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ANL/EVS/R-07/5

Life-Cycle Thinking for the Oil and Gas Exploration and Production Industry

Environmental Science Division

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work sponsored by
U.S. Department of Energy
Office of Fossil Energy
National Energy Technology Laboratory

September 2007

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NOTATION

ACRONYMS AND ABBREVIATIONS

BAT	best available technique
CBA	cost benefit analysis
CO	carbon monoxide
CO_2	carbon dioxide
CO_2E	CO_2 equivalent
CP	cleaner production
DfE	design for the environment
E&P	exploration and production
EEA	European Environment Agency
EIA	environmental impact assessment
EMA	energy and material analysis
EMA	environmental management accounting
EMS	environmental management system
EOL	end of life
EOR	enhanced oil recovery
EPA	U.S. Environmental Protection Agency
EPR	extended producer responsibility
ERA	environmental risk assessment
EU	European Union
GHG	greenhouse gas
GJ	gigajoule
GWP	global warming potential
HCl	hydrogen chloride
HF	hydrogen fluoride
IOA	input/output analysis
IPPC	Integrated Pollution Prevention and Control
ISO	International Organization for Standardization
LCA	life-cycle assessment
LCC	life-cycle costing
LCF	life-cycle framework
LCI	life-cycle inventory
LCIA	life-cycle impact assessment
LCM	life-cycle management
LCVA	life-cycle value assessment

MFA	material flow accounting
N_2O	nitrous oxide
NCPC	national cleaner production center
NGO	nongovernmental organization
NH_3	ammonia
NO_2	nitrogen dioxide
NO_x	nitrogen oxides
O&G	oil and gas
OPF	organic-phase drilling fluids
OSPAR	Commission for the Protection of the Marine Environment of the North-East Atlantic
P2	pollution prevention (North America)
PL	produccion mas limpia (Latin American phrase for P2)
PPM	process and production methods
SETAC	Society of Environmental Toxicology and Chemistry
SFA	substance flow analysis
SME	small and medium-sized enterprise
SO_2	sulfur dioxide
TCA	total cost accounting
TCC	thermal mechanical continuous conversion
TFM	total fluid management
TPH	total petroleum hydrocarbons
TRACI	Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts
UNEP	United Nations Environment Program
UNIDO	United Nations Industrial Development Organization
VOC	volatile organic compound

UNITS OF MEASURE

bbl	barrel (s)
Btu	British thermal unit
ft	foot (feet)
ft^2	square foot (feet)
ft^3	cubic foot (feet)
g	gram(s)
gal	gallon(s)
GJ	gigajoule
h	hour(s)
kg	kilogram
km	kilometer(s)
km^2	square kilometer(s)
L	liter(s)
m	meter(s)
m^2	square meter(s)
m^3	cubic meter(s)
mg	milligram(s)
mi	mile(s)
mi^2	square mile(s)
mph	mile(s) per hour
ppm	parts per million
μm	micrometer(s)

LIFE-CYCLE THINKING FOR THE OIL AND GAS EXPLORATION AND PRODUCTION INDUSTRY

ABSTRACT

Life-cycle assessment (LCA) is a systematic process for identifying, quantifying, and assessing environmental impacts throughout the life cycle of a product, process, or activity. It considers energy and material uses and releases to the environment from "cradle to grave," (i.e., from raw material extraction through manufacturing, transportation, use, and disposal). LCA can be used to help ensure that cross-media and multimedia environmental impacts are considered in design and implementation decisions, identify "hot spots" of potential environmental impact, compare one or more aspects of specific products or processes, and establish baselines for further research. LCA is often used in conjunction with other environmental management tools such as risk assessment and environmental impact assessment. A life-cycle approach does not necessarily embody every methodological aspect called for in a traditional LCA, but it does use a cradle-to-grave systems perspective to evaluate the full life-cycle impacts of a product or process. Various industries, the military, and governments have been using life-cycle approaches — and often LCAs — to increase the role of science in decisions on product and process designs. This paper describes the concept of life-cycle thinking and how LCAs and other life-cycle approaches might be used to evaluate oil and gas industry issues, particularly those related to exploration and production. It summarizes case studies of life-cycle approaches that have been used to address oil and gas issues, and it builds a foundation for conducting additional life-cycle studies, the results of which can add scientific input to the decision-making process.

SUMMARY

As demand for energy continues to grow, new sources of oil and gas (O&G) must be found and produced. Challenges for exploration and production (E&P) today and into the foreseeable future include the deployment of new or newly adapted E&P technologies, evolving environmental laws and regulations that vary among (and within) nations, socioeconomic concerns, and providing adequate returns to investors. Decisions on new technologies for drilling efficiency, drilling waste management, produced water management, and land management must consider costs, timing, technology availability, cost-effectiveness, regulatory factors, country-specific issues (e.g., environment), and political issues.

Life-cycle concept

The concept of life-cycle thinking and the use of life-cycle approaches, such as life-cycle assessment (LCA), can add scientific input to those decisions. The traditional LCA is a systematic process for identifying, quantifying, and assessing environmental impacts throughout the life cycle of a product, process, or activity. It considers energy and material uses and releases to the environment from "cradle to grave," (i.e., from raw material extraction through manufacturing, transportation, use, and disposal). LCA can be used to help ensure that cross-media and multimedia environmental impacts are considered in design and implementation decisions, identify "hot spots" of potential environmental impact, compare one or more aspects of specific products or processes, and establish baselines for further research. LCA is one tool used in environmental decision making; it is generally used in conjunction with other tools such as risk assessment and environmental impact assessment. Other life-cycle approaches do not necessarily embody every methodological aspect called for in a traditional LCA, but they do use the cradle-to-grave perspective to evaluate the life-cycle impacts of a product or process.

Life-cycle evolution

Life-cycle applications have evolved since the 1960s and 1970s, when they were used to account for cumulative energy use and to estimate environmental emissions and economic costs associated with various energy technologies over their life cycles, to the present time, where they are used to estimate actual impacts of environmental emissions from processes and products over their life cycles. Work is underway to extend life-cycle application to sustainability issues by incorporating social aspects into life-cycle thinking. Today, there are consensus-based international standards for LCA developed by the International Organization for Standardization (ISO), and numerous organizations including the Society of Environmental Toxicology and Chemistry (SETAC) and the United Nations Environment Program (UNEP) are exploring ways to improve and expand the capabilities of life-cycle approaches.

According to the ISO standards, a traditional LCA consists of the following four phases: goal scope and definition; inventory analysis; impact assessment; and interpretation. While many LCAs include all four phases and employ sophisticated software tools, many others stop after the second phase. These less rigorous endeavors, along with other life-cycle thinking approaches that do not necessarily embrace all facets of the standards, can still provide useful information for decision making, and often with fewer resources.

Life-cycle applications

To date, life-cycle approaches have been used primarily in Europe and Japan for product development, and, to a lesser extent for strategy development. Specific applications include identification of critical environmental points along the product life cycle, comparisons of products with other existing products or with planned alternatives, product design, and waste management. The use of life-cycle approaches to study processes, and in particular O&G E&P processes, is less mature. Nonetheless, several case studies in which life-cycle thinking has been either directly or indirectly applied to O&G E&P have been identified. Some of these applications, along with their study objectives and/or findings are highlighted below.

- *Environmental effects of deep drilling projects*. A study that used LCA to identify and control environmental aspects from deep drilling projects concluded that drilling fluids and drill cuttings were the largest contributors to environmental impacts.

- *Drill cuttings management*. Life-cycle energy use and air emissions were estimated for various waste management components and then aggregated into several scenarios for comparative evaluations.

- *Offshore drilling waste disposal*. Decision makers used LCA, risk assessment, and economic considerations to identify preferred technology options for drilling waste disposal from offshore operations.

- *Integrated management of fluids and wastes*. A life-cycle approach was used to minimize cost and maximize environmental performance. By involving the supplier chain from procurement through the life cycle of the operations, the recycling of drilling fluids was increased significantly, thereby reducing drilling waste and saving costs.

- *Ex situ bioremediation of diesel-contaminated soil*. Alternatives were compared, and process optimizations for improving life-cycle environmental performance were identified, but poor data quality may limit validity of conclusions.

- *Two life-cycle approaches* (full LCA and simplified approach) for assessing remediation options were evaluated for their use in understanding the potential environmental burdens of generic remediation options; a simplified life-cycle approach was found to be adequate for identifying impacts at and beyond the contaminated site and over short and long time periods.

- *Hydrocarbon remediation techniques*. Environmental impacts caused by the remedial actions themselves were identified using LCA. The largest environmental impacts were correlated with the most energy-consuming activities.

- *Greenhouse gas (GHG) emissions for crude oils*. Life-cycle GHG emissions were estimated for seven crude oil types. Concerns ranging from allocation of emissions among many refinery processes to selection of emissions factors suggested that more refinements would be needed before the results could be used in monetary decisions.

- *Oil sands development.* Energy and GHG emissions were identified and compared for different energy sources used to produce oil sands. The study found that life-cycle energy use and GHG emissions are higher for gasoline produced from oil sands than for gasoline produced from crude oil if either natural gas or coal are used to fuel oil sands operations, but are about the same if nuclear power is used to fuel those operations.

- *CO_2 storage in active reservoirs*. A study that evaluated environmental impacts over the life cycle of an enhanced oil recovery process found that GHG process emissions associated with enhanced oil recovery are minimal compared with those avoided through storage in active reservoirs.

- *Investment decision making.* A study found that addressing the value to a corporation of an investment over its life cycle will be most successful when attempts to tackle issues in detail are avoided and the focus is on risk and uncertainty.

- *Corporate policies and operations*. At least three major oil companies have explicitly integrated life-cycle thinking into their policies and operations.

Life-cycle benefits and concerns

These studies illustrate how life-cycle applications can be used for gathering quantitative data to inventory, weigh, and rank the environmental burdens of products, processes, and services in a transparent and scientific way. The results can help identify areas of potential environmental concern or activities that cause the greatest environmental impacts — early on in a process. They can also help identify opportunities for improving environmental performance of products or processes at various points in their life cycle, and, when used in conjunction with other information (such as cost and performance data), help select a product or process optimized for a given application. Life-cycle information can also be used to help avoid shifting environmental impacts from one life-cycle stage to another, from one location to another, and from one environmental medium to another.

Despite the benefits of using life-cycle approaches, there are barriers to using LCA, which can mean lost opportunities for improved environmental decisions. Examples of such barriers include the perceived or actual need for significant resource requirements, limited guidance, incomplete or unavailable data, and the need for participation by various functions within an organization.

Potential future O&G E&P applications

Assuming that these barriers can be overcome, for example, through the dissemination of information on the successful use of life-cycle approaches, or the recognition that while barriers may exist, they do not outweigh the potential benefits of using LCA, O&G companies can benefit from continued and expanded use of life-cycle thinking. Such applications could include life-cycle studies for evaluating onshore and offshore produced water management options; for evaluating various E&P waste infrastructure options; for comparing treatment options for a variety of E&P wastes, for assessing water and land impacts from oil sands development; for comparing techniques to manage scale formation; and for identifying hot spots in upstream processes. They may also be used to influence external (e.g., regulatory or other in-country development) decisions by bringing life-cycle-based information to the debate. Linking sustainable development with life-cycle thinking through sustainability planning and integrating social aspects into LCA are other options for expanding the use of life-cycle approaches. Because data availability is often a barrier to conducing LCAs, understanding the types of data that are needed — not only for E&P studies, but also for other LCAs that incorporate E&P — could be a focus for data collection efforts.

Practical considerations

While life-cycle approaches can contribute to improved environmental decision making for O&G E&P, users need to be aware of potential pitfalls and to plan their LCAs to maximize potential benefits. Suggestions for doing so include being clear on the objectives of the study and the measures of success, recognizing that life-cycle studies contribute only one component of a more comprehensive decision-making process, understanding the tradeoffs between resource requirements and the level of detail that can be accommodated in a study, and including as many participants as possible in the study (to ensure the broadest coverage and enhance buy-in).

1 INTRODUCTION

Oil and gas (O&G) exploration and production (E&P) today require the simultaneous consideration of a variety of economic, social, political, and environmental concerns. As energy demand continues to grow, O&G companies must find and produce increasing quantities of oil and gas. But doing so requires more than merely ramping up production from traditional sources. As nearby, relatively easy-to-produce resources diminish, new sources (e.g., oil shale) and locations (e.g., the deep offshore), are being developed. A particular concern regarding increasing development is the need to consider a range of potential upstream environmental impacts, often before regulations are in place. These impacts pertain to such topics as waste management, chemical use, water consumption, energy use, and climate change.

As resources become more difficult to find and produce, improved or new E&P technologies, methods, and products are constantly sought and evaluated to meet these demands in a cost-effective manner. Specific concerns stem from the following characteristics of today's oil and gas industries:

- *Global- and local-level environmental concerns*. O&G E&P activities contribute to environmental concerns that range from climate change to local soil contamination, and include habitat protection and biodiversity issues, air emissions, marine and freshwater discharges, incidents and oil spills, water use and consumption, and soil and groundwater contamination. Key concerns and their sources are highlighted below; for more detail, see UNEP (1997).

    - Atmospheric emissions result from flaring and venting, combustion processes including diesel engines and gas turbines, fugitive gases from loading operations and process equipment, and airborne particulates from soil disturbances during construction. Principal emission gases include carbon dioxide (CO_2), carbon monoxide (CO), methane, volatile organic compounds (VOCs), and nitrogen oxide (NO_x).

    - Aqueous waste streams resulting from E&P operations include produced water, drilling fluids, cuttings, and well treatment chemicals; process, wash, and drain water; sewage and sanitary wastes; cooling water; and spills and leaks.

    - Impacts to soil result from physical disturbance during construction, contamination from spills, leaks, or solid waste disposal, and indirect impacts.

- *Changing regulatory environments*. Political concerns and new scientific findings can lead to new or stricter regulations in the United States. Developing countries that are creating regulatory programs may look to both U.S. and European regulations. Sometimes they pick one over the other, or they may pick the most stringent elements of both. New programs may attempt to address social as well as environmental concerns.

- *New operating sites*. To help meet the energy needs of developed and developing countries, O&G E&P activities continue to grow across the globe. These activities can induce both positive and negative economic, cultural, and social changes and can affect the traditional lifestyles of local indigenous populations. E&P operations can alter existing land uses, and new access routes can lead to unplanned settlement and further development. Local population levels may increase or change due to immigration (e.g., for labor), and there may be differential impacts on various subpopulations. Social structures may be affected. Aesthetics may change. Benefits that stem from O&G E&P revenues can include improvements to infrastructure, water supplies, sewage and waste treatment, and health care and education; but the distribution of those benefits may provoke concern.

- *Public opinion*. Some people view the O&G industry as focused on profits with little concern for the environment. Responsible parties in the O&G industry are trying to improve their image and performance, and greater transparency in operators' decision-making processes can help counteract negative industry images and improve public perception.

- *Sustainability issues*. Sustainability, which includes environmental, economic, and social concerns, is becoming increasingly important, particularly in developing countries.

- *Increasing costs*. O&G E&P costs can be expected to increase — not only for the development and deployment of new technologies in new areas, but also to ensure environmental protection and sustainability.

In this environment, decisions are being made regarding use of alternative new technologies for drilling efficiency, drilling waste management, produced waste management, land management. These decisions must consider cost, timing, technology availability, cost-effectiveness, regulatory factors, country-specific issues (e.g., environment), and political issues.

The concept of life-cycle thinking, life-cycle approaches, and the use of life-cycle assessment (LCA) as a tool can help provide input to some of those decisions and thereby help address some of these concerns. Life-cycle thinking considers the cradle-to-grave implication of an action, and as such, it can help:

- Quantify environmental releases to air, water, and land for each life-cycle stage and major contributing process;

- Develop a systematic evaluation of the environmental consequences of a given product or process;

- Analyze environmental tradeoffs among various products or processes;

- Identify shifts in environmental impacts between environmental media and life-cycle stages;
- Assess human and ecological effects of environmental releases and material consumption at various geographic levels;
- Identify the impacts of a specific product or process throughout its entire life cycle or selected stages of the life cycle;
- Understand the relative environmental burdens resulting from evolutionary changes in given processes or products over time;
- Compare the impacts of alternative process or products;
- Determine the impacts of product substitution;
- Provide information on the tradeoffs among alternative processes, products, and materials;
- Help create a better informed public regarding environmental issues and consumer choices; and
- Establish a baseline of information on an entire system or for certain processes given current or predicted practices. The baseline could consist of the energy and resource requirements and the environmental loadings from the product or process systems that are analyzed. Such baseline information can be useful in improvement analysis, when specific changes are applied to the baseline system.

2 BACKGROUND

2.1 LIFE-CYCLE CONCEPT

The life-cycle concept is based on the premise that products and process have life cycles. Products are made from raw materials, transported, used, and eventually disposed of. Processes also have life cycles. During each stage of the life cycle (extracting and processing raw materials, manufacturing, transportation, and distribution, use/reuse, recycling and waste management), products and processes interact with the environment (substances are extracted, modified, and added; land is used; and substances are emitted). Life-cycle thinking considers the cradle-to-grave implications of actions, and it acknowledges that the responsibilities of individual companies are not limited to those life-cycle phases in which they are directly involved. Life-cycle approaches are tools, programs, and procedures used to assess proposals, processes, and products from a life-cycle perspective. Throughout the life cycle, products and processes also interact with the economy and with social systems. Integrating economic and social aspects into LCA moves the concept from life-cycle environmental impact (its original focus) to life-cycle sustainability impact, an area of increasing importance — particularly for industries that operate in developing countries.

Life-cycle approaches reflect guiding principles such as dematerialization and eco-efficiency. Dematerialization refers to a substantial reduction in the volume of material and energy used to meet the demands of a user, while simultaneously increasing the quality of service. Eco-efficiency refers to the delivery of competitively priced goods and services to satisfy human needs while reducing resource intensity and ecological impacts throughout the life cycle — that is, producing more with less.

A variety of approaches, including life-cycle tools, checklists, models, and other techniques can be used to implement life-cycle thinking. The most common approach is the LCA. LCA is an analytical tool for the systematic evaluation of the environmental aspects of a product, process, or service system throughout its life cycle. It quantifies energy and resource inputs and outputs from cradle to grave and identifies and assesses the associated impacts. Chapter 3 describes the LCA process, and Appendix A identifies resources that contain detailed information on LCA and other life-cycle approaches.

Tools that relate to and can be used in conjunction with LCA include energy and material analysis, material flow accounting, substance flow analysis, environmental risk assessment, input/output analysis, life-cycle costing, total cost accounting, environmental management accounting, and cost benefit analysis. These tools, which model systems quantitatively, are intended to provide scientific information to help facilitate improved decision making. Other life-cycle approaches are meant to translate the concept of life-cycle thinking into practice. These include cleaner production programs, sustainable procurement, supply chain management, end-of-life management, product stewardship, integrated materials management, environmental management systems, design for sustainability, design for environment/eco-design, environmental labeling, environmental certification systems, and environmental impact assessment. Appendix B provides summary descriptions of many of these tools and approaches.

2.2 LCA HISTORY AND EVOLUTION

In the 1960s and 1970s, life-cycle approaches were used to account for cumulative energy use and predict future supplies of raw materials and energy resources. They were also combined with economic input-output models to estimate environmental emissions and economic costs associated with various energy technologies over their life cycles. In the early 1980s, interest in such approaches in the United States waned as the oil crisis diminished, and concern over hazardous waste increased. Life-cycle thinking moved to Europe, where inventory analysis continued, and regulators became interested in the concept. Until the late 1980s and early 1990s, LCA consisted primarily of emissions estimates and was typically used internally to evaluate packaging alternatives. But the desire to move from emissions to impact estimates led to the introduction of life-cycle impact assessment, or the translating of quantities of emissions into actual environmental impacts. This was important, because information on the release of emissions provides little indication regarding the degree of actual harm or environmental impact.

In the early 1990s, LCA was used for external purposes such as marketing. However, the lack of transparency on crucial aspects, need for assumptions, questionable data, and subjective valuations in many of these LCAs caused inappropriate marketing claims to be made and a reduced confidence in LCA.

Soon thereafter, interest in LCA approaches was rekindled as the regulatory focus shifted from end-of pipe treatment to pollution prevention and environmental optimization. LCA allowed for the quantitative, structured comparison of alternatives to identify environmentally preferred options, while addressing multiple environmental issues simultaneously. LCA application broadened from its earlier focus on packaging into applications in the building materials, construction, chemicals, automobiles, and electronics industries.

With the expanding range of applications, the need to standardize LCA approaches emerged, and efforts to effect such standardization began. Important players in this area were (and still are) the Society for Environmental Toxicology and Chemistry (SETAC), the United Nations Environmental Program (UNEP), and the International Organization for Standardization (ISO). SETAC is an academic society that organizes regular conferences on LCA, particularly on LCA methodology, and it sponsors workgroups on unresolved issues. It provides a forum where researchers and industry representatives discuss and exchange ideas on methods development. In 1993, SETAC published its Code of Practice, which described the components of the "traditional" LCA, i.e., goal and scope definition, inventory analysis, impact assessment, and improvement assessment (See Chapter 3). A number of other guidelines, manuals, and handbooks were prepared, but because they were written for specific purposes and were fairly rigid in their requirements, they provided little benefit for those not familiar with LCA. The demand for standards grew, and in the late 1990s, the ISO started to develop such standards. The ISO is a worldwide federation of national standards bodies, which, through various technical committees, prepares international standards for various topics. ISO standards are drafted according to a prescribed set of rules, draft standards are subject to review, and at least 75% of the member bodies casting a vote must approve a standard for it to be published. ISO published a series of LCA standards between 1997 and 2000.

After these standards were published, SETAC and the UNEP identified the need for (1) disseminating information about and (2) implementing life-cycle approaches in industrialized and nonindustrialized countries. In 2002, they launched a joint international partnership to put life-cycle thinking into practice worldwide and to improve the supporting tools through better data and impact indicators. In this partnership, known as the Life Cycle Initiative, the SETAC provides technical knowledge and advice, and the UNEP facilitates the process by involving stakeholders from different regions. Together, they work to enhance the application of sound life-cycle tools, to communicate achievements, and to establish training activities. Appendix C provides additional information on the Life Cycle Initiative.

In 2006, ISO published a second edition of the LCA standards. ISO 14040, *Environmental Management — Life-cycle Assessment — Principles and Framework*, together with ISO 14044, *Environmental Management — Life-cycle Assessment — Requirements and Guidelines,* cancels and replaces the previous LCA standards. The revisions in ISO 14040 and 14044 focused on improved readability and removal of errors and inconsistencies; the core technical contents remained largely unchanged.

ISO standard 14040 describes the principles and framework for LCA. It provides an overview of the practice and its applications and limitations. It does not describe the LCA technique in detail, nor does it specify methodologies for the individual components of the LCA (goal and scope definition, inventory, impact assessment, and interpretation). Because the standard must be applicable to many industrial and consumer sectors, it is rather general. Nonetheless, it includes a comprehensive set of terms and definitions, the methodological framework for each of the four components, reporting considerations, approaches for critical review, and an appendix describing the application of LCA. ISO standard 14044 specifies requirements and provides guidelines for LCA. It is designed for the preparation, conduct, and critical review of life-cycle inventory analysis and provides guidance on the impact assessment and interpretation phases of LCA and on the nature and quality of data collected.

In 2006, Phase 1 of the UNEP-SETAC Life Cycle initiative was completed. Over the four-year effort, individual task forces worked to improve life-cycle thinking in the following three areas:

- *Life-cycle management*. Created awareness and improved skills of decision makers by producing information material, establishing forums for sharing best practices, and conducting training across the globe.

- *Life-cycle inventory*. Improved global access to high-quality life-cycle data by facilitating expert groups to develop web-based information systems.

- *Life-cycle impact assessment*. Increased the quality and global reach of life-cycle indicators by promoting the sharing of views among experts.

Appendix D identifies key achievements and deliverables from Phase I of the initiative. At the end of Phase I, the partnership concluded that although significant progress had been made in life-cycle assessment methodology, understanding life-cycle management, and laying the foundation for building the skills and knowledge for the application of life-cycle approaches worldwide, more was required. The partnership found, for example, that life-cycle inventory databases and impact assessment methods are generally based on European or North American information and experiences, and that regional databases and appropriate impact assessment methods are still needed. The partnership also found that academic research and industry applications needed to be better balanced. In the fall of 2006, the partnership announced Phase II of the initiative. On the basis of feedback from Phase I, the mission of Phase II will be to bring science-based life-cycle approaches into practice worldwide. Specific objectives of Phase II include the following (UNEP 2006):

- Enhance the global scope of life-cycle approaches;

- Collect, develop, maintain, and disseminate information on successful applications of life-cycle approaches worldwide to resources (e.g., natural resources, chemicals, energy, water);

- Facilitate the use of life-cycle approaches worldwide by influencing management decisions in business and administration related to key "consumption clusters"; and

- Create capacity in the use of life-cycle approaches in key public policy and business stakeholders worldwide, in collaboration with regional life-cycle networks and other organizations.

The Phase II initiative is intended to go beyond the work on methodologies and capacity-building to practical applications that make a difference in the real world, and thus, contribute more effectively to ongoing international efforts to change unsustainable patterns of consumption and production.

Several of the expected results of the Phase II initiative may be particularly applicable to life-cycle thinking in the O&G industry. For example, one expected result is the integration of economic and social aspects into the LCA framework to establish economic and social life-cycle approaches that complement environmental LCA, with a long-term goal of standardization. Other expected results relevant to O&G LCA include the following:

- Long-term development and maintenance of a global life-cycle inventory database registry;
- Identification of relevant life-cycle studies and guidelines and assurance of their availability to interested parties;
- Life-cycle approaches developed and adopted for better application to resources; and
- Web-based database of practical guides, lists of information, tools, methodologies, and examples of life-cycle approaches in application for resource management.

Appendix E, which contains the entire list of expected results and near term activities, illustrates the current thinking on needs and future directions for LCA.

Industries are increasingly adopting LCA, and some larger companies with their own LCA specialists use LCA on a regular basis. Journal articles addressing LCA are increasing, and at least one journal (*International Journal of Life Cycle Assessment*) is devoted to LCA. This journal publishes articles and commentaries on LCA methodology and case studies. With increasing LCA experience, users are recognizing that LCA applications can vary, and that the use of life-cycle thinking, without necessarily conducting a "full-blown" LCA that follows rigid standards, can provide a useful decision-making tool for managers.

