REFERENCES

Burgess, A., A., and Brennan, D., J. (2000). Application of life cycle assessment to chemical processes. Chemical Engineering Science 56 (2001), 2589-2604.

Capacity Building on Life Cycle Assessment in APEC Economies. 15-16 December 2005. Bangkok, Thailand.

Consoli, A., and Paster, M. (1993). Guideline for Life-Cycle Assessment: A 'Code of Practice'. 1st ed. USA: SETAC.

European Commission (2004). Life Cycle Assessment of PVC and of principal competing materials: Final Report.

Frankl, P., Rubik, F. (2000). Life Cycle Assessment in Industry and Business. Germany: Springer

Goedkoop, M., and Spriensma. (2001). The Eco-Indicator 99 A Damage Oriented Method for Life Cycle Impact Assessment: Methodology Report. 3rd ed.

Haes, H., A., U., and Rooijen, M., V. (2005). Life Cycle Approaches: The Road from Analysis to Practice. 1st ed. UNEP/ SETAC Life Cycle Initiative.

Hauschild, M., Wenzel, H. (1998). Environmental Assessment of Products: Volume 2: Scientific background. Chapman & Hall, London, Great Britain.

Huijbregts, M., Thissen, U., Guinée J., B., Jager, T., Kalf, D., Van de Meent, D., Ragas, A., M., J., Wegener, S., A., Reijnders, L. (2000). Priority assessment of toxic substances in life cycle assessment. Part I: Calculation of toxicity potentials for 181 substances with the nested multi-media fate, exposure and effects model USES-LCA. Chemosphere 41 (2000) 541-573

Jolliet, O., Margni, M., Charles R., Humbert, S., Payet, J., Rebitzer, G., Rosenbaum, R. (2003). Impact 2002+: A new life cycle impact assessment methodology. Int J LCA 8 (6) 324-330

Jolliet, O., Brent, A., Goedkoop, M., Itsubo, N., Mueller-Wenk, R., Peña, C., Schenk, R., Stewart, M., Weidema, B., *et al* (2003). Final Report of the LCIA Definition Study.

Kang, H., Y., *et al.* (2005) A methodology for building national LCI databases and a plan for management and dissemination of the databases. KNCPC Report RE-5.

Lewis, H., and Gertsakis, J. (2001). Design + Environment: a Global Guide to Designing Greener Goods. UK: Greenleaf Publishing.

Narita, N., Sagisaka, M., and Inaba, A. (2002). Life cycle inventory analysis of CO_2 emissions. Int J LCA 7(5), 277-282.

Paoluglam, J. (2005). Life Cycle Assessment of Petrochemcal Products: Polystyrene and Polyurethane Foam. M.S. Thesis in Petrochemcal Technology, Chulalongkorn University.

Pre Consultants. (2006). Introduction to LCA with SimaPro 7.

Steen, B. (1999). A Systematic Approach to Environmental Priority Strategies in Product Development (EPS). Version 2000 - General System Characteristics. Chalmers University of Technology, Technical Environmental Planning. Göteborg, Sweden.

Udo de Haes, H., A. (1993). Applications of life-cycle assessment: expectations, drawbacks and perspectives. Journal of Cleaner Production 1(3-4), 131-137.

Udo de Haes, H., A., Lindeijer, E. (2002). The Conceptual Structure of Life-Cycle Impact Assessment. SETAC-Europe, Brussels, Belgium.

Udo de Haes, H.,A., et al., 2002. Towards Best Available Methods for Life cycle Impact Assessment. Society of Environmental Toxicology and Chemistry (SETAC).

UNEP. (2002). Global Environmental Outlook (GEO-III) – Past, Present and Future Perspective. United Nations Publication.

UNEP. (2003). Evaluation of Environmental Impacts in Life Cycle Assessment. 1st ed. United Nations Publication.

UNEP. (2004). Why Take a Life Cycle Approach? 1st ed. United Nations Publication.

Wenzel, H., Hauschild, M., Alting, L. (1997). Environmental Assessment of Products, Vol. 1.1st ed. Chapman & Hall, London, Great Britain.

