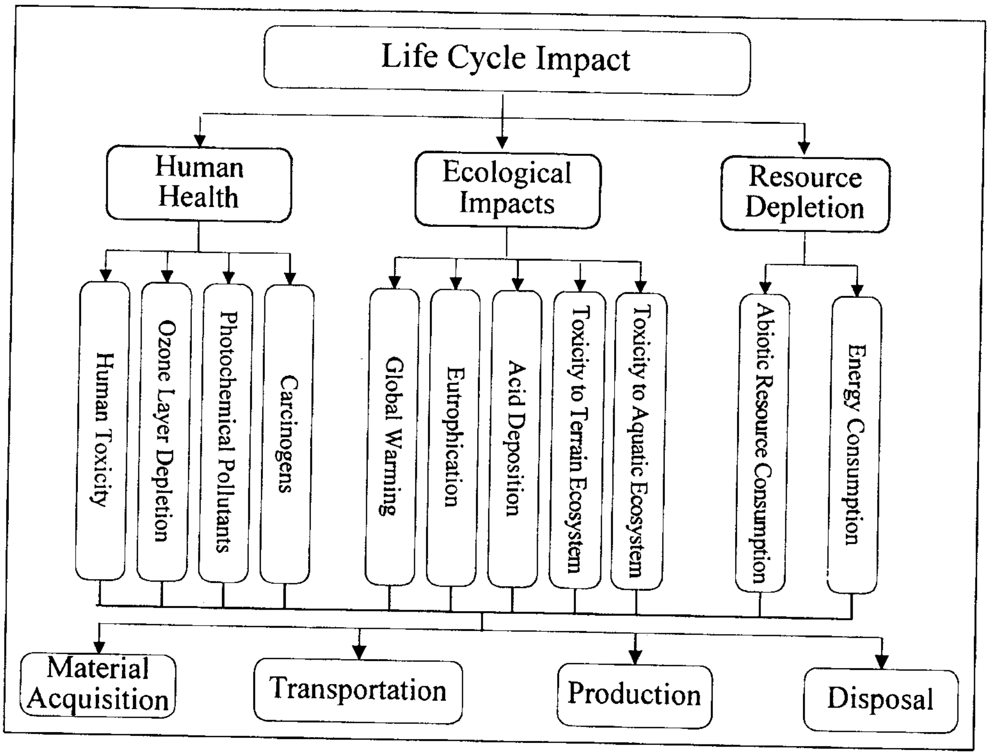

Fig. 4. Hierarchy of the environmental concerns and impacts considered in the study.

Buckley [15] and Laarhoven and Pedrycz [16], is an extension of Saaty's AHP [17] to deal with the imprecision and subjectiveness in the pairwise comparison process. The analysis procedure of the FAHP can be generally divided into five stages. Pairwise comparison matrices with fuzzy number quantifying decision-maker's preferences are constructed first. An eigenvector method is then applied to solve the reciprocal matrix for determining the criteria importance and alternative performance. Consistency indices should be defined and calculated at the third stage to avoid inconsistent (irrational) decisions. After the criteria are weighted, the overall utilities of alternatives (the fuzzy utilities) are aggregated by fuzzy arithmetic. The stage is commonly called as the defuzzification procedure. At the end, alternatives or various affecting factors in the study can be weighted and prioritized with the defuzzified (crisp) overall utilities. Fig. 5 illustrates the analysis procedure of the FAHP.

In the study the authors conduct a questionnaire survey to obtain the fuzzy weights on the 11 impact categories considered. Shan [18] describes the valuation method and the survey results in greater details. Take the production of the component of A-200 (a type of kraft linerboard) as an example. Table 4 summarizes the results of impact assessment including the values of impacts, the FAHP weights, and weighted impact scores. Table 5 lists accordingly the impact indices of every environmental concern at various lifecycle stages along with the ranking weights evaluated by the FAHP. The impacts at the production stage appear to be the most severe ones. The relative ranking of environmental concerns from FAHP emerges to be similar to that directly from questionnaire survey. In addition, the categories of human toxicity, global warming, eutrophication, acid deposition, and terrain eco-toxicity are those with higher impact scores. Similarly, the impact of abiotic resource depletion at the stage of transportation and the toxicity to terrain ecosystem when disposing wastes are the two issues with more significant effects.