3 LIFE-CYCLE APPROACHES

This chapter focuses on the components and current thinking regarding the traditional LCA (Section 3.1). Section 3.2 highlights other life-cycle approaches that can also help improve environmental decision making.

3.1 LIFE-CYCLE ASSESSMENT

The term life-cycle assessment (LCA) is generally reserved for the analytical procedure or method that includes the compilation and evaluation of the inputs and outputs and the potential impacts of a product or process throughout its life cycle. Generally, an LCA consists of the following four components (or phases):

- Goal scope and definition
- Inventory analysis
- Impact assessment
- Interpretation

The ISO standards include additional phases for reporting and certifying the results. While these reporting and certification phases are important for LCAs whose results will be compared with other LCAs, conformance with these ISO standards is not necessary for LCAs whose results will be used solely for internal decision making.

LCA is an iterative method, where earlier phases may be revised on the basis of findings in later phases. LCA techniques, which typically cover cradle-to-grave inputs and outputs, can also be used in “cradle-to-gate” and “gate-to-gate” studies and to analyze specific parts of a product life cycle, such as waste management. Table 1 indicates for each LCA phase, its purpose, significance, and potential implementation issues and comments. The paragraphs that follow provide further descriptions.

TABLE 1 LCA Components

Component	Purpose/Results	Significance/Results/Benefits	Comments
Goal Scope and Definition	Defines purpose of study. Sets boundaries. Establishes functional unit.	Depends on subject and intended use of the study. Sets stage for entire analysis, including quality assurance. Breadth and depth of the study can vary considerably depending on the goal.	Must be clearly specified.
Life-cycle Inventory (LCI)	Provides inventory of input/output data of the system under study.	Data are collected to meet the goals of the study.	Data collection is resource intensive. Data may not be available at level needed. Data may be confidential.
Life-cycle impact assessment (LCIA)	Provides information to understand and assess the magnitude and significance of the potential environmental impacts associated with the inventory results.	Provides a system-wide perspective of environmental and resource issues.	Standard impact categories may not be sufficient to identify and assess all impacts. May need to use software packages that require licensing. LCIA results indicate potential environmental effects; they do not predict actual impacts.
Life-cycle Interpretation	Provides conclusions and recommendations based on the results of the inventory and impact assessments.	Uses a systematic approach to identify, evaluate, and present conclusions to meet the requirements described in the goal and scope.	

3.1.1 Goal Scope and Definition

In this first step, the goal and scope of the study are determined. The goal of an LCA includes the intended application (e.g., for analysis, design, information), the reasons for conducting the study, and the audience (e.g., within the company, the public). Goals could include gaining a better understanding of an existing system, identifying the main environmental problems in the product or process life cycle, identifying opportunities for improving the existing system, comparing systems and their potential impacts, and selecting options prospectively.

The scope identifies the product system or process to be studied, the functions of the system, the functional unit, system boundaries, allocation procedures, impact categories, data requirements, assumptions limitations, and type and format of the final report. While most of these terms are intuitive, the following explanations are offered:

- A *product system* is not defined in terms of the final product, but instead by its function. A product system consists of a set of unit processes that are linked to one another by flows of intermediate products or wastes. These flows include resources used and releases to air, water, and land. Dividing the product system into its component unit processes helps in the identification of the inputs and outputs of the product system.

- The *functional unit* provides a quantitative reference to which inputs and outputs are related. Examples of functional units for E&P studies could include barrels of oil produced, meters drilled for oil and gas, or one million Btu of gasoline available at the fueling pump of a refueling station.

- *System boundaries* are formulated based upon the scope of the LCA, and an initial collection of data. The quality of the life-cycle inventory (LCI), and the subsequent life-cycle impact assessment (LCIA), depend on an accurate description of the system and the boundaries drawn. According to UNEP (2005), at least three types of boundaries can be considered. These are the following:

  - *Boundaries between the system and the environment*. These identify the types of environmental and economic processes that are included or excluded. Because the processes included and excluded can greatly influence the results of the study, they should be described clearly.

  - *Boundaries between the system under study and one or more other related systems*. These boundaries define how the environmental load is allocated in a "multifunctional process." A multifunctional process generates several different products as a result of co-production, recycling, or waste processing. Petroleum refining is an example of a multi-functional process. The emissions and resource extractions of a multifunctional process must be allocated over the different functions that such a process provides. The defined boundaries will determine whether all products of a certain process are included in the analysis, or whether just one or a few products are included. Allocation can be based upon mass, commercial value, energy content, or similar product or process features.

  - *Boundaries between relevant and irrelevant processes*. This type of boundary addresses the removal of processes from the analysis. Processes can be removed (or cut off) for two reasons:
    - For simplicity; processes that do not represent a large part of the flow or are found to have insignificant environmental consequences are not analyzed; and
    - Lack of (accessible) data; a process cannot be quantified if there are insufficient data.

- *Impact categories* refer to the types of environmental impacts to be considered. Most LCAs cover a subset of about 20 such categories that include resource use, global warming, acidification, and others (see Section 3.1.3 for more discussion of impact categories.) The selection of impact categories will determine the types of data that will need to be collected.

- Data requirements depend on the level of detail of the study and the need for site-specific or generic data.

3.1.2 Life-Cycle Inventory

In the LCI phase, data are collected to quantify inputs and outputs of the system being studied to meet the goals of the defined study. The types of data include energy, raw materials, and other physical input; products, co-products, and wastes; releases to air, water, and soil; and other environmental aspects. Generally, a flow model (or flow chart), consistent with the system boundaries defined in the goal scope and definitions is constructed. The flow model shows the activities in the system (e.g., processes, transportation, waste management) and the input and output flows among them throughout the life cycle. Input and output data (e.g., raw materials, energy, products, solid waste, emissions to air and water) are collected for all the processes in the system. Calculations are then performed to estimate the total amounts of resources used and pollution emissions in relation to the functional unit. The results consist of an inventory of the environmental input and output data of the system being studied. Data can be presented in tabular or graphic form. An LCI will usually record all of the inventory results, but will typically focus on a subset of the total.

An inventory analysis can produce hundreds of inputs and outputs, but a simplified example is shown in Table 2. Table 3 is a sample inventory for comparing three alternative processes.

Once the data have been collected, users may decide to refocus the study on the most significant aspects by narrowing the scope and possibly even modifying the goal of the study. This iterative process can reduce the size of the study to a more manageable level, but it runs the risk of missing some impacts.

Many LCAs stop at the end of the LCI phase. This is perfectly acceptable, particularly for process-oriented LCAs, where relatively simple products such as oil and gas are produced, and where the users understand the significance of various chemical substances. Also, because LCIA methodologies have not yet been developed to characterize the environmental impacts of all substances, it may not be worth the additional effort to try to determine impacts in all cases. For manufactured products, in which vastly more parts and materials contribute to inventory results, aggregating and characterizing those results to show environmental effects may be more useful for decision making. Even for process-oriented LCAs, decision makers may want to know the impact of inventory results. The objective of the third step in the LCA is therefore to estimate the environmental impacts of the inputs and outputs of the product or process over its life cycle.

TABLE 2 Hypothetical Sample Inventory Results for Single Product or Process

Input/Output	Total Amount[a] (Per barrel of oil produced)
Energy Inputs	
Fossil	12.2
Electricity	6.3
Resource Inputs	
Oil	2.3
Water	62.0
Emissions to Air	
CO_2	22.4
Particulates	9.2
NO_x	4.5
Emissions to water	
Oil and grease	66.1
Arsenic	.01
Waste Generated	
Solid	200
Organic	50

[a] from all processes throughout the life cycle.

3.1.3 Life-Cycle Impact Assessment

LCIA assesses the results of the LCI (the quantified inputs and outputs) to understand their environmental significance. LCIA embodies a number of concepts that have evolved over several years. These concepts, and the terms used to denote them continue to evolve as various organizations in many countries contribute to the development of this component of LCA. Consequently, the first-time reader may feel somewhat overwhelmed by the number of concepts and the fact that several different terms are used to denote the same or similar concepts. The following paragraphs highlight essential LCIA concepts, incorporating many of the terms that are currently in use.

Objective. The objective of LCIA is to translate — or convert — inventory results (also termed environmental loads) obtained from the LCI into consequences. In LCIA, the significance of the emissions and extractions calculated in the LCI can be made more relevant. Thus, knowing that a process can result in acidification and that the potential for increased acidification is high relative to other impacts resulting from the process (a possible LCIA result), may be more useful than knowing that the process emits a certain number of tons of SO_2 (a typical LCI result). LCIA can also reduce the number of LCI inventory results (which can easily be more than 200 in some studies) to a more manageable number (20 or fewer) environmental impact categories. For example, LCIA can aggregate CO_2, methane, and other greenhouse gases (GHG) into one impact category (i.e., climate change, also referred to as global warming). LCIA can also be used to

TABLE 3 Hypothetical Sample Inventory for Three Process Alternatives

	Total Amount (Per barrel of oil produced)		
Input/Output	Alternative 1	Alternative 2	Alternative 3
Energy Inputs			
Fossil	12.2	9.3	4.5
Electricity	6.3	10.2	8.9
Resource Inputs			
Oil	2.3	3.5	4.2
Water	62.0	50.2	72.6
Emissions to Air			
CO_2	22.4	21.7	19.5
Particulates	9.2	7.8	10.6
NO_x	4.5	7.2	9.4
Emission to water			
Oil and grease	66.1	22.5	44.8
Arsenic	.01	.6	.05
Waste Generated			
Solid	200	250	180
Organic	50	44	60

[a] from all processes throughout the life cycle.

reduce the number of impact categories (through a weighting scheme) to an index value, intended to capture the results of the analysis in a single number.

Impact and damage categories. LCIA typically uses one or more models to generate impact category indicators, which relate to actual environmental impacts. For example, an LCIA might produce an estimate of the amount of global warming that could result from a given process in terms of Kg of CO_2 equivalents per functional unit. While this measure is not an impact per se (actual impacts would be, for example, effects on fish due to increase ocean temperatures), it provides a numerical indication of potential impact.

There is no standard or universally agreed-upon set of environmental impact categories. However, commonly identified impact categories include acidification, eutrophication, climate change, stratospheric ozone depletion, aquatic toxicity, human toxicity, fossil fuel depletion, water depletion, and land use. Sometimes, the term "stressor category" is used instead of "impact category." Stressor categories fall under one of three broad impact categories: human health, ecological health, and resource depletion. These broader impact categories are also referred to as "general areas for protection"; a general area for protection is composed of a class of "category endpoints." A category endpoint is simply an aspect of human health, the natural environment, or resource that identifies an environmental issue of potential concern. Endpoints represent quality changes to the environment and are also referred to as damage categories. Examples of category endpoints (damage categories) include forests, crops, and fisheries. A damage indicator would be the quantified representation of the damage category (although few, if any, LCIAs actually get to this point). Sometimes, the term midpoint is used to refer to the impact category, meaning that the impact is somewhere between the LCI result and the endpoint or broader impact category. The UNEP/SETAC Life Cycle Initiative has investigated potential damage categories and indicators and reported its results in Jolliet et al., 2003. Damage categories investigated include damage to human health, damage to the biotic natural environment (wild plants and animals, ecosystems), damage to the abiotic natural environment (occurrence of natural materials and structures of the non-resource type), damage to biotic natural resources (wild plants and animals used by humans), damage to abiotic natural resources, and damage to man-made abiotic environment (buildings and other structures).

Most impact categories are for results that occur early in the cause-effect chain. Thus, while an LCIA may aggregate and characterize emissions into a potential for acidification, (a midpoint category), the ultimate impact (e.g., change to forests, vegetation) — or endpoint — of that potential is not typically addressed. This is largely due to a lack of information on how to translate impact categories (midpoints) to damage categories (endpoints). However, a substantial amount of research is underway to develop better ways to relate impact categories (midpoints) to damage categories (endpoints). Not surprisingly there is no consensus on these issues. Jolliet et al. (2004) have summarized the current state of knowledge for various impact categories including those that are typically evaluated (e.g., eutrophication, ozone depletion), and those that are less frequently used (e.g., casualties, noise). Findings that may be particularly relevant to O&G LCAs are highlighted below.

- *Casualties*. To date, very few LCAs have considered accidents, but neglecting damages to human health due to accidents over the life cycle of a product could lead to biased decisions, if no other tools (e.g., risk assessments) are used in conjunction with the LCA.

- *Noise*. Noise can impact both human and ecological health. Inventories typically do not contain data on noise emissions, and quantitative impact pathways leading to a possible midpoint or directly to the human health damage need to be developed.

- *Land use impacts.* Use of land surfaces for anthropogenic processes can threaten species and ecosystems, and generic inventory databases have begun to register information on land use. While there are no agreed-upon models of land use impacts, high-resolution, satellite-based data on the earth's land cover may offer a basis for developing a globally applicable, location-oriented assessment model for the most significant land use types. Such a model could yield indicator values at the midpoint level, or it could express effects at the level of the damage category 'biotic natural environment'. The type of land use is of significance, particularly in developing countries, as are impacts on soil salinization, desiccation and erosion.

- *Species and organism dispersal*. The dispersal of invasive species due to anthropogenic processes may result in substantial changes in animal and plant populations. The resulting direct impact (midpoint category) is an altered species composition.

- *Abiotic resource depletion*. Use of abiotic natural resources (mainly metallic and non-metallic ores/minerals, energy, freshwater) is considered to be environmental damage because the exploited resource generally leaves the system 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 focusing on resource extraction. The applicability of these concepts to LCIA needs to be verified, and the manner in which resource use is quantified in the inventory needs to be better defined in most cases. Specific issues associated with freshwater and soil resources are connected with the fact that their geographical location is an important descriptor of their quality and value: The amount of freshwater available in Iceland is not the same as the amount available in Saudi Arabia, and quality of soil in the midwestern United States is not the same as the quality of soil in the Mississippi Delta. The resource impact category is especially crucial for developing countries, where a large part of resource extraction takes place. Developing the assessment of related impacts on soil quality such as salinization, desiccation, and erosion is essential for assessing relevant impacts in these countries.

A given LCIA does not necessarily assess all impact categories. Only those specified in the goal and scope definition phase of the LCA are addressed. The methodologies to be used for estimating impacts and the level of detail also depend on the goal and scope of the study.

3.1.3.1 Necessary LCIA Steps

To conduct an LCIA, three steps are generally followed, and in a formal LCA, these steps are required. Additional steps may be taken to normalize or otherwise refine the results, and methods for these steps (which require more subjective input than the first three) have been prescribed. The three basic steps required by the ISO standard for conducting an LCIA are as follows:

1. *Identification and selection of impact categories.* The set of impact categories to be evaluated for a given LCA will depend on that LCA's goal and scope. The impact categories will also dictate the types of inventory data to be collected in the LCI. The category indicators and models used to calculate the indicators are also selected in this step.

2. *Classification of LCI results*. In this step, results from the LCI (e.g., amount of SO_2 emitted per functional unit, amount of land used per functional unit) are assigned to the environmental impact categories (selected in the first step) to which they contribute. For example, contributors to the acidification impact category include NO_2, SO_2, HCl, HF, and NH_3, all or some of which may have been identified in the LCI. There are published lists of materials, chemicals, and other inventory results that contribute to individual impact categories. Some environmental inventory results or loads can be assigned to multiple impact categories. For example, SO_2 can be apportioned between the human health and acidification impact categories, and NO_x can be assigned to both ground-level ozone formation and acidification. Care must be taken to avoid any double counting of such results.

3. *Characterization*. Characterization provides an estimation of the magnitude of the environmental impacts for each impact category. After the inventory parameters are classified, they are characterized in a quantitative fashion to produce what is generally termed an impact category indicator or, more simply, a category indicator. Thus, the contributions to each impact category (or environmental problem) are quantified. A category indicator is not a measure of actual environmental impact. Rather, it is a quantitative indicator of change that is believed to correlate with one or more actual impacts. In the characterization calculations, the relative contributions of the LCI results (emissions, resources consumed per functional unit) to each environmental impact category are calculated. To do this, the LCI results that are assigned to a given impact category are first converted to common units. For example, tons of methane and CO_2 assigned to the climate change impact category would be converted to kilograms of CO_2 equivalents per functional unit. Conversion to common units is done through the use of equivalency factors. Equivalency factors are also referred to as equivalents, potentials, or characterization factors. Equivalency factors are derived from scientific cause-and-effect models of the natural systems, and they indicate how much a substance contributes to an impact category compared to a reference substance. Each impact category has its own environmental mechanism. The environmental mechanism is the system of physical, chemical, and biological processes for a given impact category that links the LCI results to category indicators (and category endpoints). For pollutants, characterization models reflect the environmental mechanism by describing the relationship between the LCI results and the category endpoints. For resources, other kinds of modeling approaches (e.g., based on occurrence) can be used.

   For greenhouse gases, characterization is based on the extent to which specific gases (e.g., CO_2, methane, chlorofluorocarbons, NO_x) enhance the radiative forcing in the atmosphere (i.e., their capacity to absorb infrared radiation and thereby heat the atmosphere). The equivalency factor for GHGs is global warming potential (GWP), which is the potential contribution of a substance to climate change. For example, the GWP for CO_2 is 1, whereas the GWP for methane, which is a more potent GHG, is 56 (over a 20-year period).

For any given impact category, there are often several models (usually of varying complexity) that can be used to develop a characterization (or equivalency) factor. For example in the case of acidification, all emissions that contribute to the acidification impact category (SO_2, NO_x, HCl, HF, NH_3) from the LCI results are summed based on their equivalency factors, producing an indication of the potential extent of the acidification impact. (Actual impacts would depend on the characteristics of the area in which they are deposited.) In the traditional acidification model, the equivalency factors of the acidifying pollutants are defined by their common denominator — they all release protons. An SO_2 molecule releases two protons, while an HCl molecule releases one. The equivalency factor for SO_2 is thus two, while the equivalency factor for HCl is one. The number of protons released by the acidifying pollutants indicates the potential acidification impact of the pollutants. In addition to this traditional model, there are several other models that include additional technical aspects and variations to produce alternative characterization factors, which their authors believe may more accurately reflect the cause and effect of chemical releases on acidification. A large portion of LCIA research is aimed at developing more robust characterization factors.

Characterization issues. Not all impact categories have adequate characterization models (and hence, characterization factors). Also, varying degrees of scientific knowledge and other factors mean that not all equivalency factors, and hence, the resulting category impacts, carry the same degree of scientific certainty and objectivity. Developing and refining models for all impact categories is an area of ongoing international research. Udo de Haes et al. (2001) describe the status of characterization models for several impacts.

Another concern regarding characterization models pertains to temporal and spatial differentiation. Depending on the goal and scope of the LCA and the environmental mechanism, the characterization model may consider spatial and temporal differentiations in relating the LCI results to the category indicator. Temporal differentiation can be important for substances that are persistent or that have delayed or long term impacts such as global warming. Spatial differentiation is an active area of LCA research, and a variety of approaches are being developed and tested. However, the issue of spatial differentiation is not simple to address in LCIA. To assess impacts in different locations, the inventory data would likely need to be collected at different locations, thereby adding another layer of effort to the LCI phase. At this stage of model development, there are few, if any, standard characterization models that apply to specific geographical or political areas. Attempts are being made to develop models for different types of situations, for example, areas that vary with population density, or for specific countries or regions.

To help ensure that the results neither over nor underestimate the impacts of those impact categories for which quantitative estimates have been calculated, the LCIA must address both impacts that have been characterized and those that have not been characterized.

Indicator results. Once all of the LCI inventory results have been classified and converted, they are summed to provide an overall category indicator result. Various terms for the results of the characterization exist. They include category indicator results, indicator results, or even LCIA results. For example, the category indicator results for acidification could be protons (which cause acidification), and the indicator results for land use could be acres or hectares. Together, the indicator results for different impact categories represent the LCIA profile for the process (or product) for which the LCA is being conducted. The precision and accuracy of the indictor results may vary among impact categories due to the differences between the model and the corresponding environmental mechanisms, the use of simplifying assumptions, available scientific knowledge, and data availability. As noted earlier, the temporal and locational aspects of LCI inputs and outputs are typically not considered in most LCAs. This means that while the impact(s) of certain emissions (e.g., toxic chemicals) depends on when and where they are emitted, such factors are not captured in most characterization models.

One of the task forces of the UNEP/SETAC Life Cycle Initiative is working to develop standardized approaches, or at least, criteria to consider when making the transition from impact to damage. This is an active area of LCA research. The Life Cycle Initiative is also working to evaluate existing characterization indicators, make recommendations on appropriate use, and inform practitioners of known practical limitations. The initiative sponsors workshops on various LCIA topics that include, but are not limited to, characterization factors, approaches for addressing land and water use, common toxicity models for classes of contaminants, transboundary impacts, and even indoor air. These efforts are aimed at providing readily available practical information on conducting LCIAs.

As noted at the beginning of, and demonstrated in, this section, LCA practitioners use a variety of LCIA terms — often to denote the same concept. Table 4 illustrates how these terms are used by (1) listing the basic LCIA steps used to identify the life-cycle impacts for two commonly assessed impact categories (climate change and acidification) and (2) mapping the various LCIA terms to the appropriate steps.

3.1.3.2 Optional LCIA Steps

The three steps (impact category selection, classification, and characterization) described in Section 3.1.3.1 constitute the basic LCIA methodology. They are relatively objective in nature, although judgments are often required (for example, in allocating inventory results to multiple impact categories). Optional steps, which may be undertaken to refine the results, require additional subjective input. Consequently, the results of these steps have a weaker scientific basis than that of the first three. Examples of some of these additional/optional steps are presented below.

TABLE 4 Illustration of LCIA Terms and Methods for Two Environmental Impacts

Term[a]	Impact Category: Climate Change (or Global Warming)	Impact Category: Acidification
• LCI result • Environmental load	CO_2, methane, N_2O, per functional unit	NO_2, SO_2, HCL, HF, NH_2. (kg/per functional unit)
LCI Results are ***classified*** into appropriate impact category:		
• Environmental impact • Environmental impact category • Impact Category • Stressor Category • Midpoint • Environmental problem	Climate change	Acidification
Classification results are ***characterized*** using a factor to produce a result		
• Impact category indicator • Category indicator	Infrared radiative forcing (W/m2) (a proxy for potential effects on the climate)	Proton (H^+) release
• Equivalency factor • Characterization factor • Equivalent • Potential	Global warming potential (GWP) for each greenhouse gas (Kg CO_2 equivalent/kg gas)	Protons (H^+) for each acidifying gas
• Category indicator result • Indicator result • LCIA result	Kg of CO_2 equivalents per functional unit	Total protons (H^+) per functional unit
Linkage between category indicator result and endpoint		
• Category endpoint • Damage category	Coral reefs, crops	Forest, vegetation
Damage Indicator	Not typically done at this point as part of an LCA.	Not typically done at this point as part of an LCA.

[a] Many of the concepts in LCIA are denoted by multiple terms. All of the terms in a given cell in the Term column are synonymous.

- *Normalization*. Normalization allows the results of the LCIA to be viewed relative to outside concerns. For example, the results of the process (or product) being evaluated in the LCA can be related to the total amount of that result for the impact category in a given region. In the normalization step, an indicator number (from the LCIA) is divided by a reference amount (from outside the LCIA) to help place the results in perspective. When the results from the characterization (the aggregated data) for each impact category are related to a reference value, these normalized results can increase the comparability of the data from the different impact categories.

- *Valuation*. In this step, the contributions from the different impact categories are weighted so that they can be compared among themselves. For example, an objective of the LCA might be to compare two processes. The results may indicate that one process has a greater impact on global warming and the other a greater impact on human health. The valuation process helps determine the relative importance of the impact categories. This exercise, which is typically conducted by using some combination of expert judgment and input from affected or otherwise interested parties, is highly subjective.

- *Weighting*. It is possible that some category indicators may be more important than others to the user of the LCA. For example, in a location at which eutrophication may not be as much of an issue as human toxicity, a higher weighting factor could be assigned to human toxicity than to eutrophication. By multiplying each indicator by its respective weighing factor, these relative values can be incorporated into the result.

- *Aggregation*. In some LCAs, particularly those used to compare two or more alternatives, the results from the characterization are further aggregated to produce a single index. The degree of aggregation depends on the purpose of the study. For example, for purposes of providing eco-labels, aggregation may be appropriate for designating whether a product is to be considered worthy of the label or not. In this case, a single index is appropriate. However, for applications in which the purpose is to identify improvement possibilities, it may be more appropriate to present the results so that they can be interpreted at both the inventory level and at the impact level.

3.1.3.3 LCIA Modeling Systems and Software

For practical purposes, unless an organization has an in-house life-cycle staff, conducting an LCIA is most efficiently accomplished through the use of existing modeling systems and software packages. These systems contain category-specific characterization models that translate inventory results directly into category indicators. They also present the results in graphic formats for use in decision making. Several such models exist, and many contain algorithms for normalization, weighting, and aggregation. Some contain input-output modules that estimate the inventory results for various portions of the LCA, for example, resource extraction, steel manufacturing, or transportation. Some provide for analysis used in the interpretation phase (see Section 3.1.4) to evaluate the quality of the results. LCIA models have been developed by universities, governments, and commercial enterprises, and their availability and licensing approaches vary. Significant variations in approach, philosophy, type of result produced, and data coverage reflect the different purposes for which they were developed.

Generally speaking, LCIA models can be grouped into two categories. The first category contains what have been termed the classical models, or those that stop once the LCI results have been linked to the midpoint categories (e.g., acidification, ozone depletion.) An example of such a model is the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) model, developed by EPA to facilitate the characterization of environmental stressors that have potential effects, such as ozone depletion, global warming, acidification, and others. The second category of LCIA models are the damage models. These models go further than the classical models, by modeling causes and effects to estimate actual damages. While the classical models produce a midpoint category indicator such as ozone depletion potential — an environmental concern that relates to depletion of the ozone layer, they do not attempt to estimate actual damages to humans, animals, and plants that stem from this depletion. The damage-oriented methods strive to produce LCA outcomes that are more easily interpreted for further weighting. In the ozone example, the damages to human health, the natural environment, and to natural resources are estimated and expressed in terms of, for example, additional cases of human health impairment or species endangerment. These results allow for making the different endpoints more comparable and reducing the number of endpoints.

Some damage models are designed to produce a single score. These are particularly useful for internal company use for product development applications. However, they generally embody cultural values that must be understood. An example of a damage-oriented model is Ecoindicator '99, which incorporates cultural perspectives ranging from an "individualist" view, in which only proven cause-effect relationships are considered environmental impacts, to an "egalitarian" view, in which the precautionary principle (nothing is left out) drives the assessment. Not surprisingly, the different models will produce different LCIA results.