Witcoff, H., A., and Reuben, G. (1996). Industrial Organic Chemicals. Canada: John Wiley.

APPENDICES

Appendix A Environmental Impact Categories

The environmental impacts listed here are of no explicit order regarding their significance.

- Climate change.

The impact pathways of greenhouse gases include temperature rise, changes in precipitation, sea level rise, change of ocean currents, storms, hurricanes and possibly others, eventually leading to impacts on human health and biotic natural environment and resources. All of these types of impacts depend on changes in radiative forcing in the atmosphere (expressed as Wm–2). This category offers the opportunity for a science-based midpoint indicator, related to the well-known Global Warming Potential (GWP). Climate equilibrium can be considered as a life support function to be protected as such: the capacity of the environment to provide the conditions for a long-term stability of climate on earth.

- Ozone depletion

Ozone is a form of oxygen (O3) that forms a layer in the atmospheric between 20km and 50km above the surface of the Earth. The ozone layer protects us against the harmful effects of the sun's radiation. Several dozen, mostly man-made, compounds such as nitric acid (created by the burning of fossil fuels) or chlorine compound (e.g. CFCs used in refrigeration or foams) released to the air have a known effect of reducing stratospheric ozone concentrations. The consequence is an increase of solar radiation, particularly UVB, on the earth's surface.

Ozone-depleting substances are being phased out under an international agreement called the Montreal Protocol. These chemicals have traditionally been used as propellants, refrigerants and blowing agents. Recent evidence suggests that bromine-based chemicals are also damaging the ozone layer, but are not covered by the Protocol.

- Photochemical oxidant formation.

Photochemical smog is caused by the reaction of volatile organic compounds (VOCs) and NOx in the troposphere, both natural and man-made, with reactive oxygen forms, particularly hydroxyl radicals, which are formed in the presence of sunlight. Ozone (an important component of smog) is a toxic gas which has been shown to cause respiratory distress in people and other mammals, as well as causing reduction in the primary production rates of plants.

Two types of models have mostly been used to analyze midpoint indicators for smog. The Northern European model is based on the calculated photochemical ozone creation potential (POCP), and measured in ethylene units. The model used in the United States is based on the Maximum Incremental Reactivity (MIR), and is measured in units of O_3.

- Resource depletion

Many of the raw materials currently being used are non-renewable, and supplies are limited. In 1972 a report to the Club of Rome warned of dire consequences to humankind unless exponential growth in population and consumption could be controlled:

"... *If the present growth trends in world population, industrialization, pollution, food production, and resource depletion continue unchanged, the limits to growth on this planet will be reached sometime within the next one hundred years. The most probable results will be a rather sudden and uncontrollable decline in both population and industrial capacity"*.

Resource conservation should be considered in the design, manufacture, use and disposal of every product. Materials need to be used efficiently and recovered at the end of their life for recycling.

- Reduced biodiversity:

Biodiversity is reduced when the number of plant and animal species is reduced at a local, regional or global level. Although insufficient information is available to determine precisely how many species have become extinct in the past three decades, about 24 per cent (1 130) of mammals and 12 per cent (1 183) of bird species are currently regarded as globally threatened. (GEO-III, UNEP 2002). This can occur for a number of reasons, for example:

+ Land clearing for urban development, mining or other human activities.
+ Timber harvesting or clear-felling in old growth forests.
+ Pollution of air, soils or waterways.

Tropical rainforests are among the most biologically diverse habitats (e.g. they are home to at least half of world's plant species). They are also experiencing extreme rates of species extinction.

Scientists and policy-makers are still grappling with complex issues relating to how we measure and protect biodiversity in the environment. Designers need to be aware that any product made or derived from biological resources, such as timber, may have implications for biodiversity. Impacts can be minimized through careful selection of materials (e.g. timber certified by the Forest Stewardship Council), design for material efficiency and use of recycled materials and by-products.

- Acidification.