SUMMARIES AND CONCLUSION

This study compares and then integrates the models for lifecycle impacts assessment. Methods such as critical volume, effect-oriented assessment, and eco-points are reviewed. Three commercialized software packages of life cycle assessment are implemented and compared on the basis of the same data. A set of streamlined production data of corrugated paperboard is collected and used

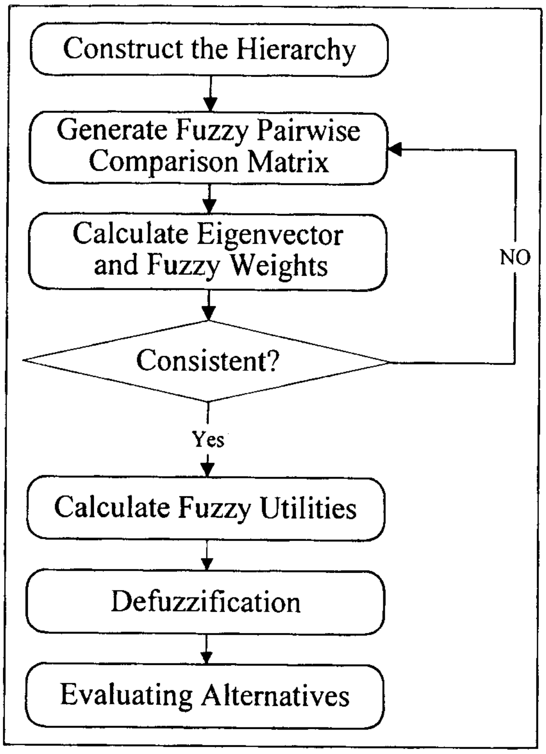

Fig.5. Analysis procedure for the fuzzy analytic hierarchy process.

as a case study. The results and discussions of the study, including a lifecycle assessment framework, a comparison of the computer models, an integrated impact assessment procedure, and a case study, can be further summarized the following.

1. With the intent of furthering the transparency of assessment process, the study compares and then integrates lifecycle impact assessment models and software packages. Among the three LCA packages compared, SimaPro appears to be the most applicable one based on its database comprehensiveness and user-friendliness. In the authors' opinion, EcoPro may be more suitable for educational or demonstrative purposes. The GaBi software, with emphases on process design, seems to be more professional oriented. Furthermore, one of the critiques on LCA software is their aspect of "black-box" operation procedures. The three packages compared still lack of transparency. Along with the shortcoming, the three packages, nevertheless, yield different assessment results (with variation of about 2 magnificence orders) based on the same data input. Developing "regulatory assessment packages" or implementing guidance on specifying impact categories appear to be the issues to be discussed further.
2. A case study, implemented with an LCA application framework proposed by the authors, is conducted with the aggregated assessment results obtaining from the application of the three LCA packages. The case study can be "interpreted" as identification procedures for significant environmental aspects or critical lifecycle stages of corrugated paperboard production. For example, the impacts of human toxicity, global warming, and eutrophication are the three most significant environmental aspects when producing the kraft linerboard A-200. The information can be therefore used as the decision-making basis of pollution control or process improvement.
3. An observation that the LCA assessment results vary with several factors can be obtained conducting the case study. Different specifications on scoping layouts, models, or procedures may yield relatively highly diverse results. Even with limited efforts devoted, we still would like to emphasize that the life cycle assessment only evaluated "relative ranking" of environmental impacts. Subject to the constraint, questions such as, "is a full-scale LCA necessary?" or "is the incorporation of lifecycle thinking more applicable than the application of quantitative assessment?" may should be answered in the very near future. We conclude that streamlined LCA may be more applicable when a complete LCA procedure still poses various shortcomings. Along with its nature of relative ranking of impacts, incorporating lifecycle thinking into administrative context may result in more benefits than the practice of an LCA study.