Most LCIA models have been developed for use in countries other than the United States, particularly in Europe or Japan, and the data they contain may be based on experiences in the countries for which they were developed. In considering whether and which particular model to use, the user should understand the various aspects of each model being evaluated so that the model selected is most appropriate for the LCA being contemplated. Consultants can help in such evaluations. They can also be hired to help direct the goal and scope definition and inventory collection phases in addition to conducting the LCIA with sophisticated models. The need for and level of such consultation will vary with the expertise of the LCA user and the nature of the LCA to be conducted. Appendix F provides summary information on several models and methods that are used today, as well as links to the original references. In general, all models are constantly being updated and expanded to incorporate new data, impact categories and characterization models as the understanding of environmental problems increases and priorities change. Also, there are increasing efforts to identify actual rather than potential impacts, and to consider geographic differences, background loads, and other factors. Readers desiring to keep abreast of these developments may wish to follow the progress of the UNEP/SETAC Life Cycle Initiative (http://lcinitiative.unep.fr/).

Much research has been conducted on the optimal approaches for estimating life-cycle impacts and the challenges associated with estimating and interpreting results. Examples of such research areas and findings are highlighted below. Readers are encouraged to consult with the original sources for more information.

- *Resource Depletion.* Stewart and Weidema (2005) discuss some of the issues associated with quantifying resource depletion in LCA. They say that, to date, methods for quantifying resource depletion impacts have focused on resource extraction, and that the concern is not the extraction of material, but the dissipative use and disposal of materials. They suggest a framework that describes impacts related to all resource categories and provide recommendations for functionality measures for these categories. While some of these framework ideas can become fairly technical, they serve to demonstrate the uncertainties and debates regarding LCA approaches and that new ideas are constantly being introduced.

- *Land Use.* The UNEP/SETAC Life Cycle Initiative has identified the need to address land use impacts in LCA in all life-cycle stages and products. In June 2006, it held a workshop to address this need. The workshop discussed whether LCA is suited to include land-use impacts and recommendations for biodiversity and soil quality indicators. In a document summarizing the workshop, Milà i Canals et al. (2006), noted that accounting for land use in LCA is inherently problematic: While land represents a scarce resource, it is not merely consumed as are mineral or fossil energy reserves, which are extracted and dissipated. Land-use effects on biodiversity and soil quality are non-linear and depend on the scale of land use, which is difficult to address in LCA. Soil is multi-functional and many threats affect its quality, which results in a case-specific selection of the most adequate indicator. In the case of biodiversity, two main options for defining indicators were identified at species and ecosystem levels. The main advantage of the former is data availability, but the election of a particular taxon may be arbitrary. Ecosystem level indicators include a higher degree of subjectivity but may be more relevant than species level indicators. Some of the conclusions from the workshop are highlighted below.

    - LCA is considered a suitable tool for incorporating land-use impacts, particularly when comparing systems that differ substantially in terms of land-use impacts (e.g., energy production from energy sources obtained from forests vs. agriculture vs. mining).

    - Regarding biodiversity indicators, there is no consensus regarding species- vs. ecosystem-level indicators. The potential ease-of-use of the first contrasts with the need to incorporate the more qualitative information (e.g., ecosystem scarcity, degree of fragmentation, etc.) captured by ecosystem level indicators. The decision on the type of indicators is left for the practitioner, and some criteria and examples to select indicators were proposed in the workshop discussions.

    - The conduct of LCA case studies of systems in which consideration of land use impacts is essential (e.g., activities which make an extensive use of land, land-based vs. abiotic- based products, etc.) could provide a good platform for addressing the research needs that follow from the above conclusions.

    - A particularly relevant case study requiring the incorporation of land-use impacts in LCA, which is important in the current energy policy context, is the comparison of energy sources (e.g., bio-energy A vs. bio-energy B vs. fossil energy). It would be important to include different eco-regions to account for the potential international trade in energy crops. These studies could be used to further develop the suggestions made here with regard to biodiversity and soil quality indicators for LCA.

- *Risk*. The traditional LCA does not produce impact values per se (e.g., number of premature deaths), but only a scale of impacts relative to some reference value (e.g., annual emissions of SO_2) at a national or global level. LCIA researchers have therefore developed an approach that moves toward integrating risk assessment with LCA. The following comes from Nishioka et al. (2005). The results of the traditional LCIA may be useful for screening the relative importance of potential impacts, but when they do not consider how emissions influence exposure, they fail to account for the regional and source-related variability of impacts. Spatially generic impact assessment approaches can lead to decisions that favor products and services that simply reduce the quantity of potentially harmful pollutants, regardless of location. However, because emissions in densely populated areas could lead to more health impacts than emissions in less-populated areas, and because atmospheric conditions can influence pollutant fate and transport differently in different areas, such a simplified approach could produce misleading results. A site-specific risk assessment could be used to account for exposure differences, but because of the very large number of sources of emissions in the supply chain, such an approach, with traditional fate and transport modeling, would not be practical. A new tool considers the geographical variability in both emissions and exposure and can be applied to all economic sectors in an input-output analysis. The method relies on screening-level risk calculations and methods to estimate population exposure per unit of emissions from specific geographic locations. The method can be useful for identifying the geographical distribution of health benefits was different from the distribution of energy savings due to differences in energy sources, population densities, and meteorology.

3.1.4 Life-Cycle Interpretation

The LCI and the LCIA provide data about environmental releases and impacts. To use these results for process, product, or design changes, or for other purposes, decision makers need an understanding of the reliability and validity of the information. Analyses to assess the robustness of the results and conclusions include the following:

- *Sensitivity analyses* identify and check the effect of critical data on the results. They can be conducted by systemically changing the input parameters. Input parameters for which only a small change leads to a major change in results would be identified as the most critical — and those for which accurate data are most important.

- *Uncertainty analyses* check the effect of uncertain data (e.g., data that are estimated or approximated). Uncertain data occurs when, for example, the environmental performance of different suppliers varies or production process under different conditions produce different emissions. To determine the effect of uncertain data, the varying data must be collected and evaluated to examine their range and distribution.

- *Variation analyses* assess the effects of alternative scenarios and life-cycle models. For example, if the same processes are used in two different countries with different energy sources, the life-cycle results could be different. Also, by changing chemicals used in a process or the materials used in various types of equipment, users can identify and evaluate which changes have significant impacts on the results and which produce only small changes.

Other analyses conducted in the interpretation phase to help evaluate results include the following:

- A *contribution analysis* identifies the environmental loads that contribute most to the total environmental impact. Once the impacts have been characterized in the LCIA, the contributions of the various emissions can be identified and compared. Thus a certain inventory item is traced back to the share for which the different unit processes are responsible. Typically, the results are presented as percentages of the total for each emission in the process's environmental profile.

- *A dominance analysis* identifies the parts of the life cycle that cause the greatest environmental impact. In a dominance analysis, the emissions or environmental impact of each activity in the life cycle are examined. A dominance analysis can show areas or processes in which improvements are most needed or desired. The dominance analysis can also help identify relatively benign activities, which may be important in debates over what production processes cause the greatest environmental concerns. Activities can be grouped together so that a dominance analysis can compare impacts (or inventory results) for aggregated phases such as production, transport, use, and waste management.

- A *breakeven analysis* is used to investigate trade-offs pertaining to the use of products. For example, energy use associated with different containers (e.g., single-use versus multiple-use containers) can be compared. Here, the intent would be to determine the number of times that a multiple-use container must be used before the energy consumed in its more complex production process (and in its washing between uses, if necessary), equals that of the more simple-to-produce (and therefore presumably less environmentally damaging) container that is used only once. Breakeven analyses can also be used to compare materials over their life cycles. For example, aluminum, steel, and plastic tankers could be compared over their life cycles to identify breakeven points. In such comparisons, manufacturing processes, recycling options, and energy consumption during the use phase would be compared with the weight of each tanker and recycling options considered for each material.

- A *perturbation analysis* identifies parameters for which a small change induces a large change in a selected result. The factor that relates a small change in input to a change in output is known as the multiplier. Multipliers larger than 1 or smaller than −1 indicate sensitive parameters; multipliers close to 0 indicate insensitive parameters.

- A c*omparative analysis.* A comparative analysis is a systematic, simultaneous listing of the LCA results for different alternatives. A comparative analysis can be used, for example, to compare CO_2 emissions corresponding to a functional unit of 1 terrajoule of electricity in several countries, each having its own alternative national electricity scenarios (Heijungs et al. 2005).

Several LCIA software packages incorporate one or more of these analyses. For example, Heijungs et al. (2005) describe the results of several of the above analyses that were conducted for a large system of interconnected processes using the Ecoinvent database. They also comment on the performance of those analyses by the software. They conclude that at least some of these analyses should be included in any LCA that goes beyond screening, as they can help understand the quality and robustness of the study results. For example, they suggest that a perturbation analysis can help discriminate between data items for which low or moderate data quality is sufficient and data items that need high-quality data. They also emphasize how the connection between inventory analysis and interpretation phases stresses the iterative nature of the LCA process. Finally, they note that the "overwhelming number of methods for life-cycle interpretation . . . may stupefy some people who have had no specific training in mathematics or statistics." They suggest using contribution and comparative analyses for communication with the intended audience or commissioner of the study, because they provide information on the ranking of options and the robustness of those rankings, but they caution that many of these analytical approaches are used solely by the LCA practitioner to support data collection.

3.1.5 Reporting and Reviewing

In addition to the above LCA phases, ISO also contains standards for reporting and critical review. The reporting standards state that the report should address, among other things, the different phases of the study and should address the data, methods, assumptions, and limitations. The critical review verifies whether the LCA has met the methodology, data, interpretation, and reporting requirements, and whether it comports with the principles. The ISO standard notes that critical review can facilitate understanding and enhance the credibility of an LCA, and describes several critical review processes.

3.2 OTHER LIFE-CYCLE APPROACHES

Besides the traditional LCA described in Section 3.1, several other life-cycle tools and approaches can be used to incorporate life-cycle and cradle-to-grave thinking into environmental decision making. Four such approaches are summarized below.

Life-cycle study. A life-cycle study reports on the results of analyses that use a life-cycle approach. It may include results from an LCA, from qualitative life-cycle reviews, life-cycle costing, etc. The specific tools used to conduct the analysis will depend on the specific decision-making or management needs.

Life-cycle costing (LCC). Life-cycle costing is a tool that looks at the complete life span of a product, process, or activity and calculates the entire life-cycle cost. LCC is generally used for decisions about the design and development of products, processes, and activities. An LCC analysis includes all internal costs incurred throughout the life cycle of the object under investigation. These include conventional costs (initial investment, capital, operating, abandonment, performance evaluation costs) and less tangible, hidden, indirect company costs (such as environmental permitting and licensing, reporting, waste handling). Normally, it does not include external costs. External costs are those for which the company is not responsible; that is, neither the marketplace nor regulations assign such costs to the firm. LCC calculates the net present value of both capital and operating expenses over the life of the project. The tool can be used to choose among alternative options during the conceptual, planning, design, construction, and operating stages of facilities. The use of LCC in the O&G E&P industry is relatively new. Historically, the financial viability of O&G industry projects has been assessed on the basis of minimum capital cost, with operating costs playing a small role, if any, in the decision-making process, and end-of-life costs not considered. By ignoring potentially large noncapital costs, higher total costs may have resulted. Obstacles to using LCC include poor data availability; inconsistently reported data; and uncertainties regarding discount rate, asset life, and estimating future operating and maintenance costs. Information on developing models for LCC analysis in the O&G industry is available in Vorarat et al. (2004).

Life-Cycle Value Assessment (LCVA). This tool extends the traditional LCA to include economic and social implications in addition to environmental issues. According to Row et al. (2002), LCVA systematically examines the planning, production, consumption, recycling, decommissioning, or disposal of a service or product. It can focus on financial and/or technical risk analysis, identification and development of system improvements, or stakeholder issue identification. The LCVA methodology begins similarly to the LCA methodology, with goal definition and scoping. Financial, energy, and material inputs and outputs are then identified qualitatively for each unit process. The relative importance of identified impacts, and the stated objectives of the LCVA, help to identify the life-cycle stages, and the environmental, financial and social issues that are likely to provide the most valuable information for improved decision making. Only these parameters are selected for quantification, effectively setting the system boundaries for the LCVA. Data are compiled and modeled to provide aggregated results for various scenarios and systems to answer the key questions outlined in the LCVA goal definition. Results are assessed in terms of their relative impacts and significance. LCVA offers a systematic approach for finding opportunities to reduce the negative social, economic, and environmental impacts throughout the full life-cycle system. It can also be combined with other concepts and tools such as pollution prevention and design for environment. Several Canadian oil companies have adopted LCVA (See Section 5.1.12).

Life-cycle management (LCM). Decisions taken at all levels of an organization influence the overall impact a product has throughout its life cycle. With life-cycle management, environmental concerns are treated in a coordinated fashion throughout the company and life cycle rather than as independent concerns in each company or operation. According to the SETAC Working Group on Life-Cycle Management, LCM can be described as a system/framework for improving organizations and their respective goods and services. It is a flexible, integrated framework of concepts, techniques, and procedures to address environmental, economic, technological, and social aspects of products and organizations to achieve continuous environmental improvement from a life-cycle perspective. Integrated among all functions of the organization, the framework addresses improvement to technological, economic, environmental, and, occasionally, social aspects of an organization and the goods and services it provides. The LCM concept is often seen to improve decision making by placing better information in front of decision makers.

Other concepts of LCM exist. These embrace the following ideas, which give a general flavor for the breadth of its application:

- LCM assures that the processes used across projects are consistent and that there is effective sharing and coordination of resources, information, and technologies. Thus, life-cycle thinking spans activities from conception of ideas through retirement of a system.

- LCM is business-management tool based on environmental life-cycle considerations.

- LCM extends the technical approach toward cleaner products and production through amending stakeholder views and by communication and regulatory tracking.

- LCM is a concept of innovative management toward sustainable products, which supports strategic decision making and product development.

According to UNEP (2005), the LCM framework is not meant to replace existing concepts, programs, and tools. Rather, it is meant to provide a synthesizing approach for improving the application of existing structures, systems, tools, and information in a life-cycle or systems perspective. Thus, according to this framework, LCM incorporates the concepts of sustainable development, dematerialization, cleaner production, industrial ecology, eco-efficiency, etc. Policy and corporate programs used with LCM include supply chain management, extended producer responsibility, sustainable procurement, stakeholder engagement, corporate social responsibility, communication, etc. Procedural tools include design for environment, integrated and environmental management systems, product development processes, audits, environmental performance evaluation, labeling, environmental impact assessment, etc. Analytical tools include LCA, material flow analysis, environmental risk assessment, etc. Models include fate, dose-response, etc., and techniques include weighting, uncertainty, sensitivity analyses.

4 BENEFITS AND CONCERNS ASSOCIATED WITH LIFE-CYCLE APPROACHES

4.1 BENEFITS

Incorporating the life-cycle concepts into decision making — via a full-blown LCA or other life-cycle approaches — can help policy makers, industry, and private organizations make decisions about design and operations that can affect the environment. LCA can be used as a scientific tool to gather quantitative data to inventory, weigh, and rank the environmental burdens of products, processes, and services. Transparent and based on science, life-cycle approaches can give decision makers information to

- Help identify products and processes that result in relatively lower environmental impacts and those that produce relatively higher environmental impacts than comparable products or processes.

- Identify opportunities to improve environmental performance of products or processes at various points in their life cycle (for example, using a different process or selecting a different vendor).

- Identify "hot spots" — areas of potential environmental concern or activities that cause the greatest environmental impacts — early on in a process.

- Help optimize the effects of improvements. By making adjustments in the stage of the life cycle where the costs of intervention are relatively low (e.g., redesigning a product to make it better suited for recycling) rather than in later stages (e.g., developing recycling methods for an existing product), the costs of environmental improvements can be minimized.

- Help select a product or process optimized for a given application when used in conjunction with other information (such as cost and performance data).

- Facilitate environmental regulatory reviews. LCA-based findings may help regulators understand the overall impacts of proposals and demonstrate that companies have carefully considered the implications of proposed actions.

By knowing extent of potential impacts, and where they occur, decision makers can address them early on — in the design or development phase. By considering environmental impacts over the entire life cycle of a technology, product, or process, LCA can help decision makers avoid "problem shifting." Problem shifting occurs when, in trying to solve a problem, decision makers shift the part or all of the impact from one life-cycle stage to another (e.g., from use to raw material acquisition), from one location to another, from one environmental impact to another (e.g., from air to water), or from the present to the future.

LCAs can be used in product development, process choices, and in developing waste management options and recycling approaches. Specific applications relate to waste minimization, material/chemical substitution, dematerialization, pollution prevention, recycling/reuse, and even pollution control through end-of-pipe technology.

4.2 CONCERNS

Barriers to using LCA can lead to lost opportunities for improved environmental decisions. Potential concerns that affect the use of LCA include the following:

- Resource requirements
- Data requirements
- Lack of appropriate methodologies
- Limited guidance
- Uncertainties over implementation of results
- Validity
- Scientific basis
- Transparency
- Absence of perceived need
- Organizational structures

These concerns are described in the following paragraphs.

- *Resource requirements.* Implementing a traditional LCA requires specific LCA expertise, know-how, commitment, and funding. Large companies interested in using LCA may be able to pay outside entities to provide needed expertise and know how, but justifying such expenditures for smaller companies may be problematic.

- *Data requirements.* Collecting data can be one of the most resource-intensive parts of an LCA, and poor data can limit the validity of the conclusions of an LCA. Accessing high-quality data can be an obstacle to conducting an LCA, particularly as the scope and detail level increase. Good data sources exist, but many are not available publicly. The range of LCI databases vary in design, format, and quality. Often, data are not available at the level (e.g., geographic, process) needed. This lack of consistency and transparency makes validation and documentation of the databases difficult. Efforts to improve data availability are underway. Some industry organizations are developing databases with data that have been vetted within the industry. Public, shared databases are being developed at the international and national levels in Europe, Japan, and Korea on specific parts of the life cycle, such as energy systems, transportation, waste management, and production of bulk materials. The UNEP/SETAC Life Cycle Initiative commissioned a study of available LCI databases around the world, including public and proprietary (or restricted access) databases and LCA software programs that contain inventory data. The final report (Curran and Notten 2006) describes activities to develop publicly available databases across the world and contains tables summarizing regional LCI data resources, national database projects, industry databases, LCA networks and societies, and LCA software. Appendix G contains excerpts from this report that may be relevant to O&G LCAs.

- *Lack of appropriate methodologies*. Standard LCA approaches and software packages may not address all potentially relevant impacts. For example, Section 1 described several potential environmental, economic, and social, concerns associated with O&G E&P. However, the standard impact categories outlined in the ISO standards do not necessarily cover all of these potential impacts, and vetted models for estimating them may not exist.

- *Limited guidance.* LCA guidance materials range in terms of quality and detail. There are few guidelines regarding indicators to be used and methods for evaluating different impacts, and because most guidance documents concern individual countries or regions, their applicability at the international level, or for other nations is limited. Recognizing these concerns, the UNEP/SETAC Life Cycle Initiative has initiated efforts to develop and disseminate guidance materials.

- *Uncertainties over implementation of results*. The results of an LCA may suggest a change in a company's operations. A study by Paulsen et al. (2006), which is described in Section 5.1.4, exemplifies this concern. Relevant conclusions from that study follow here. "Dedicated competence groups within an organization are somewhat reluctant to changes and particularly changes that don't evolve from activities within the group itself." Changes required from outside the organization (e.g., from suppliers) may also be difficult to effect. The scale of a company's operations may affect the ability to successfully implement LCA results. For example, one life-cycle analysis found that changes to drilling fluid supplier operations that would allow for efficient reuse and handling of fluids would reduce overall life-cycle impacts. Such changes would require contracts that cover several wells or operations, and possibly, additional infrastructure and rig-based facilities for handling and treatment of drilling wastes. The requirement for using contracts with large-scale operations combined with the need of fluid providers to control all equipment related to waste minimization (because this influences total performance) could create a monopoly situation. A monopoly situation would disadvantage smaller companies. On the other hand, experience has shown that innovative and improved technical solutions often come from smaller companies, whereas large service companies can be more reluctant to improve technology.

- *Validity.* Validation checks whether a model is correct by comparing its results to those of the system it is imitating. Ciroth and Becker (2006) note that the LCA methodology has been "astonishingly successful" over the past decade, as evidenced by the standardization of the LCA concept, the proliferation of LCA activities (particularly in Europe), and the increased number of conferences and publications. However, they suggest that there are no checks on whether the output of LCA models match the output of the real system they were built to address and that from a scientific viewpoint, the LCA method lacks empirical validation concerning its most important aspect — the overall result. They note that under the current LCA approach (as reflected in the ISO standards), following the rules has become as important, if not more important, than obtaining accurate results. They suggest that the power of and value provided by LCA would increase significantly if it were validated.

A study by Norman et al. (2007) explained the effects of trade — a relatively subtle and recently identified concern — on LCA results. The study found that accounting for trade can significantly alter the results of life-cycle assessment studies, and that the production and consumption of goods in one country can exert significant energy and GHG influences on the other. While life-cycle techniques that are being used to estimate total energy use and GHG emissions cross an industry's entire supply chain, the predominance of internationally supplied resources and products can complicate attempts to account for total supply chain effects. This is because the same industry in different countries can exhibit significant differences in production structure and overall manufacturing energy intensity. Hence, international differences in resource use, energy efficiency, production methods, and environmental laws and practice may produce dissimilar life-cycle environmental impacts from industrial production. In their study, Norman et al. identified differences in industrial energy use intensity and GHG emissions intensity between Canada and the United States, interpreted the major causes of the differences, and examined the implications of these differences for LCA on the basis of the level of trade between Canada and the for different sectors of the economy though an input-output-based LCA model. The results showed that in general, both countries exhibit similarly low energy and GHG intensities for light manufacturing (e.g., clothing production) and secondary manufacturing (e.g., appliance, motor vehicle production). However, for O&G extraction (and mining, electric utilities, and chemical production) the differences were greater. For oil and gas extraction, differences in energy and GHG intensity are influenced by international variations in processes. For example, in Canada, energy-intensive oil sands production accounts for more than one-fourth of Canadian oil production, but in the United States, little if any oil is produced from oil sands. The high levels of energy required for oil sands extraction likely explain much of the cross-border discrepancy in energy intensity and GHG intensity. Energy intensity is 50–100% greater, and GHG intensity is 10–50% greater for oil and gas extraction in Canada than in the United States.

- *Scientific basis.* Although the claim that LCAs are scientifically based is usually considered a positive aspect, unless the LCA follows the standards in ISO 14040, there is no guarantee that the results are actually based on science.

Thus, life-cycle studies that do not follow the steps of a traditional LCA may be criticized as lacking scientific support.

- *Transparency.* Transparency is also generally considered as a positive aspect of LCA. But sometimes it is difficult to demonstrate. When the results of different LCA studies are compared, it is particularly important that the assumptions and methodologies are clear, consistent, and documented. Existing standards and guidance provide some guidelines, which, if followed, will ensure consistency, but for some issues, the standards are silent or ambiguous, leaving room for the use of an extensive range of methods. Many of these methods lack transparency on core methodological issues, making it difficult to compare them with other methods (UNEP 2005).

- *Lack of awareness and perceived need.* Many companies do not see how life-cycle thinking can be applied to their specific operations — or even the benefits of doing so. While demands from customers to incorporate life-cycle thinking could stimulate the interest of more companies in life-cycle thinking there is a low level of awareness on the part of consumers. Many potential users are unaware of how life-cycle approaches can aid in decision making. Documentation of performance improvements can be tedious and resource intensive, but may be necessary to verify the results of changes resulting from life-cycle thinking. The results of many LCA studies remain within the confines of a particular company or organization and are never published. Options for integrating or at least considering LCA analytical approaches and results in conjunction with other environmental and decision making tools will be needed to show how LCA can contribute to improved decisions.

- *Organizational structure.* Often, life-cycle practitioners are functionally a part of a company's environment, safety, and health division — separated or disconnected from the process design and product development departments. Thus, the knowledge of the life-cycle practitioners is not shared with developers, and the developers may not be aware of how life-cycle thinking can be integrated into design and development.

While many organizations have been reluctant to use LCA because of these and other issues, they also recognize that considering the life-cycle aspects of products and processes can improve decision making, optimize long-term project costs, and minimize adverse environmental and social impacts. Interest has also been increasing over the past few years due to the issuance of the new ISO standards and efforts by organizations such as the UNEP and SETAC to address many of these issues. As a result, many more companies have begun to incorporate life-cycle thinking in some fashion, though not necessarily embracing all of the requirements of the ISO standard. Today, life-cycle approaches range from back-of-the-envelope calculations to full-blown, traditional LCAs. The next chapter provides examples of several LCA applications, with an emphasis on those conducted within the O&G E&P industries.

5 APPLICATION OF LIFE-CYCLE THINKING

In addition to the benefits described in Section 4.1, drivers for using life-cycle thinking can include the following:

- The use of a life-cycle approach can be formally required. For example, some European countries have waste management or packaging directives.

- Governments can encourage the use of LCA approaches with policy instruments such as taxes or subsidies.

- For companies seeking green labels, a yearly updated management plan that contains results of life-cycle studies may be compulsory.

- Using life-cycle approaches may help to identify win-win situations, where with the same amount of money, better results may be obtained.

- The use of a life-cycle approach may improve the image of an organization in the eyes of consumers and other stakeholders which may otherwise believe that a company is only interested in shareholder value and impacts in its direct sphere of influence.

In the countries where it has been used most often (Germany, Italy, Sweden and Switzerland), LCA has been used primarily for product development, and, to a lesser extent, for strategy development. Specific applications include identification of "bottlenecks" (critical environmental points along the product life cycle), comparisons of existing products with planned alternatives, product design, and waste management. Life-cycle thinking and tools can be integrated into environmental management systems, integrated management systems, environmental reporting, product design and development processes, and purchasing decisions (e.g., green procurement).

The UNEP (2005) identifies how several industries use life-cycle thinking. These include the following:

- *Chemical industry*. Years of experience with product safety and risk assessment are used in conjunction with life-cycle thinking, product stewardship, and eco-efficiency to inform decision-making processes.

- *Raw materials industries.* Particularly in the metals and mining industries, life-cycle thinking is part of integrated material management strategies, and LCA is used in conjunction with substance flow and material flow analyses.

- *Durable consumer products.* Current regulatory pressures, such as end of life regulations in Europe, drive the application of life-cycle thinking in conjunction with recycling assessments, design for recycling, or design for environment. Also, material restrictions and supply chain management are used jointly with, or supported by, LCA.