Through oxidation and hydrolysis, a number of atmospheric gases as sulfur dioxide and nitrogen are transformed to acidifying substances. These acids can be deposited as dust (dry deposition) or dissolved in precipitation (wet deposition) and may cause undesirable effects on terrestrial and aquatic ecosystems (decrease of pH, detrophication of soils), man-made resources and even human health. For this category as well as for other transboundary impacts, it is of high importance to rely on the expertise and timely contribution of various experts from different fields. Present methods take advantage of models as RAINS (Regional Acidification Information and Simulation) and underlying models and data from EMEP (Cooperative Programme for Monitoring and Evaluation of the Long-Range Transmission of Air pollutants in Europe) for Europe and NAPAP (National Acid Precipitation Assessment Program) for North America to develop acidification fate and transport.

- Eutrophication.

Nitrogen and phosphorus are essential nutrients required for life, but, in excess, these substances cause eutrophication. It is necessary to subdivide the impact category into aquatic and terrestrial eutrophication. The increase of these nutrients in water areas contributes to the increased growth of phytoplankton, and may cause algae blooms. Reduced oxygen availability and decreased transparency of the water causes reduction of fish populations. Only one of the two nutrients will normally be limiting in a given water body, typically phosphor in fresh waters and nitrogen in marine water. The larger part of airborne emissions will be deposited on land where basically only nitrogen contributes to terrestrial eutrophication, since natural land is typically not limited by phosphor. The present attitude is therefore to explicitly consider them as two separate impact subcategories.

- Ecotoxicity.

It is generally accepted that populations of nonhuman life may be substantially threatened by chemical emissions, although the toxicological knowledge is much more fragmentary than in the case of human toxicity, due to the enormous diversity of animals and plants. One challenge is to agree on a suitable damage indicator at the level of 'biotic natural environment' at which the impact pathway ends. It may be necessary to divide the impact category into a number of subcategories, like aquatic, terrestrial or marine ecotoxicity.

- Land use impacts.

Usage of land surfaces for anthropogenic processes is recognised to be a primordial threat to species and ecosystems, and generic inventory data bases have begun to register information on land use. Human activities contributing to land degradation include unsuitable agricultural land use, poor soil and water management practices, deforestation, removal of natural vegetation, frequent use of heavy machinery, overgrazing, improper crop rotation and poor irrigation practices.A great challenge is the location dependency of the damaging effects of a given type of land use. In spite of many proposals, there is no agreed model of land use impacts available. In addition, the type of land use is of significance specifically in developing countries, in addition the assessment of impacts on soil salinisation, dessication and erosion.

- Abiotic resource depletion.

Use of abiotic natural resources (mainly metallic and non-metallic ores/minerals, energy, freshwater) is seen as an environmental damage because the exploited resource generally leaves the system of anthropogenic processes in a degraded form, so that the resource loses its potential to deliver the functionality for which it is desired. The corresponding threat to future humans is more serious where the available stock of virgin, non-degraded resource is comparatively small (relative scarcity) and where non-reversible effects are observed. This concept places the emphasis for the definition of this impact category on the ultimate form of the resource leaving the system and its remaining potential to deliver the functionality for which it is desired; as opposed to focussing on resource xtraction. One of the current challenges is to describe the impact pathway from resource use at LCI results level up to the damage category of 'abiotic natural resources' in such a way that agreement can be reached in principle, even if undiscovered stocks and future technologies are not fully known. Specific problems of the resource types of freshwater and soil are connected with the fact that their geographical location on the earth's surface is an important descriptor of their quality: freshwater in Iceland is not the same as freshwater in Saudi Arabia, and soil in the US Midwest is not the same as soil in the Mississippi delta. The resource impact category is especially crucial for developing countries, where a large part of resource extraction takes place.

- Noise.

Traffic noise also affects human health. The current challenge is to develop, on the basis of available knowledge, quantitative impact pathways to a possible midpoint or directly to the human health damage. Inventories so far do not contain data on noise emissions, proposals for the format of noise-relevant data in LCI need to be prepared.