ACKNOWLEDGEMENTS

This study is financially supported in parts by National Science Council, the Republic of China under the grant number of NSC88-2621-Z-005A-004. The technical advice from Mr. Lee, Mr. Wu, Mr. Lin, and Mr. Ke as well as the production data of corrugated paper provided by the Cheng Loong Co., Ltd. are highly appreciated. The free full-functional trial of GaBi 3.0 Lean provided by the PE Product Engineering GmbH is also grateful.

NOTICE OF THE SOFTWARE

EcoPro is developed by Swiss Federal Laboratories for Materials Testing and Research (EMPA) and distributed by the Sinum GmbH. GaBi is developed at the IKP University of Stuttgart in cooperation with PE Product Engineering GmbH and distributed by PE Product Engineering

Table 4. Results of the lifecycle impact assessment of the A-200 kraft linerboard

Environmental Concerns	Lifecycle Stages	Lifecycle Impacts	FAHP Weights	Weighted Impacts	Normalized Values
HC (Human Toxicity)	Material	5.44E + 02	0.253	5.22E + 00	0.5451
	Transportation	8.30E + 01	0.184	1.53E - 01	0.0160
	Production	8.90E + 02	0.316	9.57E + 00	1.0000
	Disposal	5.14E + 00	0.247	7.70E - 01	0.0804
ODP (Ozone Depletion)	Material	1.28E + 00	0.318	5.30E - 05	1.0000
	Transportation	1.76E - 01	0.246	1.04E - 05	0.2097
	Production	1.19E + 00	0.277	1.05E - 05	0.2146
	Disposal	1.41E - 01	0.158	6.30E - 07	0.0124
POCP (Photochemical)	Material	4.48E + 00	0.265	1.40E - 01	1.0000
	Transportation	2.10E + 00	0.308	2.24E - 02	0.1598
	Production	1.20E + 01	0.257	2.28E - 02	0.1628
	Disposal	3.15E - 01	0.169	2.03E - 03	0.0145
Carcin. (Carcinogens)	Material	1.67E - 04	0.153	6.44E - 06	1.0000
	Transportation	4.23E - 05	0.258	7.19E - 07	0.1116
	Production	3.79E - 05	0.284	2.15E - 06	0.3346
	Disposal	3.98E - 06	0.305	4.17E - 08	0.0065
GWP (Global Warming)	Material	5.30E - 01	0.250	1.36E + 02	0.5213
	Transportation	7.27E - 02	0.206	1.71E + 01	0.0655
	Production	8.89E - 02	0.293	2.61E + 02	1.0000
	Disposal	1.20E - 02	0.250	1.29E + 00	0.0049
NP (Eutrophication)	Material	2.06E + 01	0.256	3.28E - 01	0.6645
	Transportation	8.32E - 01	0.119	2.09E - 02	0.0423
	Production	3.03E + 01	0.414	4.93E - 01	1.0000
	Disposal	3.12E + 00	0.211	2.97E - 02	0.0602
AP (Acid Deposition)	Material	4.20E - 05	0.264	1.18E + 00	0.2976
	Transportation	2.79E - 06	0.268	5.63E - 01	0.1415
	Production	7.59E - 06	0.331	.98E + 00	1.0000
	Disposal	1.37E - 07	0.137	4.33E - 02	0.0109
TEC (Terrain Eco-Toxicity)	Material	1.81E + 00	0.247	6.58E + 02	0.3291
	Transportation	2.20E - 01	0.169	5.31E + 01	0.0266
	Production	1.96E + 01	0.321	6.96E + 02	0.3481
	Disposal	3.30E + 00	0.262	2.00E + 03	1.0000
AEC (Aquatic Eco-Toxicity)	Material	2.66E + 03	0.245	4.43E - 01	0.0739
	Transportation	3.14E + 02	0.166	3.65E - 02	0.0061
	Production	2.17E + 03	0.306	6.00E + 00	1.0000
	Disposal	7.63E + 03	0.283	9.35E - 01	0.1560
E-15AD (Resource Depletion)	Material	2.83E + 04	0.251	2.48E + 00	0.0002
	Transportation	1.03E + 03	0.269	1.07E + 04	1.0000
	Production	3.48E + 04	0.331	4.28E + 02	0.0399
	Disposal	8.92E + 01	0.149	1.83E + 00	0.0002
Energy (Energy Consumption)	Material	9.87E + 00	0.217	6.14E + 03	0.5878
	Transportation	4.00E + 04	0.329	3.40E + 02	0.0325
	Production	1.30E + 03	0.301	1.05E + 04	1.0000
	Disposal	1.23E + 01	0.154	1.37E + 01	0.0013