- *Capital goods and the retail industry.* Life-cycle thinking is often used with total cost assessment or life-cycle costing.

Use of LCA in O&G E&P industry

To date, most LCA applications and studies have focused on products — particularly product design, and, to a lesser extent, communication of environmental performance of products to customers. The use of life-cycle approaches to study processes, and, in particular, O&G E&P processes, is less mature. However, some applications, such as LCA for waste minimization, are relevant to E&P, as the following paragraph illustrates.

Reduction of environmental impact was initially accomplished primarily through end-of-pipe controls. Subsequently, cleaner production strategies were introduced to reduce the production of wastes and emissions. Such strategies included integrated approaches such as modifying processes and recycling waste streams. However, these waste minimization strategies take on a production site perspective, and reducing emissions at the site may increase emissions or energy use in another part of the life cycle, thus opening an opportunity to use LCA. In such cases, the LCAs are more often cradle-to-gate (rather than cradle-to-grave), because the production process is so far upstream, with the products going to a variety of end uses. LCA waste management studies generally seek to answer the question of which waste management option is the best one from an environmental perspective. Several waste management LCA models have been developed, and many target municipal waste planning, where a range of classes of waste compose mixtures of many different materials. Such models do not apply directly to the management of E&P wastes and produced water, but some LCA work has been done in these areas, and there are opportunities for integrating life-cycle thinking into E&P waste management, as is illustrated in some of the following subsections.

Several case studies in which life-cycle thinking has been either directly or indirectly applied to O&G E&P have been identified. Topics include environmental effects of drilling on the environment, drill cuttings management, drilling fluids management, site remediation, and greenhouse gases. Section 5.1 summarizes these case studies. Potential future applications of life-cycle thinking to O&G E&P have also been identified. These pertain to oil sands, produced water management, identification of hot spots, integrating social aspects, and E&P infrastructure options. They are discussed in Section 5.2.

5.1 CASE STUDIES OF THE USE OF LIFE-CYCLE APPROACHES IN O&G E&P

This section summarizes 12 case studies that apply to O&G E&P. Each study comes from the open literature, and readers are encouraged to consult the original references for details. Table 5 lists the case studies, their objectives, and findings (or other pertinent comments).

TABLE 5 Life-cycle Case Studies Pertaining to O&G E&P Industries

Case Study	Objective	Findings/comments	Reference(s)
1. Environmental effects of deep drilling projects	Using ISO LCA standards, define environmental objectives and targets	Adds realism to pollution prevention and environmental protection commitment by collecting and analyzing data for the entire life cycle. Concluded that drilling fluids and drill cuttings are the largest contributors to environmental impacts from deep-drilling projects.	Ulrich and Franz 2002
2. Drill cuttings management	Evaluate various scenarios for managing drilling waste	Life-cycle energy and air emissions were estimated for various waste management components and then combined into scenarios for evaluation and comparison.	Garcia and Kapila 2006
3. Offshore drilling waste disposal	Compare options for offshore drilling waste disposal	Within legislative and regulatory constraints, decision makers used life-cycle assessment, risk assessment, and economic considerations to identify preferred technology options for drilling waste disposal from offshore operations.	Paulsen et al. 2003
4. Integrated management of fluids and wastes	Use life-cycle approach to minimize cost and maximize environmental performance	Involves supplier chain from procurement through the life cycle of the operations. Integrating fluids and waste management significantly increased recycling of drilling fluids, reduced drilling waste, and saved costs.	Paulsen et al. 2006
5. Ex Situ Bioremediation of Diesel-Contaminated Soil	Compare alternatives and identify process optimizations to improve environmental performance	For temporary treatment centers, site preparation and closure were the major contributors to environmental impacts. For permanent treatment centers, impacts of site preparation and closure are allocated to the total quantity of soil treated during the center's operation time. Overall data quality may limit validity of conclusions. Integration of risk analysis data into the LCIA toxicity models would allow more accurate assessment of residual soil contamination.	Toffoletto et al. 2005
6. Two approaches for assessing remediation options	Improve understanding of the potential environmental burdens of generic remediation options	A simplified life-cycle approach can be used to identify impacts from remediation actions at and beyond the contaminated site over short and long time periods.	Diamond et al. 1999

TABLE 6 (Cont.)

Case Study	Objective	Findings/comments	Reference(s)
7. Hydrocarbon remediation techniques	Quantify and evaluate environmental impacts of remedial actions	Environmental impacts caused by the remedial actions themselves are identified using LCA. For hydrocarbon-contaminated soils, in situ bioremediation using hydrogen peroxide as an electron donor produced the highest potential environmental impacts because of the highly energy-consuming process used to produce the hydrogen peroxide. For soil vapor extraction, the largest environmental impacts were also correlated with the most energy-consuming activities.	Bender et al. 1998
8. GHG emissions for crude oils	Provide first step toward cost-effective management of GHG emissions by identifying sources of those emissions in the life cycle of crude oil	GHG emissions were estimated for each life-cycle phase for seven crude oil types. Concerns ranging from allocation to selection of emissions factors indicate that more refinements will be needed before the technique can be used for assigning monetary values for emissions trading.	McCann and Magee 1999
9. Oil sands development — Energy and GHG emissions	Compare life-cycle energy and GHG emissions for different oil sands production energy sources	Production of oil from oil sands requires significant amounts of energy. Energy use and GHG emissions are higher for gasoline produced from oil sands than from crude oil if either natural gas or coal are used to fuel oil sands operations, but are about the same if nuclear power is used.	Larsen et al. 2005
10. CO_2 storage in active reservoirs	Determine benefits of storing CO_2 in active reservoirs and evaluate environmental impacts over process life cycle	GHG process emissions associated with enhanced oil recovery (EOR) are minimal compared with those avoided through storage in active reservoirs. EOR activity is almost carbon-neutral when comparing net storage potential and gasoline emissions resulting from use of the additional oil extracted.	Aycaguer et al. 2001
11. Investment decision making	Demonstrate value and approach for life-cycle thinking in optimizing value	Addressing the value to a corporation of an investment over its life cycle will be more successful when attempts to tackle issues in detail are avoided and the focus is on risk and uncertainty. Outcomes can help direct resources to the most significant decision factors and provide a means for managing risk and uncertainty in a team environment.	Harding 1996
12. Corporate policies and operations	Integrate life-cycle thinking into a company's policies and operations	At least three major oil companies have explicitly cited life-cycle thinking in their policies. Generally these are integrated with sustainability goals.	Suncor 2005; Petro-Canada 2005; Total 2003

5.1.1 Environmental Effects of Deep Drilling Projects

This LCA case study adapted the provisions of the ISO LCA standards for deep-drilling projects. The case study methodology and results summarized in the follow paragraphs are derived from Ulrich and Franz (2002).

Goal and scope definition. The goal of the study was to assess effects on the environment of deep-drilling projects by identifying environmental impacts for improving the environmental performance of deep-drilling projects. The functional unit was defined as meters drilled for oil and gas. The model boundaries were defined to include all inputs up to their place of receipt and all outputs up to their release. The spatial boundary is the drilling site, and the time period is from site construction, through drilling (including cementing, logging, and testing) until recultivation (if the well proves uneconomic) or building to a production site. Capital goods production and production of materials needed for operating the capital goods or the drilling process were not considered. However, the environmental impacts arising from the use and disposal of these materials are included.

Inventory Analysis. This study used both general and specific data from internal data collection or from accepted specialized literature. The data collection structure was based on Austrian drilling projects to help evaluate the present state of data availability and to create the necessary conditions for determining additional data requirements. Using these data, analysts determined that roughly 80 to 100 input and output materials needed to be considered in each inventory analysis to attain the desired precision. Services conducted by contractors were included in the inventory analysis. Environmental impacts of these activities were determined through numerous conversations with the contractors and supplying companies. Chemicals were assessed according to their material qualities from material safety data sheets. To ensure a clear and transparent inventory analysis, the drilling process was subdivided into four modules: (1) transportation, (2) logging and testing, (3) drilling activity, and (4) infrastructure. These modules can be broken into submodules. For example, infrastructure includes construction, operations, and recovery. The operations submodule includes total fuel consumption, the water balance of the drilling process, noise emissions, operating and auxiliary materials, and all waste data. To avoid double-counting and to ensure that all waste management data are collected, all waste, wastewater, and air pollution flows were arranged according to their respective modules and their respective point of origin. Inputs included energy, air, water, ground, and materials. Outputs included emissions to air, water, ground, noise, waste, and land use. At the end of the inventory analysis stage, the results were integrated into an input-output table and checked for completeness, representativeness, and accuracy.

Impact Assessment. In accordance with ISO 14040, the following LCIA steps were conducted: definition of impact categories; selection of impact categories, category indicators, and models; classification; and characterization. In this phase of the assessment, the quantified data produced in the inventory analysis were assigned to potential environmental impacts. Findings regarding the impacts of emissions or toxicological effects were considered. The model of ecological scarcity was used to evaluate the deep-drilling project. This model assesses emissions, energy consumption, and physical effects, such as noise pollution or land use. An eco-factor determines the potential effect of impacts to the environment through a comparison of the actual pollution levels and the pollution levels considered as critical, deduced from scientifically or politically supported goals. The eco-factors are then multiplied by the results of the inventory analysis to obtain environmental loading points. The model provides transparency and repeatability, and it allows for the direct comparison of different national and international drilling projects by aggregating impacts to one unit. It also shows the ecological weak points, or "hot spots," of aggregate or individual processes. (National eco-factors are available only for Holland, Norway, Sweden, Belgium, Switzerland, and Austria, and there are no explicit eco-factors for noise or land use.)

Interpretation. Interpretation is necessary to evaluate information and to derive conclusions or recommendations from the results of the impact assessment. These results serve as a basis for ecological and economic decisions and improvements for further deep-drilling projects. In this case, the results indicated that the largest source of environmental influence (79%) is caused by the disposal of wastes (drilling cuttings and drilling fluid). Because of their composition and structure, these wastes must be classified as dangerous waste. The second-largest source of environmental impact is emissions to soil, particularly drilling fluids and sanitary waste waters. Air emissions resulted in 2.4% of overall impacts. Energy consumption, noise pollution, and land use together represent about 0.6% of the total load.

Conclusions. Options to reduce the environmental impact of deep-drilling projects on waste and soil emission categories were sought. The simplest task was to collect and dispose of sanitary waste waters, which contributed more than a third of the emissions to soil. By doing this, the environmental services were improved by about 5–10%. Decreasing drilling wastes will provide a greater ecological and economic service potential. Studies indicate that some of these wastes may be used for plant cultivation and that the implementation of a total fluids-management process for deep-drilling processes together could reduce costs and environmental impacts by nearly 20%.

5.1.2 Drill Cuttings Management

The following case study is from Garcia and Kapila 2006. To reduce the environmental impacts associated with the generation of drilling fluids and cuttings, recycling and waste treatment options are often considered. The choice of a particular management method depends on regulatory, economic, operational, and environmental concerns. This case study describes a project in which the air emissions and energy requirements of various waste management components are characterized to help evaluate scenarios that combine one or more such components. The study does not follow the steps of a typical LCA (e.g., goal and scope definition, inventory analysis, impact assessment, interpretation), but it does provide a systematic approach for considering both energy and air emissions associated with one of the most significant environmental aspects of E&P drilling waste management.

The waste management components characterized in this case study include the following:

- Discharge (offshore)
- Injection
- Haul to shore (offshore)
- Haul to facility
- Treatment options. These included the following:
  - Pre-treatment of cuttings. (Dryer equipment in which liquid/solid separation minimizes the fluid content of the cuttings and allows for possible recovery of valuable drilling fluid and minimizes the volume requiring further treatment or disposal.)
  - Thermal desorption. (Application of heat to cuttings to separate and recover hydrocarbon drilling wastes.)
  - Biodegradation. (Slurry bioreactor employing indigenous bacteria from topsoil that utilize the base oil as a primary carbon source.)
  - Composting. (Mixing the cuttings with a solid, degradable organic substance [e.g., straw, wood chips] and nutrients [e.g., animal manure].)
  - Vermiculture. (Using worms to aid the decomposition process in biodegradation.)
  - Landfarming. (Application and plowing of cuttings into a soil surface to ensure adequate mixing and aeration.)
- Nontreatment options:
  - Disposal, including land spreading
  - Solidification (mixing the waste with a material, such as activated lime or fly ash, to form a solid product that immobilizes potential contaminants).
  - Mixing waste with soil or subsoil to decrease the concentrations of potential contaminants.

For each component, energy use was calculated using the fuel usage rate of the equipment and activities required. Equipment included supply boats, cranes, trucks, tractors, dozer/loaders, and diesel generators. Air emissions of (NO_x), total hydrocarbons (THC), SO_2, CO, total suspended particulates (TSP), and CO_2 were estimated by using emissions factors. These factors relate the production of air pollutants to the period of time that the equipment is operated and the amount of fuel consumed. Results for selected sample scenarios are summarized in Table 6.

5.1.3 Offshore Drilling Waste Disposal

This case study demonstrates how LCA can be used in conjunction with other tools as a part of the decision making process to identify optimal approaches for disposing of offshore drilling wastes. It is based on a study reported by Paulsen et al. (2003). In this case, recently implemented legislation and regulations help set boundaries for options. Within these legislative and regulatory constraints, decision makers used life-cycle assessment, risk assessment, and economic considerations to identify preferred technology options for drilling waste disposal from offshore drilling operations.

TABLE 7 Summary Energy and Emissions Estimates for Selected Drilling Waste Management Scenarios

Scenario	Components	Diesel Consumption (gal)	NO_x (tons)	SO_2 (tons)
Offshore A	Pretreatment followed by injection	1,000	0.71	0.047
Offshore B	Pretreatment followed by thermal desorption	9,600	1.6	1.2
Onshore C	Pretreatment, haul to injection site, injection	1,300	0.79	0.05
Onshore D	No pretreatment, haul to facility, thermal desorption	6,000	0.76	0.05

Note: Only some of the results are shown here. See Garcia and Kapila, 2006 for other scenarios and for energy use and other air emissions. Estimates are rounded to 2 significant digits.

Regulatory setting. The European Council Directive 96/61/EC of September 24, 1996, also called the Integrated Pollution Prevention and Control (IPPC) Directive, contains measures designed to prevent, or, where that is not practicable, to reduce emissions to the air, water, and land from energy, chemicals, minerals, and other activities. The intent of the directive is to achieve a high level of protection of the environment taken as a whole, through integrated prevention and control of pollution. The integrated approach addresses undesirable environmental impact transfers that can result from discrete, source- or media-specific laws and regulations. Such transfers include shifting pollution from one medium to another, shifting pollution among different geographical areas, and replacing pollutant emissions with increased energy or material consumption. The directive does not prescribe the use of specific technologies; rather, it requires the use of “best available techniques” (BATs) to meet emission limit values, taking into consideration the technical characteristics of the installation concerned, its geographical location, and local environmental conditions.

At the same time, the Commission for the Protection of the Marine Environment of the North-East Atlantic (OSPAR) regulation on drill cuttings (OSPAR Decision 2000/3) prohibits the discharge of whole organic-phase drilling fluid to the maritime area, prohibits the discharge into the sea of cuttings contaminated with oil-based fluids at a concentration greater than 1% by weight on dry cuttings, and requires authorization for the at-sea discharge of cuttings contaminated with synthetic fluids.

Thus while the IPPC Directive requires an integrated approach to pollution reduction (or avoidance), the OSPAR Decision is essentially zero discharge for cuttings treatment with the current generation of technology, regardless of the potential for this approach to generate pollution transfers or increased energy or material use.

In addition to complying with the IPPC Directive and the OSPAR regulation, , the company conducting the study, Statoil, employs its own Total Fluid Management (TFM) concept, which requires the company to investigate first those options that prevent waste generation, followed by those that reduce, reuse, recycle, dispose of the wastes — in that order.

To comply simultaneously with the IPPC Directive, the OSPAR regulation, and its own internal TFM concept, Statoil considered a number of options for disposing of drill cuttings from a new offshore oil field under development in the early 2000s. In doing so, it recognized that generating drilling waste is associated with a chain of decisions related to the cradle-to-grave life cycle of the drilling fluid. The life-cycle stages begin with raw material processing and include production, drilling, and one or more of the following: reuse, subsurface injection, discharge, and land disposal. Issues that must be balanced to identify BAT include waste volume, reuse/recycling, life-cycle assessment, risk and liability, cost and safety in operation, handling, and transport. Specific considerations include transport distance, waste-handling technology, risks associated with loading and offloading, crane lifts, accidental spills, and interfaces with human exposure. Drilling technology issues include well design, drilling fluid type, and solids-handling equipment on the rig. Impacts of the different waste disposal options to be considered include energy requirements, gas emissions, environmental impact factor (ranking scheme that considers ratios of predicted environmental concentrations to no-effect concentrations) if discharged offshore, risks of jeopardizing drilling processes, and human hazard. In these investigations, Statoil noted that LCA is "an attractive strategy, although laborious."

The fate of cuttings depends on the type of drilling fluid used. Because oil-based drilling waste is categorized as hazardous, it cannot be discharged. It must either be injected into a subsurface disposal area or shipped to the shore for disposal. In this case study, because there were no suitable receiving geological formations nearby, subsurface injection was not a viable option. From a life-cycle perspective, waste volume reduction offers numerous health, safety, and environmental benefits. Offshore-based technologies for treating cuttings offer smaller volumes to be discharged or transported and reduce safety risk.

Three technologies were evaluated for environmental impact: use of containers to ship wastes to shore for thermal mechanical continuous conversion (TCC) treatment, use of a bulk-transfer system to ship drilling wastes to shore for TCC treatment, and TCC treatment offshore with discharge of residuals (a dry-rock powder, clean-recovered base oil, and water with less than 20 ppm oil content.) The evaluation also included an analysis of the fate of the chemicals during the TCC processing, the behavior of the residuals upon discharge, and the environmental impact of the drilling waste discharges. Risk issues were also evaluated, because in a total BAT-balancing exercise, zero harm to personnel and the environment must be considered.

In balancing the alternatives, several observations were made. Subsurface injection complies with the zero-discharge mandate. Because water-based discharges are allowed, the authors assumed implicitly that zero discharge means zero harmful discharges. The water-based fluid waste discharge strategy seems to be based on the assumption that using low-toxicity, water-based drilling fluid chemicals can justify a discharge. However, LCA analysis shows that use of water-based fluids and discharge of waste does not provide the best option in all cases. This is because the total environmental burden and consumption of resources exceeds that of using oil-based fluids in several cases.

Shipping oil-based drilling fluid waste to shore has a significant risk component because of the number of crane lifts, practicalities associated with storage and container logistics, and the attendant risk of accidents. Shipping also uses energy and generates emissions. While the TCC technology has the potential to reduce environmental load and risk associated with transfer of waste, it is uncertain whether the technology can be developed to meet the space and weight limitations of a drilling rig. Also, the impacts of discharging the residual powder need to be investigated on a site-specific basis — particle behavior in seawater is unknown, and toxic chemicals may remain attached to the particles. However, the small uncertainties about possible harm from the particles must be balanced against the risks and environmental loads and energy demands associated with shipping the residue to shore.

In the above analysis, several factors were considered in evaluating alternatives, and LCA is one component. The authors suggest that further work on an LCA tool that incorporates risk and cost management would add value to the traditional LCA approaches. In any case, the selection of BAT for drilling waste disposal should use a systematic approach that leads to the highest protection of the environment as a whole and is transparent to all stakeholders. In this case, the systematic method combined waste minimization, cost management, risk assessment, and LCA.

5.1.4 Integrated Management of Fluids and Wastes

This case study used life-cycle thinking to integrate the management of drilling wastes with management of drilling fluids. The approach involves the supplier chain from procurement through the life cycle of operations. It extends the responsibility of fluids providers to account for wastes accrued by the use of their products. The following paraphrased observations come from Paulsen et al. (2006).

The public generally perceives the drilling operator to be responsible for the environmental impact of drilling operations. However, while the operator has the managerial responsibility, numerous companies are involved in the operations. Environmental concerns pertain to the amount and the nature of the drilling waste generated.

Costs for drilling operations include not only those for fluids, rigs, and manpower, but also costs for handling and treatment of drilling wastes (e.g., cuttings, spent fluids, slop water). At Statoil, fluids costs were traditionally managed separately from waste treatment costs. Costs accrued on the rig (fluids costs) are managed daily, whereas the costs for handling and treatment of wastes are incurred after the drilling projects are completed. This system created a structural barrier to effective cost management of fluids and wastes. Statoil found that cost savings and improved environmental performance can result when a formal relationship exists between supplier and operator. In this context, supplier involvement is referred to as extended producer responsibility (EPR). EPR is a policy principle for procurement and cooperation aimed at promoting resource efficiency and environmental improvements of product systems. The EPR principle identifies suppliers as having the greatest potential to influence the overall environmental performance of a product system, because design criteria influence the entire life cycle.

The traditional, non-life cycle approach to materials control and remediation options often relies on recycling to minimize loss of materials and avoid environmental impacts.

However, because the cost of treatment rises rapidly with decreasing concentration of recoverable material in the wastes, this approach has very high costs, and pollution prevention would appear more cost effective than recycling. The use of preventive rather than end-of-pipe measures can be accomplished by extending the responsibilities of the fluid supplier to various parts of the fuel life cycle — especially to take-back, recycling, and final disposal.

In the 1990s, Statoil instituted total fluid management (TFM) as a systematic approach to link fluid services with sound drilling waste management. TFM refers to the efficient management and cycling of drilling and completion fluids during their life cycles. The TFM approach resulted in the following:

- A significant increase in the reuse of water-based drilling fluids — from zero to 40–50% reuse;
- A significant increase in the reuse of oil-based drilling fluids — from about 60% to about 70–80%;
- A 90–95% reduction in hydrocarbon-contaminated drilling waste water (slop) delivered to the waste management company;
- An increase in recycling of drill cuttings sent on shore of about 15% (implying a reduced need for deposition area and or substitution of other resources); and
- Cost reductions for waste handling and treatment and reductions in fluid procurement costs.

A further point regarding life cycle is important in this case study. The European Union IPPC Directive defines BAT as “protection of the environment as a whole” and requires a life-cycle approach to improve environmental performance. The IPPC Directive requires the simultaneous evaluation of the risks posed onshore and offshore through an extended list of chains of effect. As a result, the TFM concept was elaborated to include sustainable resource management. This means that ideally all waste is treated to recover as much as possible of useful components, and, where possible, residual waste is used as a substitute for other resources (e.g., use of drill cuttings for road construction, composting of waste to produce fertile soil).

5.1.5. Ex Situ Bioremediation of Diesel-Contaminated Soil

In this case study, LCA was used, in accordance with ISO standards, to assess secondary environmental impacts associated with bioremediation of diesel-contaminated sites. Secondary impacts are those generated by the remediation process itself and can be local or global. Primary impact refers to the local impact caused by the contamination in the soil. The information for this study comes from Toffoletto et al. (2005).

On-site, permanent treatment centers using biopiles are used to reduce the concentration of petroleum constituents in excavated soil through biodegradation. In this study, two types of bioremediation approaches were compared: (1) construction of a single-use, on-site treatment facility, and (2) use of a permanent treatment center that can accept 25,000 m^3 soil/year.

The functional unit for the study was “the remediation, during a two-year period, of 8,000 m^3 of diesel-contaminated-soil (6145 mg C10–C50/kg) to the B generic criterion (700 mg C10-C50/kg) with an aboveground biopile treatment.”

The LCI used 11 life-cycle stages (e.g., soil excavation, biopile treatment), each of which was composed of one or more processes (e.g., material production, transportation, equipment operation). Primary data came from site-specific design calculations, and secondary data came from commercial databases. LCA modeling was conducted using commercial software (SimPro5).

Numerous assumptions were made. For example, transportation to and from the site was included with distances for equipment set at 150 km and for the laboratory and landfill (for soil that did not meet the cleanup criteria) at 200 km.

The LCIA model was chosen on the basis of model transparency and simplicity. Secondary impacts were assessed and presented as a single score (in points), meaning that the impacts were normalized, weighted, and aggregated.

Results. The analysis showed that for a single-use treatment center, site preparation and site closure were the major contributing stages to the overall impact, mainly due to the asphalt paving and landfilling processes. Off-site transport and the biotreatment process did not contribute notably to the level of environmental impact. The permanent treatment center has a significantly lower secondary impact. However, global impacts increased significantly when soil was transported more than 200 km from the site.

The initial contaminated soil (primary impact) has a residual impact of more than 18,000 points, or about 10 times the number of points generated by the remediation activities (secondary impacts). The bioremediation process itself (without excavation, site preparation, etc.) generates only 4% of total impact. Only two of the eleven stages (site preparation and site closure) were determined to be significant. While more than 214 substances contributed to secondary impacts, only 12 contributed to more than 1% of total impact. The most important, is “final waste” (the asphalt requiring disposal), which contributes 28% of total impact.

For the permanent treatment center, impacts generated by the site preparation stage and closure stage are not allocated exclusively to the 8,000 m^3 of contaminated soil, but to 250,000 m^3, and thus, 85% less impact would be generated during remediation. For the single-use site, most impacts would be local.

Recommendations from the study include the following: To reduce environmental impact, contaminated soil should be treated to achieve the lowest level of residual contaminants. If a temporary site cannot be used, improvements should be made to the site preparation stage, for example, to use recycled rather than virgin asphalt.

Issues. The results warrant additional interpretation. For example, the model assumes that all of the contamination in the soil is available to produce ecotoxicological and toxicological effects. Thus, the toxicological and ecotoxicological impacts are probably overestimated. Also, the calculation of human toxicity and ecotoxicity factors does not consider whether there are people, animals, or plants near the site.

While all attempts to conduct a complete analysis were made, overall data quality is low and may limit the validity of the conclusions drawn from the analysis. This is particularly true for the geographic specificity of the data. (Lacking North American data, European data were often used.) A comprehensive North American database with weighting factors could make future American LCAs more consistent with their geographic context. Similarly, the LCIA model is based on European considerations. (A new EPA model has been developed, but it does not consider emissions to soil.) An improved impact assessment would allow for a more accurate comparison between primary and secondary impacts and thus provide better guidance for decision makers.

Use of the LCA tool helps manage contaminated soil in a sustainable way. However, because of the major contribution of residual soil contamination to environmental impacts, additional spatial and temporal data should be collected and integrated in the characterization models.