Appendix B Brief Review of the Eco-Indicator Methodology

❖ Eco indicator 95 and Eco-indicator 99

These methods were developed by the Pré Consultant for the Dutch government in conjunction with a large range of manufacturing companies and research agencies. Eco-indicator 95 is one of the most widely used indicators, and a comprehensive one as well. However, like many impact models, it deals poorly with land-use and biodiversity impacts. It also weighs acidification highly (essential concern in European countries), which makes it a difficult model to use in those countries where acidification is not a major impact. In additaion, with respect to weighing system between different environmental aspects, the core of Eco-indicator method, the Eco-indicator 95 used the so-called distance-to-target approach, which was criticized because there is no clear-cut objective way to define sustainable target levels.

Eco-indicator 99 (EI_{99}) is a complete rebuild of the Eco-indicator 95 method, with substantial improvements in the modeling of damage occurring from emissions (damage-oriented method). This is done by taking greater account of the probable fate of the emission (where the emission will probably ultimately have an impact) and the sensitivity of the environment receiving that emission. The EI_{99} method is a complete "top-down" impact assessment method (Goedkoop and Spriensma, 2001). This is in contrast with the "bottom up" approach that can be found in the more traditional midpoint methods, where the modeling starts with the release of the pollutant to the environment, the use of land or the extraction of resources.

In the development of the EI_{99} methodology, the weighting step is considered to be the most difficult, controversial and uncertain, in addition to the uncertainty of the endpoint modeling, so it was the starting point. To simplify the weighting procedure, damage categories had to be identified, and as a result new damage models were developed that link inventory results into three damage categories and thus reduced substantially the number of weighed objects.

Here is three damage categories (end-point in ISO terms) that need to be weighed in order to end up with single eco-point:

• Damage to Human Health : damage models were developed for respiratory and carcinogenic effects, the effects of climatic change, ozone layer depletion and ionizing radiation. In these models for Human Health, four steps are used:

+ Fate analysis, linking an emission to a temporary change in concentration.

+ Exposure analysis, linking this temporary concentration change to a dose.

+ Effect analysis, linking the dose to a number of health effects, such as occurrence and type of cancers.

+ Damage analysis, links health effects to DALYs (Disability Adjusted Life Years) using estimates of the number of Years Lived Disabled (YLD) and Years of Life Lost (YLL); it includes a first weighting step.

• Damage to Ecosystem Quality: damages to Ecosystem Quality are expressed as percentage of species disappeared in a certain area due to environmental load (Potentially Disappeared Fraction or PDF). The PDF is then multiplied by the area size and the time period to obtain damage. This damage category consists of:

+ Ecotoxicity expressed as the percentage of all species present in the environment living under toxic stress.

+ Acidification and Eutrophication treated as one single category. Damage to target species in natural areas is modeled.

+ Land use and land transformation based on empirical data. Both damages related to land occupation and transitions in land use are taken into account.

• Damage to resources: damage to resources, minerals and fossils fuels, are expressed as surplus energy for the future mining of resources:

+ For minerals, geo-statistical models are used that relate availability of a resource to its concentration.

+ For fossil fuels, surplus energy is based on future use of oil shale and tar sands.

Regarding to this "top-down" approach the most fundamental problem is the definition of possible values of the decision maker . To deal with the fact that in the valuesphere (value choices and weighting), a single truth simply does not exist, three perspectives are used: the hierarchist, the individualist and the egalitarian. Table B.1 specifies some different characteristics per perspective.

Table B1 The three cultural perspectives used in Eco-Indicator 99 (Goedkoop and Spriensma, 2001)

Perspective	**Time perception**	**Manageability**	**Required level of evidence**
Hierarchist	Balance between short and long term	Proper policy can avoid many problems	Inclusion based on consensus
Individualist	Short time	Technology can avoid many problems	Only proven effects
Egalitarian	Very long term	Problems can lead to catastrophe	All possible effects

The EI_{99} methodology allows for an analysis of the relative contribution of the different impact category indicators to one of these three endpoints without any weighting, using the values of the three perspectives. The methodology may include rather complex environmental models with possibly high uncertainties, but the developers of this method claim that the ease of interpretation compensates for this problem.