Table 5. Aggregated lifecycle impacts of the A-200 linerboard at various lifecycle stages

	Material Acquisition	Transportation	Production	Waste Disposal
HC (Human Toxicity)	0.1930	0.0057	0.3542	0.0285
ODP (Ozone Depletion)	0.1664	0.0349	0.0357	0.0021
POCP (Photochemical)	0.1822	0.0291	0.0297	0.0026
Carcin. (Carcinogens)	0.2972	0.0332	0.0994	0.0019
GWP (Global Warming)	0.1078	0.0136	0.2068	0.0010
NP (Eutrophication)	0.1392	0.0089	0.2094	0.0126
AP (Acid Deposition)	0.0736	0.0350	0.2473	0.0027
TEC (Terrain Eco-Toxicity)	0.1107	0.0090	0.1171	0.3365
AEC (Aquatic Eco-Toxicity)	0.0286	0.0024	0.3870	0.0604
E-15AD (Resource Depletion)	0.0001	0.3515	0.0140	0.0001
ENERGY (Energy Consumption)	0.1537	0.0085	0.2616	0.0003
Overall Impacts	1.4526	0.5316	1.9622	0.4487
Normalized Overall Impacts	0.3305	0.1210	0.4465	0.1020
Ranking Weights from FAHP	0.2467	0.2314	0.2917	0.2301

GmbH. SimaPro is a product of PRe Consultants.

REFERENCES

1. International Organization for Standardization (ISO), ISO 14040: Environmental Management-Life Cycle Assessment - Principles and Framework (1997).
2. Society of Environmental Toxicology and Chemistry (SETAC), *A Technical Framework for Life-cycle act Assessment*, SETAC, Pensacola FL (1991)
3. Society of Environment Toxicology and Chemistry (SETAC), *A Conceptual Framework for Life Cycle Impact Assessment*, SETAC, Pensacola FL (1993).
4. International Organization for Standardization (ISO), ISO 14042: Environmental management-Life Cycle Assessment-Life Cycle Impact Assessment (2000).
5. Guinee, J. B., R. Heijungs, H. A. Udo de Haes, and G. Huppes, "Quantitative life cycle assessment of products: 2. Classification, valuation and improvement analysis," *Journal of Cleaner Production*, 1 (2), 81 (1993).
6. Society of Environment Toxicology and Chemistry (SETAC), "Evolution and Development of the Conceptual Framework and Methodology of Life-cycle Impact Assessment," Addendum to *Life-Cycle Impact Assessment: The State-of-the-Art* edited by Barnthouse L, Fava J, Humphreys K, Hunt R, Laibson L, Noesen S, Norris G, Owens J, Todd J, Vigon B, Weitz K, and Young J, SETAC, Pensacola, FL (1998).
7. Heijungs, R and P. Hofstetter, Part II: Definitions of Terms and Symbols. In: Udo de Haes (ed.). *Towards a Methodology for Life Cycle Impact Assessment*, Society of Environmental Toxicology and Chemistry (SETAC) - Europe, Brussels (1996).
8. Lindfors, L.-G., K. Christiansen, L. Hoffmann, Y. Virtanen, V. Juntilla, O. J. Hanssen, A. Ronning, T. Ekvall, G. Finnveden, *Nordic Guidelines on Life-Cycle Assessment*, Nordic Council of Ministers, Copenhagen (1995).
9. Lindeijer, E., Part VI: Normalisation and valualtion. In: Udo de Haes (ed.). *Towards a Methodology for Life Cycle Impact Assessment*. Society of Environmental Toxicology and Chemistry (SETAC) - Europe. Brussels (1996).
10. Menke, D. M., G. A. Davis and B. W. Vigon, *Evaluation of Life Cycle Assessment Tools*, Environment Canada, Ottawa (1996).
11. Lee, Y.-M. and J. C-M Shan, " Comparison and Integration of Lifecycle Impact Assessment Methods and Models," Proceeding of the International Conference on Cleaner Production and Sustainable Development'99, Ministry of Economic Affairs, ROC, December 15-16, 1999, Taipei, Taiwan (1999).
12. Product Ecology Consultants (Pre), SimaPro 4 User Manual, Amersfoort, The