5.1.6 Two Approaches for Assessing Site Remediation Options

The analysis developed in this case study identified the main environmental and health concerns associated with each of six commonly used remediation options at and beyond the contaminated site for both short and long time periods. It comes from a 1999 study of a life-cycle framework (LCF) for assessing site remediation options (Diamond et al. 1999).

Remediation actions are often selected on the basis of site-specific financial and technical considerations. When potential environmental and health issues are addressed, they are often directed toward minimizing risks posed by contaminants on-site. However, it is possible that the remediation activities themselves may increase risks over larger geographic areas and over longer time periods. The use of life-cycle thinking to examine site remediation activities allows for a systematic review of potential impacts — at and beyond the site, and over shorter and longer time periods.

In this analysis, a LCF based on LCM and an adaptation of LCA was developed to broaden consideration of potential impacts for a range of remediation options beyond the contaminated site and over a prolonged time frame.

The LCF can be used to design site remediation options or analyze remediation case studies. The framework provides information to help decision makers choose the optimal remediation option to minimize environmental and human health burdens, considering the types of raw materials and energy used, transportation, and long-term impacts of post remediation activities. For the design application, generic data, models, and burden estimates — rather than site-specific information — can be used; the amount of information required depends on the goal of the study. For analysis, a single site or related sites can be examined to identify opportunities for decreasing environmental impacts or increasing awareness of the impacts associated with a particular remediation approach.

The framework was developed to accommodate remediation options including (1) technologically complex ex situ approaches, (2) in situ biotechnology, (3) risk management approaches, and (4) no action. To ensure its general applicability, the framework offers two approaches: the quantitative LCA approach, and a simpler, qualitative LCM approach. The LCA approach is used when quantitative information on resource use or information on potential impacts is required. The LCM approach is used for increasing awareness of life-cycle related issues, identifying potential impacts related to a remedial activity, or investigating implications of resource use.

The LCA Approach

The traditional LCA approach provides a systematic and rigorous assessment of site remediation options. Key aspects of its application to a particular contaminated site are highlighted below.

- *Boundaries*. The temporal boundary was 25 years, beginning with the start of remediation (not contamination). It is intended to capture the longer-term effects that could arise from the no-action or limited-containment scenarios, and to not prejudice options that may have high impacts over a short time (e.g., soil washing) relative to those having lower impacts over a longer time (e.g., in situ bioremediation). The system boundaries include all operations involved in remediating the contaminated soil and groundwater. The geographical boundary encompasses activities at and beyond the contaminated site itself, thereby allowing for consideration of burdens shifting from one site to another (e.g., those for the relocation of contaminated soil, transport of clean fill).

- *Process*. The process can be illustrated by a flow diagram that first identifies the main process flow, and then adds ancillary material flows. Process descriptions can vary widely because of the nature of remediation options.

- *Functional unit*. The functional unit relates to the production of an equivalent amount of treated soil and groundwater. The quality of the remediated soil (e.g., contaminant concentrations, nutrient content) is addressed separately.

- *Impact assessment*. The LCIA component identifies stressors and potential impacts that are classified within three impact categories: pollution, which relates to all types of emissions to the environment; depletion, which includes inputs that are extracted from the environment; and disturbance, which reflects human social impacts and structural changes to the environment. It also translates inventory items into relevant indicators of potential environmental and health impacts using various models or other assessment approaches and metrics.

The LCM Approach

This simplified method consists of four components: identify, inform, assess, and implement. They are summarized below for the same contaminated site application.

- *Identification*. The identification component specifies the purpose of the study — in this case, to help maintain focus and determine the extent of information or assessment required. The remediation options are described by compartmentalizing all activities into life-cycle stages, and subsequently, into unit processes. Life-cycle stages include acquisition of energy and raw materials (e.g., nutrients and soil amendments for bioremediation, clean backfill); site processing (the actual treatment of the contaminated soil and groundwater); and post-site processing (e.g., activities to maintain site security, upgrading barrier walls, leachate collection, migration control). Life-cycle substages, which may be associated with any life-cycle stage(s), are transportation (changing the location of the soil, groundwater, and materials used as inputs); distribution (stockpiling, warehousing); waste management (techniques and/or emission control systems to treat, handle, or contain waste generated from remediation activities, before its release into the environment); and monitoring.

- *Inform*. In this component, inputs and outputs (the inventory) are determined on the basis of the flowcharts and associated potential impacts. Inventory information may be qualitative or quantitative. Inventory items that are stressors (physical, chemical, or biological conditions that can induce positive or negative impacts on the environment, humans, or resources) are identified and linked with potential environmental impacts. The stressors and their potential impacts are grouped into the same three categories as for the LCA (pollution, depletion, and disturbance). Unlike LCA, which involves translating inventory items into indicators of impact through the use of models and other assessment approaches, the LCM identifies potential impacts with all stages of the remediation option under consideration using a potential impacts checklist. The checklist allows for the ranking of impacts (albeit subjective) by level of concern (e.g., low, moderate, high). In this case, individual team members ranked concern level for each item for the six technologies. To minimize bias, the rankings were refined in a group discussion.

- *Assessment*. In this component, the results are assessed and reviewed for further study. Indications for further study could be linked to the toxicity of the inventory items, liabilities associated with the inventory items, and whether a sensitive species, population, or community may be disturbed.
- *Implementation*. In this component, actions for responding to the conclusions are addressed. At the simplest level, the LCM approach provides increased awareness through life-cycle thinking and a cursory investigation into potential impacts associated with each remedial technology. At a more

complex level, LCM can help identify key areas for improvement that are consistent with the purpose of the study.

Results

The remediation options considered in the analysis were no action, encapsulation, excavation and disposal, vapor extraction, in situ bioremediation, and soil washing. Because the purpose of the study was to improve understanding of the potential environmental burdens of the six generic remediation options, a qualitative study was appropriate, and the LCM approach was used. The LCM approach highlighted concerns beyond those deduced from other commonly used methods such as risk assessment, which identifies toxicity impacts only. For example, the analysis indicated that because contaminants remained on-site, the no-action and encapsulation options resulted in potential land use, land consumption, ecosystem, and human health impacts. The relocation of contaminants required excavation and disposal that would produce off-site impacts such as land consumption, emissions, and resource use due to transportation. Potential impacts associated with in situ bioremediation included changes to aquifer and soil quality. In situ bioremediation and soil washing could cause adverse effects through the discharge of process chemicals. For soil washing and excavation and disposal, air quality could be impaired due to excavation and transportation.

The LCM approach is conceptually simple, requires qualitative data, and can be used to assess numerous options. It is flexible, promotes life-cycle thinking, and provides a method to investigate and highlight potential, often ignored, or discounted impacts associated with a remediation approach. Relative to the more rigorous LCA, however, unforeseen subtleties may be overlooked or neglected. Such concerns, which can also exist in quantitative analyses, can be mitigated somewhat by using a consultative process and peer review. The LCF approach, using either LCA or LCM, can provide an environmental and human health perspective for decision making (e.g., for choosing an option or identifying stages within an option that contribute to the overall burden). It may also be used to minimize overall ecosystem and human health impacts using a broad and holistic analysis.

5.1.7 Hydrocarbon Remediation Techniques

This case study pertains to a site where aliphatic and aromatic hydrocarbons from a petrol spill have contaminated both the saturated (groundwater) and unsaturated zones. It is based on information presented by Bender et al. (1998). The analysis used the standard LCA phases of goal and scope definition, inventory, impact assessment, and interpretation; highlights follow.

Regulations in the Federal State of Baden-Wurttemberg, Germany require that remediation decisions consider both economic and environmental aspects — including the negative potential environmental impacts produced by the remediation itself. By using LCA, these secondary impacts can be quantified.

System boundaries were defined by the remedial actions, each of which is comprised of one or more of 60 specific modules (e.g., mobilization of equipment, transport of persons, drilling). Impacts were identified for the neighborhood of the contaminated site. Data quality was governed by the accuracy of the input data available at the remediation planning stage. The analysis used average data for machines and services.

The *inventory phase* documented the inputs (materials and energy used) and the related outputs (emissions, land use and resource consumption).

Impact categories addressed in the LCIA phase included depletion of nonrenewable resources, water consumption, land use, global warming, acidification, summer smog, human toxicity, smell, and noise.

In the *interpretation phase*, impacts of the different remedial actions were compared, and a sensitivity analysis was conducted wherein impact assessment results (e.g., cumulative energy demand) were considered to be significantly different from other alternatives if they varied by more than a factor of two.

Results. For groundwater remedial actions, the analysis identified in situ bioremediation using nitrate as an electron acceptor as having the least potential environmental impacts. In situ bioremediation using hydrogen peroxide as the electron acceptor produced the greatest environmental impacts. The difference results from the production of hydrogen peroxide, which is a highly energy-consuming process. The energy consumption in turn, causes resource depletion and emissions to air, water and soil. For remedial actions in the unsaturated zone (e.g., soil vapor extraction), the highest potential environmental impacts were also correlated with the most energy-consuming activities. Here, the production and thermal desorption of activated carbon were by far the most energy consuming processes. The analysis also estimated potential environmental impacts induced by different operating times, i.e., 22, 29, and 36 months, and found only minor differences in environmental impacts for the different time frames. This consistency was also attributed to energy consumption, which is directly proportional to the mass of activated carbon needed for adsorption of contaminants. This amount was nearly the same for all operation times, because large quantities of activated carbon were needed at the beginning of this remedial action technique. Also, because the hydrocarbon concentrations were lower in the later stages of soil vapor extraction, additional amounts of activated carbon were not needed.

5.1.8 GHG Emissions for Crude Oils

Knowing the magnitude of GHG emissions over the life cycle of crude oils produced from various sources can offer a first step toward cost-efficient minimization of those emissions. In this case study, the authors estimated GHG emissions for each stage of the life cycle for seven different crude oil sources from production through combustion. The remainder of this section comes from their study (McCann and Magee 1999).

The LCA analyzed production, including field upgrading where applicable (e.g., for some oil sands scenarios); transport of crude to refinery; refining; and product combustion. Natural gas and electricity purchases were also included; GHG emissions associated with exploration, capital facility fabrication and construction, and chemical and catalyst inputs were not included. A pseudo-refinery process scheme was selected for each crude that was judged most appropriate for the specific crude in the specific market area, which, for this study, was the Chicago, IL, area. Emissions were normalized to a fixed volume of transportation fuels (1 cubic meter, or 6.3 bbl).

The analysis indicated that of the seven crude oils evaluated (Canadian light, Brent North Sea, Saudi light, “typical 1995 synthetic crude oil,” “typical 2005 synthetic crude oil,” Venezuelan heavy, and Venezuelan very heavy), Brent North Sea crude produced the lowest level of emissions — 3.3350 metric tons of CO_2E[1] per cubic meter of transport fuel used in central North America. Venezuelan very heavy crude produced the highest (4,018 metric tons), or roughly 20% more than the Brent North Sea Crude. In all cases, combustion of the transportation fuel produced the largest share of CO_2E emissions (about 68–77% depending on the crude), and transportation emissions to Chicago area using pipeline or marine plus pipeline produced the smallest share (about 1% for most crudes, and about 5% for the Saudi light.) The share of emissions associated with refining ranged from about 4% (for typical 1995 synthetic crude and Venezuelan very heavy crude) to about 7% for Venezuelan heavy crude. The share of emissions from production ranged from about 5% for Brent North Sea Crude to about 20% for typical 1995 synthetic crude.

Challenges associated with the study included the following:

- Allocation of inputs and outputs. (refineries produce not only transportation fuels, but also petrochemicals, heavy fuel oils, and asphalt);
- Emissions from natural gas (there are many variables in natural gas production and transportation modes);
- The need to evaluate CO_2, methane, and N_2O separately (methane and N_2O become important when biological activity is involved); and
- Variations in national and regional emission factors for methane and N_2O, for the transportation and fuel combustion portions of the analysis.

While the authors acknowledge these challenges and weaknesses, they suggest that with the monetizing of CO_2 and CO_2E emissions, full life cycle and partial life cycle-type comparisons will become more universal. Detailed breakdowns at the project level will become essential in accounting for and defining trading potential.

5.1.9 Oil Sands Development — Energy and GHG Emissions

As existing reserves of conventional oil are depleted, reserves of unconventional oil become more attractive for recovery and upgrading. The production of one source of such unconventional oil — oil sands in western Canada — has been increasing over the past several years and is predicted to continue to increase in the future. The case study highlighted in this section comes from Larsen et al. (2005).

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[1] The term CO_2 equivalent (CO_2E) accounts for the other GHG gases besides CO_2 (methane and N_2O according to the formula: Tons of CO_2E = tons of CO_2+(21 x tons of methane) + (310 x tons of N_2O).

Large amounts of steam are needed to recover and upgrade oil sands, and large amounts of hydrogen are needed to upgrade oil sand products. Today, natural gas is the primary energy source for oil sands recovery and upgrading. If oil sands operations continue to increase as predicted, and natural gas remains the fuel source for operations, the amount of natural gas consumed for Alberta oils sands operations in 2030 would be greater than the total amount of natural gas consumed for all uses in all of Canada in 2005. Because of the GHG emitted from these operations and the increasing cost of natural gas, alternative energy sources are being investigated for oil sands recovery and upgrading. In this study, a life-cycle approach was used to estimate energy use and GHG emissions associated with three alternative energy sources. These include the use of (1) high-temperature, gas-cooled small-scale nuclear plants, and (2) coal gasification plants using Alberta's indigenous coal reserves. To analyze and compare energy use and GHG emissions of Canadian oil sands recovery using these three separate approaches, a "wells-to-wheels" life-cycle approach was used. With this approach, the energy and GHG emissions from energy feedstock recovery (the wells) to energy delivered at vehicle wheels (the wheels) were calculated for each energy source. The specific tool used was the GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) model. In GREET, the well-to-pump, or upstream stage, consists of feedstock production, transportation, and storage; fuel production, transportation, distribution, and storage. The pump-to-wheels, or downstream stage, consists of vehicle operation (vehicle refueling, fuel combustion/conversion, fuel evaporation, and tire/brake wear). For oil sands, the model simulates hydrogen and steam production from natural gas, nuclear power, and coal. The functional unit is one million Btu of gasoline available at the fueling pump of a refueling station.

The analysis showed that if natural gas continues to be used for hydrogen and steam production, energy use and GHG emissions will be higher for oil-sands-based gasoline production than for conventional, crude-oil-based gasoline production. If coal is used for hydrogen and steam production, GHG emissions from oil-sands-based fuels will be much higher than those from crude-oil-based fuels. If nuclear energy is used, the energy and GHG effects for oil-sands-based and crude-oil-based options will be about the same.

5.1.10 CO_2 Storage in Active Reservoirs

CO_2 injection into active enhanced oil recovery (EOR) formations allows for extraction of additional oil and repressurization of the formation. Currently most of the CO_2 used for EOR comes from natural CO_2 reservoirs. Because CO_2 is used for EOR to extract more oil out of aging reservoirs, it is possible that existing technology could be used to reduce GHG emissions to the atmosphere through CO_2 storage in active reservoirs. However, although CO_2 injection into reservoirs is technically feasible, these formations have only recently been studied for possible long-term CO_2 storage. In this study, LCA was used to identify the benefits of storing CO_2 in active reservoirs and to identify and quantify the emissions and resources needed over the lifetime of the process. The information in this section comes from a study conducted by Aycaguer et al. (2001).

The LCA focused on GHG emissions, and the processes included the following: extracting the oil and associated gas from the oil reservoir; processing the associated gas for separation of the different components (water, hydrogen sulfide, CO_2, methane, natural gas liquids); compressing the separated CO_2 stream destined for injection; and transporting and injecting the CO_2 in the oil reservoir for extraction of additional oil and for long-term storage. (Extracting and transporting the CO_2 from the natural reservoir was not part of the analysis.)

The LCA was for a specific reservoir in west Texas, and the time period was the 40-year lifetime of active EOR production. The functional unit was a kilogram of oil produced; thus, the storage quantities, emissions, and resource requirements were calculated per 1 kg of oil produced. The reservoir is estimated to require injection of 5.5 kg of CO_2 to recover 1 kg of oil. The process assumed that all of the produced CO_2 was reinjected into the reservoir as solvent, and during the 40-year lifetime, roughly 43% of the cumulative CO_2 needed for injection was estimated to come from the recycling plant.

The analysis found that the use of captured and recycled CO_2 (rather than CO_2 from natural reservoirs only) reduced greenhouse gas (GHG) emissions from EOR, thereby preventing depletion of naturally occurring CO_2 reservoirs and significantly reducing the emissions of greenhouse gases to the atmosphere (by reusing CO_2 that would otherwise be vented). The study also showed that GHG generated by gasoline combustion from the additional oil produced by EOR was almost offset by CO_2 storage in the reservoir.

Without capture and reinjection through the recycling plant, the produced CO_2 would be vented to the atmosphere, and the CO_2 needed for injection would come exclusively from natural CO_2 reservoirs. Without recycling, 2.6 kg of CO_2 per kg of oil produced would be vented to the atmosphere.

Some, but not all of the injected CO_2 was extracted from the reservoir along with the oil. The remaining CO_2 was trapped in the formation. The amount of CO_2 stored in the reservoir was the difference between the amount of CO_2 injected and the amount of CO_2 produced; these data were obtained from continuous monitoring and forecasting information. It was estimated that the reservoir studied had the capacity to store about 3 kg of CO_2 and 0.1 kg of methane per kg of oil produced. The fossil fuels used in the engines and machines to compress and separate CO_2 from the throughput stream after produced-gas recycling created emissions of greenhouse gases estimated to be 0.36, 1.5×10^{-3}, and 2.1×10^{-5} per kg of oil produced for CO_2 , methane, and N_2O, respectively. These emissions were both direct (from on-site equipment powered by natural gas, flaring, and process equipment leakage) and indirect (from electricity generated by a power generating facility outside the facility boundary).

Further research will study the duration of storage and its relationship to safety. It will also compare storage in active reservoirs with storage in depleted reservoirs.

5.1.11 Investment Decision Making

Life-cycle thinking can aid in oil and gas investment decision making. The information in this section is based on an analysis by Harding (1996), which discussed issues associated with life-cycle value decisions, factors that can influence life-cycle value in the upstream O&G industry, and an approach aimed at addressing identified concerns.

Life-cycle value is the optimized value to the corporation of an investment, which is based upon an economic calculation taking into account all of the significant factors of uncertainty that could influence the value, and demonstrating that these factors have been realistically addressed in the economic calculation. Many industries with significant capital investment and operating costs (e.g., defense, aerospace) employ life-cycle cost evaluation methods. These industries generally have clear specifications for what they will design and build. The oil industry, however, because there is significant uncertainty at the planning stage regarding the reservoir, often has less knowledge of exactly what will be needed to build and exploit a reservoir. Thus, the O&G industry takes on more risk and must build in more flexibility. Consequently, the approach to life-cycle evaluation in the O&G industry must recognize that life-cycle value should be managed at a level beyond the typical aspects of the life-cycle process. Attempts to address life-cycle value meaningfully at the planning stage of many complex hydrocarbon investments have failed because "we have been over ambitious in trying to tackle the issues in detail."

Some of the barriers to meaningful life-cycle value decisions include lack of strategy for life-cycle impact assessment, problem complexity, unclear objectives, uncertainty, poor communications, and poor data. Factors to be addressed when planning to optimize life-cycle value, particularly in North Sea investment decisions, include reservoir definition and behavior, operability, maintenance regime, equipment selection, trade offs between capital and operating costs, projected oil prices, decommissioning provisions, extending productive life, environmental safeguards, and political stability. For mature assets in the North Sea, extending field life and delaying decommissioning costs is a major issue. Teams making decisions regarding these mature assets need to consider operating the facility and managing the reservoir at the end of production as well as the ramp-up-to-production plateau.

While numerous processes, tools, and methods for evaluating investments exist at the discipline level, most are compartmentalized, sequential, require the input of deterministic data, do not operate across discipline boundaries, and do not easily support multiple iterations. While such processes can usually provide a solution to a problem that has been clearly identified, they cannot identify such problems in the first place.

Because project managers seek a clear scope, budget, and schedule for their projects, they generally prefer to lock in a concept as early as possible. But such early decisions put pressure on reservoir engineers to develop a single, deterministic project profile. Focusing on minimizing capital expenditures can divert attention away from the potential values that can be provided by other sources. There are numerous North Sea projects in which both recoverable reserves and production rates have increased in the early years of production, resulting in the need for modification, debottlenecking, and retrofitting of new equipment, because the original plan design assumed a lower production rate.

Processes that support life-cycle value decision making must employ open communication, be accessible to and understood by the team, be easily understood by the users, make use of all skills and disciplines, be probabilistic rather than deterministic, accept input from many sources, avoid the need for detail, help focus on the major uncertainties, be part of the decision-making process, be employed as early as possible in the asset life, and generate ideas.

An effort to achieve a discovery-to-production time not previously achieved in the North Sea at a life-cycle cost below the industry norm provides an example of how these principles were used. The available time did not allow for a detailed analysis, but attention was directed to the decision making on the total life of the field. In this case, a high level of uncertainty needed to be managed, and the asset team focused on managing the risk and uncertainty. The team also recognized that it might not be possible to meet the original targets, and that missing those targets would not be deemed a failure. Key lessons learned included the following:

- The process should be introduced early in the decision-making phase; the project phase is too late.
- The process is most valuable when all the major disciplines are represented and are committed to the process.
- While it is often difficult to rise above detail, doing so is essential for success.
- Participants may need to be convinced that life-cycle thinking need not be as complex as they may have thought.
- Detailed data and analysis of the key decision factors are not needed initially; the process will help to form opinions on these factors, direct resources toward the most significant ones, and provide a means of managing risk and uncertainty within a team environment.

As with other LCA applications, those used for investment decision-making benefit from the engagement of multiple skills and disciplines, good communication, early management support, definition of objectives, recording of assumptions, and feedback among the different phases of the analysis.

5.1.12 Corporate Policies and Operations

Some O&G companies have begun formal processes to integrate life-cycle thinking into their policies and operations. This section highlights examples of these practices.

Life-Cycle Value Assessment

As noted in Section 3.2, life-cycle value assessment (LCVA) is a business analysis and decision-making methodology that helps employees, project teams, and business units identify, examine, and balance the social, environmental, and financial implications of projects and product purchases. The tool is based on the premise that good information enables better decisions. LCVA covers the full life-cycle of a new or existing project, from upfront planning and material and equipment selection, through to final decommissioning and reclamation. Through the process, new ideas and opportunities emerge to improve technical designs, to reduce environmental pollutants and other impacts, and to increase efficiencies. It can be tailored to a particular application and level of detail. As illustrated below, at least two oil companies have incorporated LCVA into their operations.

Suncor Energy uses life-cycle thinking, including a formal LCVA tool, to help evaluate the impact of a project's design, construction, and operation. LCVA covers everything from the manufacture of materials by third-party vendors to waste disposal and reclamation (Suncor 2005). Suncor’s policy is included as Appendix H.

Petro-Canada also has a policy regarding decision making based on LCVA. It states that LCVA is a key method by which employees integrate and balance social, environmental, and business decisions. LCVA was first used in 1988. In 2003, it was integrated into the project delivery model, and in 2004 into the company’s Total Loss Management standards. In the last few years, the LCVA methodology has been “updated to better fit our diverse assets and projects.” Petro-Canada says that the level of LCVA analysis is guided by consideration of both the number of potential social and environmental issues and the dollar value of the decision. Because the process is so flexible, Petro-Canada has increased the number, scope, and scale of projects assessed. For major projects, LCVA is part of the project management process and environmental management system. For small-to-medium projects, checklists that consider economic life-cycle costing, environmental impacts, and employee and social/community issues are employed. This simplified process for smaller projects allows environmental costs and impacts to be considered at an early stage so steps can be taken to minimize the impacts (Walter 2004). “Petro-Canada conducts LCVAs to integrate and balance environmental, social, and economic decisions related to major projects. A key component of the LCVA process is the assessment and planning for all life-cycle stages involved in constructing, manufacturing, distributing, and eventually abandoning an asset or a product. This process encourages more comprehensive exploration of alternatives. The LCVA is a useful technique; however, its predictive capability is limited by assumptions that involve the reliance on the current regulatory regime or one that can be reasonably expected.” (Petro-Canada, 2005) Appendix I contains the company’s LCVA policy.

Life-Cycle Management

Total has identified LCA as a tool to improve its products and their use. In its October 2003 report, *The Paths to Sustainable Development,* Total states that in developing new products, it “takes the entire life cycle, from manufacture to end use, into account in its technical, strategic, and marketing decisions. Fuels, lubricants, plastics, and leading edge materials are covered by this approach.” Total has developed a proprietary method for Managing Products throughout their Life Cycle, which is deployed from the design stage to guide research and determine specifications. This methodology assigns a score to each of several health and safety, environmental, resource, economic, and social criteria. Examples of these criteria include (but are not limited to) impacts over the product’s lifetime on acid rain, photochemical oxidants, ecotoxicity; societal considerations such as public perception of risk, contribution to local economies; and economic criteria such as availability and sustainability of raw materials and capital expenditures. Each criterion is scored independently on a five-point scale. High scores denote a significant contribution to sustainable development; lower scores indicate that the product has effects that are not compatible with sustainable development and can no longer continue to be produced or used in their present form (Total 2003).

5.2 POTENTIAL APPLICATIONS

Section 5.1 contained examples of actual cases in which life-cycle thinking has been used in O&G E&P-related application. Additional topics for which life-cycle thinking could be used in the O&G industry to help improve environmental decision making include the following:

- Produced water,
- Infrastructure options for E&P waste management,
- Comparing treatments for E&P wastes,
- Oil sands — water and land use,
- Hot spot (i.e., areas of potential environmental concern or activities that cause the greatest environmental impacts) identification,
- Sustainability,
- Scale management,
- Regulatory applications, and
- Extending existing studies.

The following subsections discuss potential applications of life-cycle thinking for these areas.

5.2.1 Produced Water

Produced water is the largest volume waste stream associated with O&G E&P. The characteristics of produced water vary with geographic location, geological formation, and the type of hydrocarbon produced. Typical produced water constituents can include oil and grease, salt, and other organic (e.g., benzene, phenol) and inorganic (e.g., mercury, arsenic) chemicals. Recognizing that produced-water discharges can potentially impact the environment, regulatory agencies generally prohibit discharges to most onshore and nearshore locations. The costs of managing produced water can be significant — treatment and disposal costs can range from less than $0.01 to several dollars per barrel. While we have identified no LCAs for produced-water management, there are several ways in which the results of life-cycle approaches could contribute to produced-water decision making. Below are three examples.