Appendix C 'Best Available Practice' for LCA Study

Some key features that come from LCA experts' experience through "everyday practice" are presented below (besides the general guidelines of the ISO standards) (European Commission, 2004).

- A precise description of the technical system under study within the goal and scope is mandatory. If the technical system is not properly understood and described by the practitioner of an LCA study, the probability of improper results increases drastically. Technical knowledge of the product, product qualities and properties, involved process technologies and possible alternative process technologies is necessary.
- The functional unit must be comparable. This means that results based on the sole assessment of different materials can not be used for comparisons on a product level. High quality LCAs only compare alternatives on an application level with comparable functional units.
- The processes that have been included, and those that have been excluded, must be clearly stated. Depending on the goal and scope, not all processes are relevant to the study. Inclusion of an explicit statement about the relevance or irrelevance of each process increases the value of a study.
- A description of the background data used for energy, transport, and resource extraction required by the system under study should be included. This can be a description of previously or newly collected data or the documentation of available (public or other professional) data sets. It is important to consistently use documented background data. When comparisons are made, the use of different background data sets from different sources may result in a high risk of improper interpretation of the results. The differences may result from differing background data sets, rather than from the differences between the compared technologies or products.
- The life cycle should be properly covered, based on the goal and scope of the study. Depending on the goal and scope of the study, not necessarily all phases of the life cycle have to be covered. If all phases are not covered quantitatively, the

important aspects and parameters, which may influence an LCA that includes all phases, should be discussed qualitatively.

- Specific data should reflect the actual situation precisely and adequately. LCAs are data intensive. It is not always possible for all relevant life cycle data to be collected for a new study. Therefore, average or representative data is used in many LCAs. Nevertheless, specific data (or primary data) of the specific core processes is usually more precise and up-to-date when collected as part of the study.

- Consistent data should be used for processes that are not included in the primary collection of data. LCA typically involves (depending on the degree of detail and the goal and scope) several hundred to thousands of different processes over the product or system life cycle. The growing availability of databases and software tools allows for the comprehensive modeling of these complex process networks. Use of databases and software tools speeds up the effort of conducting LCAs. The source of the secondary information and data sets used (that are not the subject of a primary data collection by the users themselves) should be clearly documented.

- An adequate set of environmental impacts should be selected and presented. A comprehensive LCA should include an adequate set of environmental impacts. This set can be composed of an accepted set of environmental impacts (e.g. Global Warming, Acidification, Nutrification, Stratospheric Ozone Depletion, Tropospheric Ozone Creation, Human Toxicity). Furthermore, the set of environmental impacts can be complemented with specific, typical or important single emissions (e.g. regulated key emissions of a particular branch).

- A discussion of the selected set of environmental impacts should be included. From many LCA experts' experience a comprehensively performed LCA seldom produces trivial, straightforward, stable and reproducible results that are valid for all products comparable to the product under study. Therefore, sole results like "A is more environmentally friendly than B" tend to be of low quality. A comprehensive and reliable LCA usually produces results like "A is more environmentally friendly than B, if the system properties are set to C, D and F". One strength of LCA is its ability to show behavior in relation to various environmental impacts of complex systems. Therefore, understanding how the system behaves should be the main goal, as this understanding is the most important basis for optimizations and improvements.

- Environmental Single Score Indicators tend to be of lower significance than adequate sets of environmental impacts. If Single Score Indicators are used to present results of an LCA, much information can be lost. For communication to non-experts this might be adequate, but the standards clearly state that there is no scientific basis for reducing LCA results to a single overall score or number as trade-offs and complexities exist for the systems analyzed at many different stages of their life cycle.