Netherlands. (1998).

13. Swiss Federal Laboratories for Materials Testing and Research (EMPA), *User's Manual of EcoPro*. St. Gallen, Switzerland (1998).
14. Yano, M., "LCA Development in Japan," Pre-Conference Workshops, International Conference on Cleaner Production and Sustainable Development '99, Ministry of Economic Affairs, ROC, December 13-14, 1999, Taipei, Taiwan (1999).
15. Buckley, J. J. "Ranking Alternatives Using Fuzzy Numbers," *Fuzzy Sets and Systems*, 15, 1-31 (1985).
16. Laarhoven, P. J. M. and W. Pedrycz, "A Fuzzy Extension of Saaty's Priority Theory," *Fuzzy Sets and Systems*, 11, 229-241 (1983).
17. Saaty, T. L., *The Analytic Hierarchy Process*, McGraw-Hill, New York (1980).
18. Shan, J. C-M, *Comparison and Integration of Lifecycle Impact Assessment Methods and Models*, Master Thesis, Institute of Natural Resource Management, National Chung Hsing University, Taipei, Taiwan (in Chinese) (1999).

Discussions of this paper may appear in the discussion section of a future issue. All discussions should be submitted to the Editor-in-chief within six months.

Manuscript Received: January 17, 2000
Revision Received: February 19, 2000
and Accepted: October 30, 2000

生命週期衝擊評估模式之比較與初步整合

李 育 明　　單 啓 明

國立臺北大學資源管理研究所

關鍵詞： 生命週期衝擊評估、簡約盤查分析、模糊分析層級程序法

摘　　要

生命週期評估，依據國際標準組織 ISO14040規範之定義，主要用以評估產品生命週期，從原料的取得，到製造、使用和棄置等階段之環境衝擊，並可區分爲：目標與範疇界定、盤查分析、衝擊評估及闡釋等四個評估階段。本研究之目的在於彙整比較生命週期衝擊評估技術與評價量化方法，並藉由造紙業之個案研究深入探討生命週期評估之應用架構。生命週期衝擊評估係以三套生命週期分析軟體針對六種不同之瓦楞紙品進行衝擊評估，並將其結果彙整比較。結果顯示瓦楞紙品之環境衝擊效應「絕對數值」有所差異，然而對環境衝擊之「相對排序」頗爲一致。生命週期衝擊評價係利用問卷調查，以模糊分析層級程序法探討瓦楞紙品生命週期各階段（包括原料取得、運輸、生產製造、棄置等階段，使用階段除外）之環境衝擊程度，以作爲廠商改善產品對環境友善程度之參考。研究結果顯示瓦楞紙品生命週期各階段對環境之衝擊程度依次爲生產製造、原料取得、運輸、棄置。