1. *Evaluating onshore produced-water management options*. Options for managing produced water onshore include disposal in surface evaporation ponds, reinjection into the ground, and treatment and reuse. These options can be implemented at the production site or off-site at a treatment facility. Studies have compared the costs of such options, and some have factored in the transportation costs, but cradle-to-grave examination of the costs and environmental impacts could help provide a more accurate estimate of the total costs and environmental impacts. Life-cycle studies of onshore produced-water management options could be done generically, but because

of the differences in the characteristics of produced waters and the in the locations in which they are produced and disposed, it may be more useful to apply the life-cycle concept to specific sites. A full-blown LCA would not be required to provide useful information; a spreadsheet analysis could be sufficient. The functional unit could be a barrel of produced water removed from the system (through disposal or beneficial reuse). The steps for each option would be identified and the boundaries could be limited as appropriate (for example, capital equipment costs could be outside the boundary of the study, but energy costs could be within the boundaries). If, because of regulatory requirements or other site-specific factors, options were limited to onsite treatment/reuse, the same approaches could be used to identify and evaluate the life-cycle impacts of alternative on-site treatment technologies. For example, the alternatives could include processes based on thermal distillation, reverse osmosis, and other membrane-based treatment technologies. Consideration would be given to the chemicals used in the process, the quality of the treated water, amount of fouling, energy use, scaling, membrane replacement, pre- and post-treatment requirements, and other factors. Life-cycle comparisons of various filter or treatment media such as activated carbon, organically modified clays, and zeolite adsorbent beds may also provide useful information regarding the choices of such materials and their related processes.

2. *Evaluating Offshore Produced Water Management Options*. Options for managing offshore produced water offshore include (1) discharging it overboard — assuming the concentrations of the discharged produced water constituents are within the regulatory limits, and (2) reinjecting it back into underground rock formations. In some cases, existing technologies may not provide the treatment necessary to meet contaminant-specific discharge limits, or to make the water quality sufficient to avoid plugging formations used for injection, but new technologies are constantly being developed and their costs and environmental impacts can be compared and evaluated on a consistent basis through the use of life-cycle analyses. Such life-cycle analyses may be particularly useful as some of the technologies generate byproducts, which themselves need to be treated, and the implications for such secondary treatment should be included in comparative analyses.

3. *Remediation options for soil and groundwater impacts associated with releases of produced water*. Despite the care with which produced water is managed, accidental releases occur, and such releases can cause adverse chemical and physical impacts to plants, soils, and groundwater. Remedies for produced water soil contamination include in situ chemical amendments, mechanical remediation, and natural remediation. Specific technology approaches requiring different energy and chemical inputs and may apply within these categories. Section 5.1 described some life-cycle approaches for remediating soil and groundwater contaminated with hydrocarbons; similar

approaches could be used to evaluate the options for remediating soils and groundwater contaminated by produced water.

5.2.2 Infrastructure Options for E&P Waste Management

A key issue confronting O&G E&P operations outside the United States is that many developing countries lack either (or both) waste management requirements and the infrastructure to handle waste management activities (Kerr 2005). The following paragraphs build on information presented in Kerr (2005) to show how life-cycle thinking may be applied to the evaluation of infrastructure and regulatory options in developing countries.

Regulatory requirements affecting O&G E&P operations can be expected to cover topics ranging from drinking water and sanitation to air pollution, protection of natural resources, and protection of human health. E&P companies may have opportunities to help shape requirements and infrastructure in these countries. (In some cases they may be required to develop or at least contribute to the development of needed infrastructure). In both areas (regulatory and infrastructure), it will be necessary to establish frameworks that are both cost effective and protective of human health and the environment. Addressing social aspects at the same time will also be important in many areas. Until waste-management infrastructure is in place, and even afterwards, companies operating in developing areas are likely to face limited and costly options for disposing of E&P wastes. Depending on existing infrastructure and regulations, disposal options for a range of wastes, including the traditional large-volume low-toxicity E&P wastes, industrial wastes (wood, scrap metal), land-clearing wastes, wastes from human activities (sewage, trash), and hazardous wastes (solvents chemicals, naturally occurring radioactive wastes), may be needed.

Because each country and even region within a country can vary with respect to climate, geography, topography, water availability, energy sources, population, and other factors that influence current and future environmental conditions, the regulations and infrastructure requirements will likely not be the same for each area. Instead they will need to be established on a region-specific basis. Life-cycle thinking may play a role in the evaluation of various options. For example, a company may be considering a number of options for waste management that involve development of new infrastructure. These options could include constructing company-specific management or treatment facilities (which would require working with the host government to develop design and operational criteria); construction of facilities that handle both the E&P wastes and other wastes, paying the government to construct government-operated facilities, and hauling the wastes out of the country to another location that may have the needed infrastructure.

In addition, at least two regulatory scenarios could be envisioned: In one scenario, the region has a regulatory regime in place, and in the other, the region has no regulatory regime. For the scenario with a regulatory regime, the constraints provided by that regime could be used to model inputs and emission outputs. With those boundaries, LCIs could be developed for each option. If a given option produced a lower level of inventory results across all impact categories, this would provide valuable information for decision making. If, on the other hand, Option A, for example, produced higher emissions in one category (e.g., air) and Option B produced higher impacts in another category (e.g., water) then further evaluations could be conducted to evaluate the significance of these impacts with respect to the environmental conditions specific to the area. These results could provide valuable input to the decision making process.

Life-cycle approaches could also help provide information for decision making if no regulatory regime were in place. In this case, the inventory could be conducted with no constraints on emissions. The results would be used to identify those categories with the highest life-cycle emissions for the various waste management options. The results could be used again in conjunction with the specific environmental conditions of the region to identify not only optimal infrastructure or waste management approaches but it also to help develop a regulatory regime that targets the most important potential impacts.

Regarding regulatory options, it is possible that the companies could work with the local authorities to help develop requirements that are at the same time cost effective, environmentally protective, and socially acceptable. Life-cycle thinking could be used to help understand the impacts of various regulatory options. Such an application would not necessarily require the use of a traditional LCA, but could still employ cradle-to-grave thinking. For example, a company could select a strawman option — to use as a test case for different regulatory approaches. Different regulatory options for different emission sources (e.g., air, water) could be tested in various combinations to determine the impact on resulting emissions and resource use over the life cycle of the strawman option. Similar analyses could be conducted on other waste management options. The results could be viewed in the context of the region's environmental characteristics to help evaluate the effectiveness of the various options. Knowing, for example, that air emissions from operating equipment did not vary significantly with different emission controls or regulations, or that the air emissions were relatively insignificant compared to water use impacts, could help focus the regulatory regime on those aspects of the most importance to the region.

By using a consistent methodology and set of data, results can be compared directly. Initial runs may show high emissions or other impacts that are much more significant than others. These results can be used to guide data collection efforts to refine the analyses. By keeping the initial modeling exercise fairly simple, key assumptions can be changed easily to test the sensitivity of such changes. Such analyses would not necessarily require the use of sophisticated LCA software systems. While spreadsheet calculations would not produce impact results, at the regional level, this may not be a serious drawback. This is because today's LCIA models may lack the capability to produce differential regional impacts anyway. Thus, life-cycle thinking could be employed without engaging in full-blown LCAs (and without losing value in the results). The results can be presented in graphic format for easy communication to management and in-country authorities.

5.2.3 Comparing Treatments for E&P Wastes

Section 5.1 described case studies regarding the management of drilling wastes and the remediation of petroleum-contaminated soil and groundwater. Many of the treatment technologies evaluated in these sections are similar to those that would used be for treating other E&P wastes (tank bottoms, drilling muds, pit sludges). Therefore, the LCA approaches used for evaluating the remediation and treatment techniques could readily be applied to E&P waste treatment. Variations for applying these approaches to E&P wastes could include the addition of more treatment techniques and more impact categories. For example, under bioremediation, techniques such as windrows, forced aeration, and static aeration could be included. Less commonly used approaches, such as in-vessel composting, bioslurry systems, and soil venting could also be included. (For more information on the application of these techniques to E&P waste management, see McMillen [2004], which compared these approaches on the basis of biodegradation rates and costs.) By using life-cycle thinking, the impact categories could be broadened to include water use, land use, resource depletion, and possibly, social indictors.

5.2.4 Oil Sands Life-Cycle Studies

Section 3.1.9 described how LCA was used to compare energy intensity and GHG emissions for three different fuel sources for steam and hydrogen production to recover and upgrade oil from oil sands. There are a variety of other ways to use LCA in oil sands evaluations, particularly in comparing the two main extraction methods — surface mining and in situ extraction.

Surface mining operations for oil sands are similar to those for coal. Trees are cleared; surface overburden is removed, and oil sands are mined and transported to crushers, where they are reduced to small sizes. They are then mixed with hot water to create a slurry that is transported via pipeline to extraction sites, where they are mixed with more hot water to extract the bitumen. Solvents are added to the bitumen to minimize water and solids for upgrading. Upgraders convert the bitumen to synthetic crude oil through coking, desulfurization, and hydrogen addition. Most of today’s oil sands operations utilize surface mining.

In situ operations are similar to enhanced oil recovery with steam injection. Conventional in situ production consists of first injecting steam into the reservoir where steam and condensed water heat the viscous bitumen, followed by pumping the heated bitumen and water to the surface. Advance drilling technologies allow for the horizontal drilling of well pairs. In a well pair, one well is used for injecting steam to heat the oil sands, and the other is used to pump the bitumen with reduced viscosity to the surface. Although in situ production requires large amounts of steam, the produced bitumen is light enough to be processed directly in downstream refineries (Larsen et al. 2005). While most oil sands production today uses surface mining, the share of production via in situ extraction is increasing.

As Bergeson and Keith (2006) explain, in situ technologies appear to require lower upfront capital costs and result in lower land-use impacts, but require large energy inputs (for steam production) than surface mining. They note that LCA can help in making sound decisions and have suggested a number of potential applications of LCA for oil sands development. They also note that the use of such techniques will help set research and development priorities by identifying technologies or combinations of technologies that would provide particularly large life-cycle benefits. The following potential applications were suggested by and are described in Bergeson and Keith (2006).

LCA on current operating facilities in Alberta. An LCA of current operating facilities could compare the two main types of extraction — mining and in situ. Metrics could include a breakdown of capital and operating costs, material flows (amount required, distance shipped, and transport method). The amount of energy required would also need to be assessed for each stage of the operation. Thus, while data indicate that about 1 GJ of natural gas energy and 0.0083 GJ of electricity are required to produce 1 barrel of synthetic crude from the in situ extraction phase, and about 0.25 GJ of natural gas and 0.0147 GJ of electricity are needed for the mining extraction phase, additional upstream energy is needed to produce the products consumed in the construction and operation of the oil sands extraction site and the energy required to transport those materials. After the cost, energy, and material flows have been identified, the environmental impacts can be assessed.

Water impacts from oil sands development. Large amounts of water are used, consumed, and produced in oil sands development. These include, but are not limited to, aquifer dewatering, direct withdrawal from water bodies from surface mining, and production of large volumes of waste associated with wastewater treatment from in situ operations. A possible application of LCA would be to expand the economic input-output tool to account for water use from these additional sectors and to use LCA to compare mining versus in situ operation. Actual impacts, of course, would depend on site-specific circumstances.

Land use impacts. In Alberta, one of the biggest impacts of development on wildlife is land fragmentation, and within a given area, the linear distance developed may be more important than the total surface area. In the Alberta-Pacific Forest Management Agreement Area, the average current density of linear development is 1.8 km/km^2. If forestry activity continues at current levels, and if energy development continues to expand at current rates, the average density will be more than 5.0 km/km^2, a density that would negatively affect many species. When comparing surface mining with in situ oil sands development, it would appear that surface mining techniques disturb much more surface area than in situ operations. However, for in situ processing, four times as much natural gas is required per barrel of bitumen than for a barrel produced using surface mining. Thus, four times as much natural gas infrastructure will also be required. LCA could be used to identify the land area disturbed for surface mining versus in situ development by considering all of the operations and processes that use land. Such an assessment would benefit from the use of complementary tools. For example, tools that provide satellite data at various levels of spatial resolution could be used to create land cover and land use maps. Metrics could be determined to measure the impact of fragmentation on the area of interest, and these maps could be interpreted using existing software.

5.2.5 Identifying Hot Spots in Upstream Processes

Many of the LCA applications pertaining to O&G E&P described in Section 5.1 compared options, methods, or processes within the E&P regime. An alternative application, which could be particularly useful when considering E&P technologies and waste management approaches in different regions or countries, would be to conduct an LCA on the entire operation to identify all impacts, releases, resources used, etc., prior to start of development This would allow decision makers to target those portions of the operations that produce the greatest environmental impacts, i.e., hot spots, for improvements. Such a study could form a foundation for identifying impacts of the same process in different countries or regions. This could be done through the use of sensitivity analyses, in which inputs that would vary from region to region (for example, energy sources, or regulatory requirements) could be modified depending on country-specific parameters. This would allow decision makers to address those parts of the system to minimize environmental impacts through, for example, product substitution, or perhaps even substitution of approach, should the estimated environmental impacts become problematic in given areas.

5.2.6 Linking Sustainability and LCA

Sustainable development is often defined as development that meets the needs of the present without compromising the ability of future generations to meet their needs. As more countries incorporate sustainability concerns into their development decisions, O&G E&P companies may have the opportunity to (or be called upon to) address social as well as environmental aspects in their plans and operations. Sustainable development is the ultimate goal of the application of all life-cycle approaches. Since a methodology for considering environmental concerns has been established in LCA, researchers have begun considering whether social aspects can be considered in the same fashion or even within the LCA. Such integration would allow for the simultaneous evaluation of social and environmental considerations with the same assumptions. This area is ripe for development, and the remainder of this section highlights two approaches that embrace a life-cycle approach. The first is a planning approach that strives to integrate social, economic, and environmental considerations without attempting to conduct a formal LCA, and the second explores the feasibility of integrating social aspects within the formal LCA approach.

Life-Cycle Sustainability Planning

This approach, summarized below and based on a case study described by Matos and Hall (2007), shows how one oil company began to incorporate social aspects into its planning and development decisions. The case study is for a mid-sized O&G company that was forced to make changes to its operations in the wake of several high-profile spills and stakeholder complaints. Because the company's activities exploited state-owned natural resources, the vice president for sustainable development stated that the company must demonstrate its contributions to society, requiring a "social license" to operate. To help meet this goal, all supply chain members are monitored and expected to behave in an environmentally and socially acceptable manner. The company recognizes interdependencies among sustainability parameters and reports them as integrated indicators. For example, the relationship between GHG emissions and company revenues and expenses are documented. Incidents and regulatory violations are linked with environmental, health, safety, and economic performance, and the company's reputation.

The company's life-cycle approach involves an integrated analysis of environmental, social, and economic aspects of new operations or expansions, and it considers both quantitative and qualitative parameters. For all new projects, workshops are conducted at which employees from different departments, including finance; communication; heath, safety, and environment; and others identify and evaluate positive and negative economic, environmental and social factors. In the workshop, a nongovernmental organization (NGO) facilitator asks practitioners to identify components of the system beginning with construction, and including operations and decommissioning, and the extended supply chain. The diversity of expertise within the workshop facilitates a broad analysis and identification of opportunities for improvement. The company also reported that involving the NGOs enhances the legitimacy of LCA results, and reduces friction with stakeholders.

Integrating Social Aspects into LCA

The second approach is more technical and from an implementation perspective, more future-oriented. It is based on the results of a recently completed feasibility study on the integration of social aspects into LCA conducted by the UNEP/SETAC Life Cycle Initiative and reported in Griesshammer et al. (2006), and it may be instructive for O&G analyses. Some of the study's findings are as follows:

- While there are ISO standards for conducting an environmental LCA there are no comparable standard or internationally recognized codes of practice for social LCAs.

- Evaluating life-cycle social aspects present special challenges. Social aspects can be highly diverse, are weighted very differently by different interest groups in different countries and regions, and are difficult to quantify (making them difficult, for example, to relate to a functional unit).

- The basic methodological structure of a social LCA would be to explore social aspects throughout the product life cycle, generally with the aim of improvement or in comparison to an alternative. The methodology would be similar to that of LCA, which includes goal and scope definition, inventory analysis, impact assessment, and interpretation.

- There appear to be no fundamental methodological problems regarding the feasibility of social LCA, but practical challenges would include categorizing indicator groups and classifying and characterizing individual indicators.

- Proposed steps for further development included

    - Conducting case studies;
    - Establishing a generally accepted list of social indicators (inventory indicators, midpoint indicators, endpoint indicators) structured after stakeholder groups and after generally accepted impact categories;

- Identifying and improving databases; and
- Developing a “code of practice” for integrating social aspects into LCA.

Weidema (2006) has suggested some specific ways for integrating societal aspects into LCA. He identified six damage categories under the general heading of human life and wellbeing. These are life and longevity; health; autonomy; safety, security, and tranquility; equal opportunities; and participation and influence. He also proposed a set of indicators, with units of measurement, and a first approximation of global normalization values. For example, changes in the expected length of life are measured by the damage indicator Years of Life Lost. To obtain a normalization reference for the current total loss of life-years, the current average life expectancy may be compared to the maximum life expectancy. One of the challenges associated with this measure is that the maximum life expectancy varies between genders and among populations.

Developing health indicators become more complex. For example, nonfatal impacts on human health are measured in terms of the type of disability (disease or injury) and the duration of the condition. The unit of the damage indicator is disability years, and to each form of disability, a severity weight may be assigned on a scale between 0 and 1, where 0 is equal to death. The resulting damage indicator is called healthy Years Lost due to Disability; and Years Lost due to Disability can be aggregated to the Years of Life Lost. Other damage indicators, such as Years of Well-being Loss can be developed for other damage categories.

After listing and quantifying the damage categories, impact pathways from the social inventory results to the damage indicators would be modeled. By taking a top-down approach, i.e., starting from the damage categories, efforts can be focused on the most important impact categories.

Impact pathways for some social indicators are fairly straightforward. For example, occupational health and safety are generally recorded in terms of diseases and injuries per working hour, which translate directly into health damages, and stress measurements can be converted to damages in terms of anxiety and disease. Impact pathways for other indicators are more complex. For example, the use of indigenous resources presents a distributional issue where modeling the impacts of deviations between the market value of the resources and the value actually paid for them is not straightforward. A key issue for impact modeling is the distributional issue; that is, impacts do not affect all groups in society equally.

Weidema suggests that the six damage categories can be seen as a first step toward a single-score indicator for LCA, which converts all impacts into a measure of well-being called Quality Adjusted Life Years. He says that this measure, which measures ultimate intrinsic value, is an attractive alternative to direct monetarization, which can only be used to measure instrumental values.

Extending the LCA methodology to include social aspects would require the addition of impact categories and most likely a different approach to characterization modeling.

5.2.7 Scale Management

Flow assurance is critical to the economic production of crude oil, and scale control is a key aspect of flow assurance. The growing complexity of new well completions, especially for offshore drilling (for example, horizontal wells, subsea tiebacks, and commingled flows), presents particular challenges for scale control. Scale inhibitor treatments are typically associated with high intervention costs. Over the past four decades, technologies have been developed to reduce the risk of scale formation, control scale formation, and remove it if formed at both onshore and offshore facilities. While most of the technologies are designed for use during operations, evaluation of scale risk and combining engineering and chemical solutions in the planning phase can greatly improve long-term field economics. Jordan et al. (2001) have suggested the need to address scale control proactively, as part of asset life-cycle management, whereby the issues are addressed before field development/production rather than in a reactive manner once water breakthrough occurs in the operations phase. They say that such an approach allows for the selection of appropriate economic technology, and point out that anticipated problems could influence the plans to develop a field, for example, in terms of water injection strategies. The following information is based on their study.

For two fields developed in the late 1970s and early 1980s southwest of Stavanger, Norway, the control of scale has been the largest single operating cost. Were these fields to be developed today, proactive options would allow more flexibility in scale management. For example, such options could include completion-installed scale inhibitors, chemical application via capillary string injection lines to below the subsea safety valve, protection against scale on first water breakthrough by employing a proactive rather than reactive approach to scale management, and oil-soluble scale inhibitors or emulsified scale inhibitors to deploy chemicals prior to water breakthrough. As the gaps between technical needs and available technological solutions are filled, additional options will include increasingly efficient scale inhibitors (meaning that lower amounts will be needed to achieve the same level of control), and scale inhibitors that are thermally stable, have good adsorption characteristics, and are easily detected. Evaluating these options in the planning phase would likely occur. The authors conclude that if such fields were to be developed today, a full risk assessment and economic analysis of the various options available for managing scale would be performed. In addition to considering the economic and technical aspects of these options, consideration of the life-cycle environmental impacts could add value to the overall total cost analysis.

5.2.8 Regulatory Applications

LCAs may aid in communicating with regulatory authorities and in formulating policies and regulations. For example, in the European Union (EU) directive on IPCC, the determination of BAT is a critical issue. BATs, which are determined at the European sector level by expert groups, serve as reference values for emissions limits and operational permits. It is not clear that life-cycle thinking is incorporated into the determination BAT (See Section 5.1.3). However, the incorporation of life-cycle thinking may improve such determinations, because reducing emissions at one source through the use of BAT may increase emissions in other parts of the life cycle.

Similarly, OSPAR Decision 2000/3 on the Use of Organic-Phase Drilling Fluids (OPF) and the Discharge of OPF-Contaminated Cuttings (OSPAR 2000) requires that

- No OPF shall be used for the purpose of drilling in the course of an offshore activity or discharged to the maritime area without prior authorization from the national competent authority;
- The discharge of whole OPF to the maritime area is prohibited;
- The mixing of OPF with cuttings for the purpose of disposal is not acceptable; and
- The discharge into the sea of cuttings contaminated with OBF at a concentration greater than 1% by weight on dry cuttings is prohibited.

Using the treatment technology in wide use today, these requirements essentially mean zero discharge of cuttings drilled with oil-based or organic-phase drilling fluids. However, from a life-cycle perspective, the deposition of residues and associated environmental load may be mitigated by the use of technologies that convert drilling waste into useful products with a commercial value. Incorporating life-cycle thinking into such regulations could result in the development of new technologies and approaches to reduce the net environmental impact of actions on the environment (see Paulsen et al. 2003).

5.2.9 Build on Existing Studies

Results from existing LCA studies could be reviewed to identify common areas of concern, i.e., those processes or life-cycle stages that consistently produce higher impacts. For those stages that are also part of E&P operations, analyses could be tailored and focused. For example, transportation emissions are major contributors to aquatic toxicity, acidification, and CO_2 loading. Thus, transportation may be an important consideration in decisions to build small process or disposal sites rather than centralized sites. Construction activities contribute to photochemical oxidation, and this could be an area of focus given today's concern with ozone depletion. Energy consumption is an area that generally produces high environmental impacts, and so the energy-consuming portions of E&P operations may benefit from targeted life-cycle analyses.

Existing studies can also be used to identify data gaps and hence, potential areas for focusing E&P life-cycle studies. As noted earlier, data availability is a key barrier to conducing LCAs. Understanding the types of data that are needed — not only for E&P LCAs, but also for other LCAs that would benefit from incorporation of realistic life-cycle impacts from E&P, could be a focus for data collection efforts. The O&G industry may want to embark on a data-collection activity similar to those undertaken by other major industries. Such an undertaking could help ensure that LCA studies (both for E&P and for those that may want to incorporate E&P) are using consistent and reliable data.

6 PRACTICAL CONSIDERATIONS FOR IMPLEMENTING LCA

As noted in Sections 4.1 and 5.1, life-cycle approaches can be used to improve environmental decision making in a variety of ways. At the same time, users need to be aware of potential pitfalls and to plan and implement their LCAs so as to maximize potential benefits. When contemplating whether to undertake an LCA, companies, users, and practitioners may want to consider the following suggestions, most of which come from the experiences of others, to help increase the prospects of obtaining useful results in a cost-effective manner.

Organizational and Strategic Considerations

- Be clear on the objectives of the study and the measures of success. By defining the scope upfront, the potential for controversy or disagreements later in the study can be minimized.

- Understand that the LCA results provide environmental information and as such, contribute but one component of a more comprehensive decision-making process that assesses environmental trade-offs with cost and performance. Recognize that the LCA will not provide data on product or process efficiency or cost effectiveness.

- Recognize the trade-offs between resource requirements and the level of detail that can be accommodated in a study. Before undertaking an LCA, potential users should weigh the availability of data, the time needed to conduct the study, and the financial resources required against the projected benefits of the LCA. Users should consider using a simple life-cycle thinking approach as a first effort, and then build on the results. While following the ISO 14040 and 14044 standards will give a study more credibility, doing so is not necessary for studies intended for internal company use only.

- Engage management support to ensure participation by both the main contributors of ideas and information and the users of the results in the process.

- To ensure the broadest coverage of all aspects and processes, include as many participants as possible. Participants can include employees representing various functions within the O&G company, suppliers, and contractors.

Operational Considerations

- Provide participants with introductory reading on the process in advance of the scoping meetings.

- In the initial meetings, a facilitator can help ensure that all perspectives are heard and that strong opinions are balanced.

- Consider using guidance to help structure and implement the LCA. In addition to the ISO standards, a number of practical guides on how to conduct an LCA exist. These guidelines are more detailed than the ISO standard, and many include guidelines for impact assessment. However, they are not consistent in terminology, many focus on specific countries or regions, and few have benefited from the involvement of a broad cross-section of regions and stakeholders. Examples of generally applicable guidance documents include the following:

    - *Code of Practice for Life-cycle Assessment* (Consoli et al. 1993)
    - *Life-cycle Assessment: Inventory Guidelines and Principles*, (Vigon et al. 1993)
    - *Life-cycle Assessment A guide to Approaches, Experiences and Information Sources* (EEA 1997)
    - *Life-Cycle Impact Assessment: Striving Towards Best Practice* (Udo de Haes 2002)
    - *Code of Life-Cycle Inventory Practice* (Beaufort-Langeveld et al. 2003)

In his study of the use of LCA in industry, Frankl (2001) identified several factors influencing the successful introduction and institutionalization of LCA in business decision-making processes. While the introduction of LCA can occur from the top down (through indications by top management) and the bottom up (by the initiative of an environmental manager), the institutionalization of LCA typically requires a mandate from top management. Factors for successful implementation identified by Frankl include the following:

- The presence and influence of a "champion," who pushes LCA activities within the company,
- Involvement of practitioners,
- Development of formalized structures,
- Establishment of internal communication channels,
- Development of internal know-how, and
- Long-term environmental commitment.