Appendix D Petrochemical Manufacturers and Templates for Collecting Data

Table D1 Major petrochemical products and their manufacturers

Products	Manufacturers	Total market share (%)
LDPE	TPI	61.24
	TPE	38.76
LLDPE	Siam Polyethylene	
VCM	TPC	68.75
	VNT	31.25
PVC	TPC	57.53
	VNT	25.7
	Alex Petrochemical	12.24
	TPC Paste Resin	4.53
Propylene	ROC	34.01
	TPI	26.53
	PTT Chem (TOC)	17.43
	ARC	11.22
	PTT Chem (NPC)	10.80
PP	TPI	38
	HMC	36.4
	TPP	25.6
Benzene	ATC	63.36
	ROC	21.71
	TPI	14.93
Toluene	TPI	65
	ROC	35
P-xylene	Exxon Chemical	38.99
	ATC	35.74
	Thai Paraxylene	25.27
Styrene (SM)	SSMC	61.54
	TPI	38.46
ABS/SAN	Thai ABS	46.6
	Lanxess (Thailand)	43.69
	Grand Pacific	9.71

Table D2 Data collection template (VCM was the targeted product in this case)

1.General Data							
1	Date of data collection						
2	Production time period						
3	Summary of manufacturing process						
4	Process Flow Diagram	yes	no				
5	Product pictures	yes	no				
6	Company Name	**VNT**					
	Item	Quantity			Source of raw material (Company... / Firm... / Import ...)	Destination / Management Method (disposed of as trash/ landfill / etc.)	Other description (if any) e.g. Specifications , Technology, etc.
2. (Products and Co-Products)		Actual data	Calculated data	Unit			
Products							
1	VCM			t/y	-	-	
2				t/y	-	-	
3					-	-	
4					-	-	
5					-	-	
	total			t/y	-	-	
Co-Products							
1					-	-	
2					-	-	
3					-	-	
4					-	-	
5					-	-	

Table D2 (cont.)

3. Input Inventory							
Raw material							
1	Ethylene			t/y	-	-	
2	NaCl			t/y	-	-	
3	Water			t/y	-	-	
4	Oxygen (Air)			t/y	-	-	
5					-	-	
Energy and Utilities							
1	Electricity (on-site)			kW	-	-	
2	Electricity (from outside sources)			kW	e.g. EGAT	-	
3	HP Steam (on-site)				-	-	T = ... K and P = ... atm
4	LP Steam (from outside sources)				eg. From ...	-	T = ... K and P = ... atm
5	Potable Water			m^3/d	e.g. Municipal Water Supply	-	
6	other, please specify						
7	other, please specify						
Fuel							
1					-	-	
2					-	-	
Other (if any), please specify							
1					-	-	
2					-	-	

Table D2 (cont.)

4. Output Inventory							
Emissions to water							
1	Flow Rate			L/h	-	-	
2	Composition				-	-	
	- BOD			mg/L	-	-	
	- COD			mg/L	-	-	
	- SS			mg/L	-	-	
	- TDS			mg/L			
	- Total Nitrogen			mg/L			
	- Total Phosphorus			mg/L			
	- Heavy Metals			mg/L			
	- other (if any) please specify						
3	Working period						
Emissions to air							
1	Flow Rate			m^3/h	-	-	
2	Composition					-	
	- CO_2			kg/m^3		-	
	- SOx			kg/m^3			
	- NOx			kg/m^3			
	- TSP			kg/m^3			
	- CFC Information (HFCs)			kg/m^3			
	- CO			kg/m^3			
	- VOCs			kg/m^3			
	- Heavy Metals			kg/m^3			
	- other (if any) please specify						
3	Working period						
Emissions to soil							
1					-	-	
Solid waste							
1					-	-	
Other (if any), please specify							
1					-	-	

CURRICULUM VITAE

Name: Mr. Nguyen Bao Nguyen

Date of Birth: July 17, 1981

Nationality: Vietnamese

University Education:

1999-2004 Bachelor Degree of Petroleum Technology Engineering, Faculty of Chemical Technology and Petroleum, Ho Chi Minh City University of Technology, Ho Chi Minh, Vietnam

Working Experience:

2004-2005 Position: Process Engineer

Company name: Nissei Vietnam Ltd. Company