Technical Considerations

- *The functional unit.* The functional unit provides a basis for calculating inputs and outputs and relates impacts to product or process function. A well-defined functional unit that assures equivalence also allows for more meaningful comparisons between alternative systems. For example, comparing the environmental impacts of, for example, one ton of structural steel and one ton of structural concrete would be misleading, since less steel may be needed to perform the same function. The functional unit should be carefully defined to be meaningful to the goal of the study. If the functional unit is not chosen appropriately, the final study results may not be sufficient for answering all of the questions posed by the users, or they may provide misleading information.

- *Geographical differences.* Traditionally, LCAs have been conducted without regard to geographical boundaries. However, for O&G products and processes, geographical differences may be important, because the characteristics of various O&G production areas vary dramatically — from desert environments in remote locations to ocean and coastal areas with significantly different ecological and other characteristics. Activities to incorporate geographic variations should be monitored for application to O&G LCAs. For example, European studies have produced country-dependent characterization factors for acidification and terrestrial eutrophication (Seppälä et al. 2006).

- *Timing.* The shorter the time period covered by an LCA, the higher the share of construction-related impacts will be of the total environmental impacts. Over longer periods, construction impacts will be more spread out. One study, for example, concluded that for a local vs. central incineration waste strategy, the cumulative impact over two decades was about 2.5 to 5 times as great for the central scenario with three incinerators than for the local scenario with 17 incinerators (Bergsdal et al. 2005). Such findings lead to questions regarding the discounting of future emissions (similar to discounting of future costs) and the effects of improved technologies that could reduce the releases or impacts of emissions as well as the possibilities that additional future impacts of emissions releases will be discovered.

- *System Boundaries*. Decisions must be made on which processes or activities to include when setting system boundaries, and it is not always clear which processes should be included. It might be possible to eliminate those processes that are identical for all items under study or to eliminate elements of the system that are beyond the purview of the study goal and purpose (that is, those components of the system that cannot be affected by the decisions, actions, or activities that are driving the study). In the production of ethylene, for example, oil has to be extracted; this oil is transported in a tanker; steel is needed to construct the tanker, and the raw materials needed to produce this steel have to be extracted. For practical reasons a limit must be set. Usually, the production of capital goods (such as tankers for transport) is excluded; however, this would not apply in cases where the capital goods were not used for mass production or mass transport. The basis for the decisions should be clearly understood and described and should be consistent with the stated goal of the study.

- *The role of standards*. ISO standards require that LCAs conducted for comparative assertions undergo a critical review. The review can be internal, external, or external with at least two parties involved. There is an issue regarding the type of critical review needed for a comparative assertion used for method development and evaluation vs. a comparative assertion regarding the environmental superiority or equivalence of one product over a competing product that performs the same function. Some have suggested that while a critical review performed by a panel of at least two external experts is required for comparative assertions disclosed to the public, requiring this level of review may stifle valuable LCA studies from being performed and published. Thus, for studies that do not include comparative assertions in the strict definition of the term but that contribute to developing new methodological aspects or internal product/process optimization, such reviews may not be necessary. Even if high-level critical reviews are not required for such studies, expert review will still help ensure high scientific quality (Lichtenvort 2005).

7 CONCLUSIONS

The integration of life-cycle thinking into environmental decision making can improve the ability to consider all aspects of a process or product and avoid shifting impacts from one medium to another. Based on a systematic process that can be tailored to specific applications, life-cycle thinking can be applied at levels ranging from back-of-the-envelope approaches that consider the entire life cycle of a product or process without much quantitative analysis, to a complete LCA that follows the ISO standards and uses sophisticated models and software packages to estimate a variety of impacts on the environment. The choice of approach will depend on the objective of the study and the resources available. Life-cycle thinking has been used in the O&G industry to compare remediation approaches, to evaluate drilling water management options, to identify environmental aspects of deep-drilling operations, to compare energy use and GHG emissions for crude oils from different sources, to identify impacts of oil sands development, to aid in investment decisions, and to evaluate environmental impacts of CO_2 storage in active reservoirs. Additional potential applications could include evaluating and comparing onshore and offshore produced water management options, evaluating infrastructure options, and assessing water and land impacts for oil sands development. Other applications could include linking sustainable development with LCA and integrating social aspects into LCA. Successful applications will recognize potential pitfalls and will match the scope and expectations of the study with the resources available.

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APPENDIX A:

LCA RESOURCES

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LCA RESOURCES

Background/General Life Cycle Information Reports

The following reports provide general background information on life-cycle thinking and assessment. Written from various perspectives, they demonstrate the breadth, depth, and variety of perspectives on the topic.

UNEP/SETAC Life Cycle Initiative, Life cycle Approaches, the Road from Analysis to Practice. Available at http://www.uneptie.org/pc/sustain/reports/lcini/Road%20report%20for%20web.pdf. Provides overview of the different life cycle approaches, including case studies that illustrate experiences been obtained during the last 10 years. Includes overview of the state-of-the-art of four core topics: Life Cycle Management, Life Cycle Inventory Analysis, Life Cycle Impact Assessment and the use of life cycle approaches in small and medium-sized enterprises (SMEs) and developing countries. Contains extensive bibliography.

LCA for Mere Mortals, A Primer on Environmental Life Cycle Assessment, by Rita C. Schenck (2000). Provides a layman's guide to the principles and application of life-cycle assessment, using examples, and nontechnical language.

U.S. Environmental Protection Agency (EPA), 2006, *Life Cycle Assessment: Principles and Practice*, National Risk Management Research Laboratory, Office of Research and Development, EPA/600/R-06/060, May. This 88-page document provides an overview of LCA and describes its general uses and major components. This document is an update and merger of two previous EPA documents on LCA ("Life Cycle Assessment: Inventory Guidelines and Principles," EPA/600/R-92/245, and "LCA101" from the LCAccess Web site, at http://www.epa.gov/ORD/NRMRL/lcaccess. It describes the four basic stages of conducting an LCA: goal and scope definition, inventory analysis, impact assessment, and improvement analysis. System boundaries, assumptions, and conventions to be addressed in each stage are presented. This document is intended as an educational tool for persons wanting to learn the basics of LCA, how to conduct an LCA, or how to manage someone conducting an LCA.

European Environment Agency, *Life Cycle Assessment (LCA — A Guide to Approaches, Experiences and Information Sources*, Environmental Issues Series no. 6, August 1997. This guide, together with the meta-database containing information sources, is a practical guide for businesses and industries. The text describes the ground-rules for credible LCAs, explains the meaning of "benchmarking," looks at the issues of management systems and environmental strategies, as well as the impacts and outcomes of LCA, the different standards, the LCA's boundaries, the means to carry simplified LCAs. It contains a comprehensive list of additional LCA resource materials. It is available on the web at http://reports.eea.europa.eu/GH-07-97-595-EN-C/en/Issue%20report%20No%206.pdf.

Web Sites

U.S. EPA, Life-Cycle Assessment Research, Life Cycle Assessment. The purpose of the *National Risk Management Research Laboratory's Life-Cycle Assessment (LCA) Web site* is to promote the use of LCA in making more informed decisions through a better understanding of the human health and environmental impacts of products, processes, and activities. The site has four primary areas to help educate people new to the concept of LCA while serving as a focal point for LCA practitioners and decision-makers to stay current with the field of LCA. These areas are information on why one would want to perform an LCA, an overview of LCA, how to find LCI data sources, and available LCA resources. The Web site is located at http://www.epa.gov/ORD/NRMRL/lcaccess/index.html.

UNEP Life Cycle Initiative Web site is a partnership between the United Nations Environment Program and the Society of Environmental Toxicology and Chemistry. Its mission is to develop and disseminate practical tools for evaluating the opportunities, risks, and trade-offs, associated with products and services over their whole life cycle. The Life Cycle Management (LCM) program creates awareness and improves skills of decision-makers by producing information materials, establishing forums for sharing best practice, and carrying out training programs in all parts of the world. The Life Cycle Inventory (LCI) program improves global access to transparent, high-quality life-cycle data by hosting and facilitating expert groups whose work results in web-based information systems. The Life Cycle Impact Assessment (LCIA) program increases the quality and global reach of life cycle indicators by promoting the exchange of views among experts whose work results in a set of widely accepted recommendations. The site, located at http://www.uneptie.org/pc/sustain/lcinitiative/, contains links to numerous publications, reports, workshop summaries, newsletters, publications event, government initiatives, and other timely and topical information.

APPENDIX B:

LIFE-CYCLE APPROACHES AND TOOLS

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LIFE-CYCLE APPROACHES AND TOOLS

Unless indicated otherwise, the information in this appendix comes from the *UNEP/ SETAC Life Cycle Initiative Report, Life Cycle Approaches — The Road from Analysis to Practice* (2005).[2]

Analytical Tools that Relate to and Can be Used with LCA

Energy and material analysis (EMA)

Energy and materials analysis is to a large extent similar to the inventory phase in a LCA since it quantifies all materials and energy that enter or exit the system under study. One major difference is that EMA does not necessarily involve the whole life cycle of a product or a service, instead focusing on one specific phase or production process. Another difference is that the results from an EMA are not explicitly translated into potential environmental impacts (EEA, 1997).

Material Flow Accounting (MFA)

Material Flow Accounting (MFA) aims at specifying the pathways of materials in, out, and through the economy of a nation, region, community, business sector, company, or household. MFA enables one to spot the major flows and stocks, to signal future problems in an early stage, to trace the fate of inflows, to link specific pollution problems to their origins in society, and to assess the consequences of management changes for the environmental flows and stocks.

Substance Flow Analysis (SFA)

SFA focuses on the metabolism of individual substances or groups of substances. The objective of SFA is to make an inflow and outflow balance of one particular substance (or group of substances) through the material economy, giving the opportunity of identifying environmental improvements related to the substance. The modeling and data collection approach is in many cases quite similar to that used in LCA, except that the substance flow is not being related to a functional unit. SFA may thus be a useful data source for LCA (and vice versa) but its main application is to identify environmental policy options, (e.g., by showing which flows might be restricted in order to reduce the emissions of a substance or a material). Most SFAs are limited to specific geographic boundaries (e.g., the national level) (EEA 1997).

MFA and SFA are two complementary approaches:

- MFA analyzes the metabolism of bulk materials (e.g., steel, wood, total mass). The results can be used to set priorities for policy measures towards increased resource efficiency and sustainable supply and waste management systems.

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2 Available at http://www.uneptie.org/pc/sustain/reports/lcini/Road%20report%20for%20web.pdf.

- SFA analyzes the metabolism of a single substance or of a group of substances that are associated with specific environmental effects. This allows for an effective cause effect modeling, linking the actual industrial metabolism to specific environmental issues in a quantitative manner.

Environmental Risk Assessment

Environmental Risk Assessment (ERA) studies are carried out to study the effects on humans and ecosystems and enable a risk management decision to be made. The principles or ERA are to identify the hazards of a substance, and to characterize the risk by performing a fate and effect analysis. The result of an ERA study may lead to a risk acceptance, or to the implementation of risk reduction measures that reduce the likelihood of the event or reduce the consequences to a satisfactory level.

The full field of Risk Assessment includes the consequences of activities, technical installations, technologies, processes or substances (or chemicals). Environmental Risk Assessment (ERA) more in particular focuses on chemicals, which are considered to be hazardous; it involves the following stages:

- the identification of the hazard
- exposure assessment
- effect assessment
- risk characterization

The risk characterization can be defined as “the quantitative estimation of the incidence and severity of the adverse effects likely to occur in a human population or environmental compartment due to actual or predicted exposure to a substance". More in general, risk assessment approaches often focus on the consequences of single activities or technical installations. Such approaches can be relevant from a life cycle perspective if a number of core activities along a life cycle are investigated in a consistent way, thus identifying hot spots for improvement.

Input/Output Analysis (IOA) and Environmental Input/Output Analysis

Input/Output Analysis (IOA) concerns the analysis of monetary flows between economic sectors. It is mainly used to display all flows of goods and services within an economy; simultaneously illustrating the connection between producers and consumers and the interdependence of industries. The use of IO-tables is important for analyzing structural adjustments in industry. Input/ Output Analysis was founded by Wassily Leontief in the 1930s, focusing on how industries trade with each other, and how such inter-industry trading influenced the overall demand for labor and capital within an economy. The basic distinction that is made in IOA is between the output of goods and services sold to "final demand" (households, governments, exports, investment), and the "total output" of the various sectors, compromising final demand, plus the output that is used as inputs into other sectors (intermediate demand). Environmental IOA is based on an extension of the traditional Leontief model. In environmental IOA, extractions and emissions are additional objects of analysis. In the environmental extensions, additional conditions must be included in order to enforce consistency among inter-industry production, pollution generation and pollution abatement activities. IOA is increasingly linked to LCA, called hybrid analysis. In such hybrid analysis, process analysis data and IO-data are combined, with the aim of reducing a number of errors. For instance, conventional LCA is likely to ignore processes connected to services, small inputs, and the manufacture of complex products from basic materials. IOA methods, while comprehensive in framework, are subject to inherent errors due to the use of economic data to simulate physical flows and the aggregation of the whole economy into one relatively simple matrix.

Total Cost Accounting (TCA)

Total Cost Accounting is a relatively new approach that works from existing financial and management costing systems to identify all costs, including previously hidden and intangible, and assigns them to a specific product or process. External costs, costs which are not paid directly by the company, but which are borne by neighbors and society, can also be factored in the method. Total Cost Accounting reveals a more complete cost per process or product than traditional ledger values. These costs can then be considered by decision makers in targeting process improvements, modifying product lines, and other business strategies. TCA is useful to companies that strive to improve efficiencies and reduce costs to achieve the 'triple bottom line' results– economic, environmental and social success. Total Cost Assessment is a tool similar to LCC, but has a focus on one particular project and usually also includes intangible costs.

Environmental Management Accounting (EMA)

Management accounting is a broad term referring to the process of identification, measurement, accumulation, analysis, preparation, interpretation, and communication of financial information used by management for planning, evaluation, and control within an organization, and for ensuring of accountability for its resources. Environmental Management Accounting serves as a mechanism to identify and measure the full spectrum of environmental costs of current production processes and the economic benefits of pollution prevention or cleaner processes, and to integrate these costs and benefits into day-to-day business decision-making. While management accounting systems are traditionally viewed as matters internal to a firm, the potential social benefits resulting from widespread use of environmental management tools calls for active governmental involvement in promoting such systems. Government programs and policies can play an important role in encouraging and motivating businesses to adopt environmental management accounting systems as an integral part of a firm's management accounting practices, such that all project costs (including social and environmental costs) become clearly articulated, fully inventoried and properly allocated over the life of an investment.

Cost Benefit Analysis (CBA)

Cost Benefit Analysis is an economic tool for determining whether or not the benefits of an investment or policy outweigh its costs. The tool has a very broad scope, and aims at expressing all positive and negative effects of an activity in a common unit (namely money), from a social, as opposed to a firm's point of view. CBA is usually applied for major public investment projects, like infrastructure projects, and also for policy evaluation. Whole production and consumption systems can be examined, and in this way it contributes to life cycle approaches. Economic and environmental elements are expressed in monetary values – as far as possible and depending on the level of detail. In terms of methodological steps, CBA involves first of all a determination of which costs and benefits are examined, then tries to identify these costs and benefits, and finally weighs them against each other.

Checklists

A checklist can be described as a series of questions or points of attention that can be phrased in terms of pass/fail criteria. Checklists can be made for multiple goals. Checklists for Eco-design can be used by a designer to check whether they did not forget any aspect. Likewise, organizations that want to obtain an ecolabel should pass all criteria of a checklist provided by the certification organization. Special types of checklists are those based on pass/fail criteria.

Models & Techniques

Models and techniques are methods of obtaining data, data processing and of presenting information. Models and techniques are frequently used in analytical tools. Examples of models are dose-response models, in which the effect of a certain level of pollutant on, for instance, human health is calculated, and ecological models. Furthermore, flows of toxins are often modeled to identify potential problem (high concentrations), and to research the effects of policy changes. Techniques concern generally statistical tools, for example: weighting or sensitivity analysis.

Life-Cycle Approaches that Translate Life Cycle Thinking into Practice

Cleaner Production

Cleaner Production (CP) is the continuous application of an integrated preventive environmental strategy to processes, products, and services to increase overall efficiency, and reduce risks to humans and the environment. Cleaner Production can be applied to the processes used in any industry, to products themselves and to various services provided to society. For production processes, Cleaner Production results from one or a combination of conserving raw materials, water and energy; eliminating toxic and dangerous raw materials; and reducing the quantity and toxicity of all emissions and wastes at source during the production process. For products, Cleaner Production aims to reduce the environmental, health and safety impacts of products over their entire life cycles, from raw materials extraction, through manufacturing and use, to the 'ultimate' disposal of the product. For services, Cleaner Production implies incorporating environmental concerns into designing and delivering services.

Therewith, Cleaner Production is the international term for reducing environmental impacts from processes, products and services by using better management strategies, methods and tools. CP is called Pollution Prevention (P2) in North America, and Produccion Mas Limpia (PL) in Latin America. Related terms include green business, sustainable business, eco-efficiency, and waste minimization. UNEP has been providing leadership and encouraging partnerships to promote the concept of Cleaner Production on a worldwide scale, especially through the creation of National Cleaner Production Centers (NCPCs) together with the United Nations Industrial Development Organization (UNIDO). Currently, more than 1000 cleaner production demonstration projects have been launched.

Sustainable Procurement

Sustainable procurement (or green procurement) is the process in which organizations buy supplies or services by taking into account:

- the best value for money considerations such as, price, quality, availability, functionality, etc.;
- environmental aspects ("green procurement": the effects on the environment that the products and services have)
- the entire life cycle of products and services, from cradle to the crave;
- social aspects: effects on issues such as poverty eradication, international equity in the distribution of resources, labor conditions, human rights.

With a Sustainable Procurement policy, organizations and governments aim to stimulate the consumption of products or services that fulfill the above-mentioned requirements. Governments can choose to stimulate the consumption of these products and services by their own organization or in their domain of influence (e.g., by tax stimulation). A number of third party organizations have developed standards and guidelines for green products and services. One form of guidelines is set up by Environment Canada. It provides a checklist focusing on the four R's (reduce, reuse, recycle, and recover) in each phase of the material life cycle. The inclusion of sustainable development principles in procurement practices is already a reality in a number of countries such as Canada, Germany, Japan, the Netherlands, Norway, Switzerland, United States and South Africa. The experiences in these countries indicate that incorporating sustainable production and consumption considerations into public purchasing is not only a viable option, but also helps to develop sustainable markets. Sustainable procurement is also a corporate program, and is increasingly implemented as business strategy.

Supply Chain Management

Supply Chain Management enables companies to look upstream beyond their own company, and involve suppliers in their sustainable initiatives. Supply Chain Management includes managing supply and demand, sourcing raw materials and parts, manufacturing and assembly, warehousing and inventory tracking, order entry and order management, distribution across all channels, and delivery to the customer. Companies can choose their suppliers based upon their environmental performance, work together with them in creating sustainable products, or provide training and information. Besides environmental benefits, Supply Chain Management can result in costs improvement, improved risk management, and enhanced image.

End of Life Management

End of Life (EOL) Management is the downstream management of products at the time their functional life has ended and they enter the waste phase. An example of an EOL management program of a company or industry sector is a take back system. These take back systems can be based on voluntary agreements, but some countries also force producers to take back bottles for instance as part of their Extended Producer Responsibility. Many companies address the challenges of EOL management by design for recyclability of their products.

Product Stewardship

Product Stewardship is defined as "the responsible and ethical management of a product during its progress from inception to ultimate use and beyond". The purpose of Product Stewardship is to make health, safety and environmental protection an integral part of designing, manufacturing, marketing, distributing, using, recycling and disposing of products (EEA 1997). Product stewardship is a principle that directs all actors in the life cycle of a product to minimize the impacts of that product on the environment. What is unique about product stewardship is its emphasis on the entire product system in achieving sustainable development. All participants in the product life cycle –designers, suppliers, manufacturers, distributors, retailers, consumers, recyclers, and disposers – share responsibility for the environmental effects of products.

Integrated Materials Management

Both integrated materials management and integrated waste management (discussed under the policy programs) manage natural resources through the life cycle. Integrated materials management is a framework for linking the concept of eco-efficiency with materials management strategies. Recycling is an important aspect of a materials life cycle where appropriate management strategies could enhance the ecoefficiency of the material. The current legislative emphasis on "take back" and the public push for recycle content in many products, coupled with the rightful concern about the proliferation of land fill sites, adds to the impetus for industry to encourage the reduction, reuse and recycling (three R's) of materials. This development can be turned into a business opportunity since materials can be sold as a secondary resource and can be recycled often at a lower energy cost than primary production. The goal of integrated materials management is to contribute to sustainable consumption by promoting science-based regulations and material choice decisions that encourage market access and the safe production, use, reuse and recycling of materials.

Environmental Management System

An Environmental Management System (EMS) specifies how an organization can formulate an environmental policy and objectives taking legislative requirements and information about significant environmental impacts into account. The overall objective is a continuous overall improvement of the organization

Design for Sustainability (or Design for Environment/Eco-design)

Two closely related procedural tools are Design for the Environment (DfE) and Eco-design that are summed up here under the general heading design for sustainability. In eco-design, products are made based upon causing minimal environmental damage over their life cycle. Several manuals have been edited with the aim to provide guidelines for industrial business to systematically introduce eco-design. These manual usually include a step-by-step plan which considers environmental issues at all stages of product development with the aim to design products with the lowest possible environmental burden at all stages of the product life cycle. The eco-design manual edited by UNEP, in 1997, provides State of the Art and practical "how to do it" information about eco-design. The backbone is a seven-step plan with integrated analytical tools and idea generation techniques. With the help of a strategy wheel all possibilities for environmental improvement can be explored. The manual includes many examples, checklists, figures, and rules of thumb, and is structured to be compatible with assessment procedures and with the traditional, systematic product development process. Design for Environment (DfE) goes one step further then eco-design, including also health and safety topics.

Environmental Labeling and Environmental Certification System

The Environmental Labeling tool provides guidelines for the use of environmental labels and declaration.

These provide communication of information on environmental aspects of products and services, to encourage the demand and supply of those products and services that cause less stress on the environment, and is especially relevant for the needs of consumers. ISO provides standards for three different types of labels: environmental claims (ISO 14021) and the type I and III environmental labeling scheme. The type I is a multiple criteria-based third-party environmental labeling program aiming at yes/no decisions whether products will obtain a label or not. Type III labeling (or environmental product declarations) aims at more detailed information on a number of criteria attached to a product, without a yes/no decision regarding the provision of a label. No standards are available for Type II labels, which are self-declared labels. Whereas labels provide information on products, certification systems provide information on companies. A single certification system can cover all of the products produced by a company or an industrial sector. Environmental Certification Systems give information on process and production methods (PPM) of a company.

Environmental Impact Assessment

Environmental impact assessment (EIA) EIA is an activity directed at the identification and quantification of the impacts of people's actions on human health and wellbeing and at the interpretation and communication of information about these impacts. EIA is generally used during the planning phase to investigate changes to the environment at a specific site caused, for instance, by construction projects. The level of detail in an EIA is often higher than in LCA because aspects like concentration of emitted pollutants and duration of exposure are taken into account. EIA is a procedural tool used to identify the environmental, social and economic impacts of a project prior to decision-making. It aims to predict environmental impacts at an early stage in project planning and design, find ways and means to reduce adverse impacts, shape projects to suit the local environment and present the predictions and options to decision-makers. EIA focuses on the entire life cycle of a project. By using EIA both environmental and economic benefits can be achieved, such as reduced cost and time of project implementation and design, avoided treatment/clean-up costs and impacts of laws and regulations.

The key elements of an EIA are:

(a) Scoping: identify key issues and concerns of interested parties;
(b) Screening: decide whether an EIA is required based on information collected;
(c) Identifying and evaluating alternatives: list alternative sites and techniques and the impacts of each;
(d) Mitigating measures dealing with uncertainty: review proposed action to prevent or minimize the potential adverse effects of the project; and
(e) Issuing environmental statements: report the findings of the EIA.

Source: www.uneptie.org.

APPENDIX C:

UNEP/SETAC LIFE CYCLE INITIATIVE

APPENDIX C:

UNEP/SETAC LIFE CYCLE INITIATIVE[3]

The Life Cycle Initiative is an international partnership launched by the United Nations Environment Program (UNEP) and Society of Environmental Toxicology and Chemistry (SETAC) to put life cycle thinking into practice. The following description comes from UNEP (2005).

In 2002, UNEP and SETAC joined forces to establish the Life Cycle Initiative. The mission of the Life Cycle Initiative is to develop and disseminate practical tools for the evaluation of opportunities, risks, and trade-offs associated with products and services over their entire life cycle to achieve sustainable development. By this, the Initiative contributes to the 10-year framework on sustainable consumption and production that is co-ordinated jointly by UNEP and the United Nations Department of Economic and Social Affairs (UN DESA) as a follow-up to the 2002 World Summit on Sustainable Development.

Equal to living organisms, products have a life cycle as well: they are produced from raw materials, transported to the shops, bought and used by consumers, and eventually disposed of. At each phase in their life cycle, products interact with the environment (extraction or addition of substances), and with the economic (the costs to produce, or the profit to sell a product) and social systems (the personnel needed to transport from factory to shop). In a life cycle economy, decisions are made by industry based upon information on all stages of the life cycle. Incentives are given by governments to produce, reuse, and recycle products and services with the right energy and resource efficiency and with the lowest environmental impact possible. In this economy, consumers will choose between different brands of a product, after balancing these products' environmental impacts such as potential contribution to climate change, social consequences as for instance poor workers rights, and price. The concept of life cycle thinking integrates existing consumption and production strategies, preventing a piece-meal approach. Life cycle approaches avoid problem shifting from one life cycle stage to another, from one geographic area to another, and from one environmental medium to another. Human needs should be met by providing functions of products and services, such as food, shelter and mobility, through optimized consumption and production systems that are contained within the capacity of the ecosystem. Life Cycle Management (LCM) has been developed as an integrated concept for managing the total life cycle of products and services towards more sustainable consumption and production patterns. Life Cycle Assessment (LCA) is a tool for the systematic evaluation of the environmental aspects of a product or service system through all stages of its life cycle. It is standardized within the ISO 14040 series.

The three programs of the Life Cycle Initiative aim at putting life cycle thinking into practice and at improving the supporting tools through better data and indicators.

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[3] The information in this appendix comes from *UNEP/SETAC Life Cycle Initiative, Life Cycle Approaches, the Road from Analysis to Practice*. Available at http://www.uneptie.org/pc/sustain/reports/lcini/Road%20report%20for%20web.pdf.

The Life Cycle Management Program creates awareness and improves skills of decision-makers by producing information materials, establishing forums for sharing best practice, and carrying out training programs in all parts of the world.

The Life Cycle Inventory (LCI) program improves global access to transparent, high quality life cycle data by hosting and facilitating expert groups whose work results in web-based information systems.

The Life Cycle Impact Assessment (LCIA) program increases the quality and global reach of life cycle indicators by promoting the exchange of views among experts whose work results in a set of widely accepted recommendations.

The first action of the Life Initiative was to draft Definition Studies to determine a roadmap for the next years on how to put life cycle thinking into practice. The goals of the Definition Studies were to identify the deliverables of the three programs, and to ensure that the deliverables identified are appropriate to the needs and concerns of all stakeholders. Special attention had to be given to life cycle approaches in small and medium-sized enterprises (SMEs) and developing countries where special needs and challenges can be formulated. For these four topic areas the state of the art, user needs and envisaged work tasks were identified.

APPENDIX D:

UNEP LIFE CYCLE INITIATIVE ACHIEVEMENTS AND KEY DELIVERABLES FROM PHASE 1

APPENDIX D:

UNEP LIFE CYCLE INITIATIVE ACHIEVEMENTS AND KEY DELIVERABLES FROM PHASE 1[4]

Achievements:

- Building capacities and an international Life Cycle community, including more and more developing country experts, facilitating global exchange of information.
- Raising awareness among Life Cycle practitioners worldwide.
- Making available free awareness-raising and training material for global use.
- Setting the scene for Sustainable Product Life Cycle Management based on triple-bottom line approach.
- Enhancing consensus among LCA experts in methodological and data availability questions.
- Providing direct input for the recently launched European LCA platform.
- Supporting the set-up of an International Panel on the Sustainable Use of Natural Resources with the European Commission.
- Raising awareness among Life Cycle experts for the particularities of resources, in particular metals.
- Ensuring that initiatives facilitated by UNEP such as UNEP Finance Initiative, Global e-Sustainability Initiative, Tour Operators' Initiative and the Sustainable Building & Construction Initiative take Life Cycle Approaches.
- Being in contacts with Multilateral Environmental Agreements, in particular Basel Convention, to base waste policies (i.e.: e-waste) on Life Cycle Thinking.

Key Deliverables:

- Worldwide network of around 1000 experts of which 200 actively participated in Initiative.
- Regional and national networks for capacity building and technology transfer.
- Support of around 50 open meetings on LCA worldwide.
- Organization of around 25 TF meetings and expert workshops.
- Set-up of an open management content system: website ESTIS for the Life Cycle Initiative and its task forces and regional networks.
- Free licenses of LCI databases and LCA softwares for 22 organisations from 14 developing countries to support LCA case studies.
- A Background report for a UNEP Guide to Life Cycle Management.
- LCA and LCM training materials (draft versions).
- International LCM guide (draft version).
- Feasibility studies for Extended LCA (incl. social aspects).
- Global LCI database registry.
- Guidance documents on how to set up LCI databases for capacity building in all regions (in preparation).

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[4] The information in this appendix comes from Dubreuil (2006).

- Guidance on how to move from current practices to global recommended practice in LCIA (in preparation).

APPENDIX E:

UNEP/SETAC LIFE CYCLE INITIATIVE PHASE TWO STRATEGIC PLAN FOR 2006–2010 EXPECTED RESULTS AND ACTIVITIES

APPENDIX E:

UNEP/SETAC LIFE CYCLE INITIATIVE PHASE TWO STRATEGIC PLAN FOR 2006–2010 EXPECTED RESULTS AND ACTIVITIES

Note: the information presented in this appendix comes directly from the UNEP/SETAC Life Cycle Initiative, Phase Two Strategic Plan for 2006–2010 (UNEP 2006)

Expected Results

1. *Life Cycle Approaches Methodologies*
    a. Improvement of Characterization Factors in Life Cycle Impact Assessment.
    b. Long term development and maintenance of the global LCI database registry.
    c. Up-to-date knowledge on the latest developments with regard to life cycle approaches methodology available.
    d. Integration of economic and social aspects into LCA framework to establish economic and social life cycle approaches that compliment environmental LCA[5].
    e. Improvement of approaches methodologies using sustainability principles recognizing regional differences in LCA development and LCM applications.
    f. Identification of relevant life cycle studies and guidelines in line with the scope of work of the Life Cycle Initiative and assurance of availability to other interested parties.
    g. Promotion of existing, but simplified LCA e-tools for rising awareness in developing countries and among small and medium-sized enterprises (SMEs).
    h. Publications from the Life Cycle Initiative in scientific journals on the core issues of the Life Cycle Initiative's activities.

2. *Life Cycle Management of Resources (e.g., natural resources, chemicals, energy and water)*
    a. Life cycle approaches developed and adopted for better application to resources producing/intensive economies.
    b. Life cycle approaches developed and adopted for better application to countries with water shortage.
    c. The International Panel on the Sustainable use of Natural Resources incorporated life cycle thinking.
    d. The Secretariat of the Strategic Approach to International Chemicals Management (SAICM) incorporated life cycle thinking.
    e. Other international key players in the area of "resources" incorporated life cycle thinking.
    f. Web-based database of practical guides, list of information, tools, methodologies and examples of life cycle approaches in application to resource management.
    g. Life cycle based pilot projects for resources implemented and economic benefits and lessons learned published.

[5] The vision is to have three life cycle approaches which each represent a dimension of sustainability.

3. *Life Cycle Management for Consumption Clusters*
    a. Life cycle thinking incorporated into Sustainable Building and Construction Initiative.
    b. Life cycle thinking incorporated into UNEP programmes (e.g., Marrakech task forces) and the UNEP/UNIDO National Cleaner Production Centers' (NCPCs) work.
    c. Life cycle thinking incorporated into other initiatives and industry led activities in the areas of mobility, food and consumer products (e.g., electronics).
    d. Web-based and public database of practical guides, list of information, tools, methodologies and examples of life cycle thinking in application to consumption clusters.
    e. Life cycle based pilot projects for consumption clusters implemented and economic benefits and lessons learned published.
    f. Consumer guide illustrating life cycle impacts of products (e.g., car, hamburger, computer, mobile phones, water, etc.) and identifying options for improvements attitudes toward sustainable consumption.
    g. An industrial roundtable set-up and promoting the dissemination and exchange of LCM approaches.

4. *Life Cycle Capacity Building*
    a. Life cycle regional networks called upon to continually promote life cycle approaches into regional policy and decision making.
    b. On-going LCA software and database awards including annual forum for dissemination of results and their implications to further capacity building.
    c. Regular training workshops and capacity building programmes using UNEP/SETAC materials in various countries and for different groups of stakeholders (e.g., the supply chain and SMEs).
    d. Web-based information and knowledge system with public training materials, updated LCA methodologies, overviews of tools and case studies.
    e. Guide on best practice in communication strategies for life cycle management.
    f. Basic UNEP/SETAC life cycle materials translated in UN languages (e.g., French, Chinese, Spanish and Arabic).
    g. Self-training on-line or via CDs for users without permanent access to internet.

Activities Foreseen for 2006 and 2007

Near term activities include the following:

1. Improvement of Characterization Factors in Life Cycle Impact Assessment of Ecotoxicity (Fate — Exposure — Effects). This project is aiming at improving characterization factors for metals ecotoxicity.
2. Long term development and maintenance of a LCI database registry. This activity will allow structured collection and dissemination of meta data about running database projects and developments achieved.

3. Dissemination of latest developments in LCA methodology. Participation in the EC Coordinated Action on Life Cycle Assessment (CALCAS) will allow the Life Cycle Initiative to disseminate latest developments and receive feedback on future activities.
4. Extended LCA: Integration of social aspects into LCA framework. This project will identify in what manner social aspects can be integrated into LCA methodologies, and shape the process towards agreement in the expert community (Code of Practice) and towards standardization in the long term. Furthermore, core elements of and core requirements upon the integration of social aspects shall be formulated.
5. Building Capacity in Global Supply Chains. The focus of the project will be producers in the production chains for extraction and processing of natural resources, primarily in less-industrialized countries and regions. Other outcomes of the project will be increases in data availability, awareness, appreciation of (and experiences of) economic benefits, and capacity related to life cycle assessment in the participating countries.
6. Partnership with the International Panel on the Sustainable Use of Natural Resources. This partnership will allow the Life Cycle Initiative the articulation of projects on natural resources with scientists and key stakeholders working with the panel as well as an exchange of opinions regarding the activities on this area.
7. Workshop with Strategic Approach to International Chemicals Management (SAICM) managed by UNEP. A workshop bringing together key participants from SAICM and the Life Cycle Initiative will be held to pursue further areas of collaboration. (The information about what SAICM is and its goal could be left our or put in a footnote.
8. Relationship with UNEP's Sustainable Building and Construction Initiative (SBCI). SBCI focus, in part, is to develop and promote economic incentives for a life cycle approach in design, construction and financing of buildings. The Life Cycle Initiative has begun conversations with the SBCI to identify useful ways to collaborate, including being member of a Think Tank and formal partnerships, participating in the SBCI planning and identify specific joint projects for subsequent years.
9. Workshop in UNEP, Consultative Meeting with Business & Industry and meetings with UNEP programme officers on mobility and food and the Marrakech taskforces, NCPCs and the Global e-sustainability Initiative (GeSI). These meetings will aim at finding ways for an inclusion of life cycle approaches in these activities.
10. Organization of International Conferences on Life Cycle Assessment and Management. One Example is the CILCA 2007 in Brazil, which is an international meeting co-organized by the regional Latin American life cycle network where an exchange of experiences with training workshops and presentations of latest developments will take place. Other examples are the LCM2007 conference in Zurich and participation in the SCORE-conferences.
11. Second phase of LCA awarded projects. Workshop to recognize the participants who have been awarded LCA software and database and to exchange learning, insights, and examples of how they have used their experiences to build capacity regionally.
12. Training workshops on LCA and LCM in Vietnam. Regional expert meetings where capacity building with the latest UNEP/SETAC materials and world class trainers will take place.
13. Start of public web-based system. This will allow LCA practitioners free access to updated information and knowledge on commercial and free databases and LCA tools.

APPENDIX F:

SUMMARY OF LCIA MODELS AND METHODS PREPARED BY THE LIFE CYCLE INITIATIVE

APPENDIX F:

SUMMARY OF LCIA MODELS AND METHODS PREPARED BY THE LIFE CYCLE INITIATIVE

The information in this appendix comes from the UNEP/SETAC Life Cycle Initiative on Life Cycle Impact Analysis.[6] It contains summaries of commonly used LCIA methods in use today. Each summary contains a short description of the method, web link, and contact information. Additional references for these methods are provided in the complete description prepared by the Life Cycle Initiative.

Eco-Indicator 99

Eco-Indicator 99 was developed in a top down fashion. The weighting problem was the key problem that was to be solved. Weighting was simplified by:

- Using just three endpoints; this minimizes the mental stress among panelist to take into account too many issues
- Defining these three issues as endpoints that are reasonably easy to understand

The weighting problem has not been solved, but weighting and interpretation of results without weighting has been made easier. Other new ideas in the methods are the consistent management of subjective choices using the concept of cultural perspectives. This has lead to a good documentation of the choices and to the publication of three versions, each with a different set of choices. Other issues are, the introduction of the DALY approach, the introduction of the PAF and PDF approach, as well as the surplus energy approach

Key Contact: Mark Goedkoop — email: goedkoop@pre.nl

Link: Eco-indicator 99: http://www.pre.nl/eco-indicator99/

EDIP97 & EDIP2003

EDIP97 is a thoroughly documented midpoint approach covering most of the emission-related impacts, resource use and working environment impacts (Wenzel et al., 1997, Hauschild and Wenzel, 1998) with normalization based on person equivalents and weighting based on political reduction targets for environmental impacts and working environment impacts, and supply horizon for resources. Ecotoxicity and human toxicity are modeled using a simple key-property approach where the most important fate characteristics are included in a simple modular framework requiring relatively few substance data for calculation of characterization factors. Comparison of the use of EDIP97, CML 2001 and Eco-indicator 99 in Dreyer et al., 2003.

Update through EDIP2003 methodology supporting spatially differentiated characterization modeling which covers a larger part of the environmental mechanism than EDIP97 and lies closer to a damage-oriented approach. This part of the general method

[6] Available at http://jp1.estis.net/sites/lcinit/default.asp?site=lcinit&page_id=138F5949-6997-4BE6-A553-585E92C22EE4#lciasum.

development and consensus programme covers investigations of the possibilities for inclusion of exposure in the life cycle impact assessment of non-global impact categories (photochemical ozone formation, acidification, nutrient enrichment, ecotoxicity, human toxicity, noise).

Key Contact: Michael Hauschild — email: mic@ipl.dtu.dk

Link:

EDIP 97: http://ipt.dtu.dk/~mic/EDIP97
EDIP 2003: http://ipt.dtu.dk/~mic/EDIP2003

EPS 2000d

The EPS 2000d impact assessment method is the default impact assessment method in the EPS system. It is developed to be used for supporting choice between two product concepts. Category indicators are chosen for this purpose, i.e., they are suitable for assigning values to impact categories. Category indicators are chosen to represent actual environmental impacts on any or several of five safeguard subjects: human health, ecosystem production capacity, biodiversity, abiotic resources and recreational and cultural values. The characterization factor is the sum of a number of pathway-specific characterization factors describing the average change in category indicator units per unit of an emission, (e.g., kg decrease of fish growth per kg emitted SO_2). An estimate is made of the standard deviation in the characterization factors due to real variations depending on emission location etc. and model uncertainty. This means that characterization factors are only available, where there are known and likely effects. Characterization factors are given for emissions defined by their, location, size and temporal occurrence. Most factors are for global conditions 1990 and represents average emission rates. This means that many toxic substances, which mostly are present in trace amounts, have a low average impact. Weighting factors for the category indicators are determined according to people's willingness to pay to avoid one category indicator unit of change in the safe guard subjects.

Key Contact: Bengt Steen — email: Bengt.steen@esa.chalmers.se

Link: EPS 2000d: http://eps.esa.chalmers.se/

(Dutch) Handbook on LCA

The (Dutch) Handbook on LCA provides a stepwise `cookbook' with operational guidelines for conducting an LCA study step-by-step, justified by a scientific background document, based on the ISO Standards for LCA. The different ISO elements and requirements are made operational to be 'best available practice' for each step. The life cycle impact assessment methodology recommended is based on a midpoint approach covering all emission- and resource-related impacts, for which practical and acceptable characterization methods are available (Guinée et al. 2002). Best available characterization methods have been selected based on an extensive review of existing methodologies world-wide. For most impact categories a baseline and a number of alternative characterization methods is recommended and for these methods comprehensive lists of characterization and also normalization factors are supplied. Ecotoxicity and human toxicity are modeled adopting the multi-media USES-LCA model developed by Huijbregts (Huijbregts et al. 2000 and 2001). The Handbook provides characterization factors for more than 1500 different LCI-results, which can be downloaded at *http://www.leidenuniv.nl/cml/ssp/projects/lca2/index.html*.

Key Contact: Jeroen Guinée — email: Guinee@cml.leidenuniv.nl

Link: (Dutch) Handbook on LCA: http://www.leidenuniv.nl/cml/ssp/projects/lca2/lca2.html

IMPACT 2002+

The IMPACT 2002+ life cycle impact assessment methodology proposes a feasible implementation of a combined midpoint/damage approach, linking all types of life cycle inventory results (elementary flows and other interventions) via 14 midpoint categories to four damage categories. For IMPACT 2002+ new concepts and methods have been developed, especially for the comparative assessment of human toxicity and eco-toxicity. Human Damage Factors are calculated for carcinogens and non-carcinogens, employing intake fractions, best estimates of dose-response slope factors, as well as severities. The transfer of contaminants into the human food is no more based on consumption surveys, but accounts for agricultural and livestock production levels. Indoor and outdoor air emissions can be compared and the intermittent character of rainfall is considered. Both human toxicity and ecotoxicity effect factors are based on mean responses rather than on conservative assumptions. Other midpoint categories are adapted from existing characterizing methods (Eco-indicator 99 and CML 2002). All midpoint scores are expressed in units of a reference substance and related to the four damage categories human health, ecosystem quality, climate change, and resources. Normalization can be performed either at midpoint or at damage level. The IMPACT 2002+ method presently provides characterization factors for almost 1500 different LCI-results, which can be downloaded at http://www.epfl.ch/impact

Key Contact: Olivier Jolliet — email: olivier.jolliet@epfl.ch

Link: Impact (2002)+: http://www.epfl.ch/impact

JEPIX — Japan Environmental Policy Priorities Index

This method is developed and applied by the JEPIX Forum, a voluntary initiative of several organizations and private persons from Environmental Accounting, Environmental Management, Eco-Rating and Life Cycle Impact Assessment in Japan.

Inspired by the Swiss EcoScarcity method, JEPIX is based on the distance-to-target principle, but in many respects takes different approaches to derive Ecofactors for the weighting of interventions. The method puts more emphasis on a transparent, simple and understandable, but trend-consistent description of the political situations rather than on the preciseness of natural science based modelling. It is designed to indicate, where political pressure is high and therefore new legal requirements are likely to occur and hence to rise environmental costs for industry. Therefore it is considered as complementary to existing LCIA methods, which indicate damage to environment and/or society.

A first version of JEPIX was published in 2003 as a draft focusing on emissions and addressing 11 focal subjects of Japanese environmental legislation. It provides weighting factors for some 1050 interventions. For substance bound legislation, the weighting is based on annual flows (actual and target), whereas for effect oriented legislation midpoint models such as GWP, ODP, Human Toxicity or POCP are used to derive national flows. As the environmental situation varies substantially across Japan, the weighting factors for some 150 substances are scaled to reflect the situation in each of the 47 prefectures as well as for some 100 rivers, 15 lakes and 3 inland sea areas/bays.

The draft version was published in 2003 with support of the Japan Environmental Ministry (MoE), the Ministry for Economy Trade and Industry (METI) and the Ministry for Education and Technology (MEXT).

Since 2003 some 40 leading Japanese Companies (including Komatsu, Canon, TEPCO, Suntory, Fuji Film, All Nippon Airways, J-Power, etc.) are applying this method to evaluate and communicate their environmental performance data and to conduct LCA of products and services. Under the Centre of Excellence Program of the Japanese government, the method will be enhanced based on their experience. The final version of JEPIX is expected for publication in 2006. An integration of resources as well as the adoption of newly available data on chemicals is already under development.

Key Contact: Claude Siegenthaler — email: claude@i.hosei.ac.jp

Link: JEPIX: www.jepix.org

LIME

LCA National Project of Japan has conducted a study aimed at the development of a Japanese version of the damage oriented impact assessment method called LIME (Life-cycle Impact assessment Method based on Endpoint modeling). In LIME, the potential damage on socio economic impact caused by the utilization of abiotic resources, increase of extinction risk and loss of primary production caused by mining of resources are measured as main damages of resource consumption. Modeling socio-economic impact was based on the concept of user-cost, which accounts for the equity of future generations. The procedure to measure damages on ecosystem is based on studies estimating the risk of extinction of specific species in the field of conservation biology. Lists of damage factors of mineral resources, fossil fuels and biotic resources like wood material have already prepared and released to the public. The development of these factors enables us to compare and integrate with the damages derived from the other impact categories like global warming and acidification without value judgment of ordinary people.

Key Contact: Norihiro Itsubo — email: itsubo-n@aist.go.jp

Link: LIME: http://www.jemai.or.jp/lcaforum/index.cfm

Swiss Ecoscarcity Method (Ecopoints)

The method of environmental scarcity — sometimes called Swiss Ecopoints method — allows a comparative weighting and aggregation of various environmental interventions by use of so-called eco-factors. The method supplies these weighting factors for different emissions into air, water and top-soil/groundwater as well as for the use of energy resources. The eco-factors are based on the annual actual flows (current flows) and on the annual flow considered as critical (critical flows) in a defined area (country or region).

The eco-factors were originally developed for the area of Switzerland (see references below). There, current flows are taken from the newest available statistical data, while critical flows are deduced from the scientifically supported goals of the Swiss environmental policy, each as of publication date. Later, sets of eco-factors were also made available for other countries, such as Belgium and Japan.

The method has been developed top-down and is built on the assumption that a well established environmental policy framework (incl. the international treaties) may be used as reference framework for the optimization and improvement of individual products and processes. The various damages to human health and ecosystem quality are considered in the target setting process of the general environmental policy; this general environmental policy in turn is then the basis for the 'critical flows'. An implicit weighting takes place in accepting the various goals of the environmental policy. The ecopoints method contains common characterization/classification approaches (for climate change, ozone depletion, acidification). Other interventions are assessed individually (e.g., various heavy metals) or as a group (e.g., NM-VOC, or pesticides).

The method is meant for standard environmental assessments, (e.g., with specific products or processes). In addition, it is often used as an element of environmental management systems (EMS) of companies, where the assessment of the company's environmental aspects (ISO 14001) is supported by such a weighting method.
The method was first published in Switzerland in 1990. A first amendment and update was made for 1997, which is the current version. A next version, based on 2004 data, will be available in 2005.

Key Contact: Arthur Braunschweig — email:abraunschweig@e2mc.com

Link: Swiss Ecoscarcity: http://www.e2mc.com/BUWAL297%20english.pdf

The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI)

TRACI is an impact assessment methodology developed by the U.S. Environmental Protection Agency that facilitates the characterization of environmental stressors that have potential effects, including ozone depletion, global warming, acidification, eutrophication, tropospheric ozone (smog) formation, ecotoxicity, human health criteria-related effects, human health cancer effects, human health noncancer effects, and fossil fuel depletion. TRACI was originally designed for use with life-cycle assessment (LCA), but it is expected to find wider application to pollution prevention and sustainability metrics.

To develop TRACI, impact categories were selected, available methodologies were reviewed, and categories were prioritized for further research. Impact categories were characterized at the midpoint level for various reasons, including a higher level of societal consensus concerning the certainties of modeling at this point in the cause-effect chain. Research in the impact categories of acidification, smog formation, eutrophication, human health cancer, human health noncancer, human health criteria pollutants was conducted to construct methodologies for representing potential effects in the United States. Probabilistic analyses allowed the determination of an appropriate level of sophistication and spatial resolution necessary for impact modeling for each category, yet the tool was designed to accommodate current variation in practice (e.g., site-specific information is often not available). The methodologies underlying TRACI reflect state-of-the-art developments and best-available practice for life-cycle impact assessment (LCIA) in the United States.

Key Contact: Jane Bare — email: Bare.jane@epamail.epa.gov

Link: TRACI: http://epa.gov/ORD/NRMRL/std/sab/iam_traci.htm

APPENDIX G:

SUMMARIES OF LIFE-CYCLE DATABASES

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SUMMARIES OF LIFE-CYCLE DATABASES

This appendix contains excerpts from the report, *Summary of Global Life Cycle Inventory Data Resources* (Curran and Notten, 2006) that may be relevant to LCAs that may be developed for oil and gas industry projects. The report provides an overview of the available Life-Cycle Inventory (LCI) databases around the world (including public, as well as proprietary, or restricted-access, databases). This summary identifies LCI databases including public, as well as proprietary, or restricted-access, databases. It includes descriptions of activities that aim to develop publicly available databases in Africa, the APEC region, and Asia, Europe, and the Americas (Canada, United States, and Latin America). Because of their close association with the distribution of LCI data, LCA software programs that contain inventory data are also included in this effort. The report also lists institutions or organizations that provide LCI data in a less formal way, as this is important to get a feel for the global spread of LCI data. Also, with the aim of facilitating access to global LCI data resources, the report provides contact details and information on regional LCA networks and societies. The focus of the report is on LCI databases and LCI data providers. It therefore does not list general environmental or process data sources (i.e., data must be in the form of life cycle inventories), nor does it list institutions working solely with LCA methodology development.

Publicly Available Database Development Efforts at the National Level

APEC Region and Asia

The need to develop a public LCA database with data applicable to the Asia Pacific region has been identified, and initial moves toward achieving this have been taken, driven largely by Japan. LCA activities in the region have been promoted by a series of symposia focusing on capacity building; the most recent meeting was held in Bangkok, Thailand, in December 2005. The need for an international LCA forum of APEC member countries was identified in these symposia, to encourage collaboration and to share LCA skills between developed and developing countries, with the ultimate aim of developing an international database for the region. An initial step has been to develop an LCA researcher's network, as a precursor to an LCA forum. In 2000, the Japan Environmental Management Association for Industry (JEMAI) launched a project with Australia, Indonesia, Korea, Malaysia, Singapore, Taiwan, and Thailand to exchange information and to develop LCI data in cooperation with these countries on energy and a few basic materials.

In China, institutions and academia are conducting LCA-related research, with an emphasis on environmental evaluations of waste recovery options and energy systems. A project, "Research on Materials Life Cycle Assessment," supported by the National R&D program, has been underway for some time, and a National LCA Centre was established. A national database is being developed in China. In Malaysia work is being done to develop LCI data for electricity production. Activity in LCA is taking place at several universities in Vietnam, and the Federal Government has commissioned several LCA studies beginning in 1999. Input-output LCA is being conducted at the National University, Ho Chi Min City, and the Open University has a team working on process-based LCAs. Case study topics include energy systems, waste management systems, and an oil product. Some case studies have been carried out in Singapore; however use of LCA is not yet widespread. The government established the Environmental Management Standards Committee, which formed a focus group on LCA, discussing all aspects of LCA. The members are from the Ministry of Environment, Universities and National Research Institutes, as well as from industry. Some case studies have been carried out in Indonesia, following national workshops introducing LCA to the country.

Europe

As the "power-house" of LCA since the late 1980's, many different databases and data sources have been developed in Europe over the years. There are many university-based and consultancy-based databases which characterize particular industrial sectors and product groups. These are generally very diverse and fragmented, with a poor level of harmonization, due to the many countries and many actors (industry, research, public authorities etc.) involved. For countries such as Germany, Sweden, and Switzerland, which have been active in LCI data development for a number of years, the current challenge is one of integrating and ensuring comparability and interchangeability of a wide variety of LCI databases.

Various European organizations and initiatives have facilitated exchange of LCA information over the years (e.g., SETAC-Europe, LCANET, CHAINET, etc.). A first attempt to facilitate the exchange of LCI data was done by SPOLD (Society for the Promotion of Lifecycle Development), which worked to develop a common format for the exchange of life-cycle inventory data. In the beginning of this century the EcoSPOLD format was developed starting from SPOLD 99 and the ISO/TS 14048 data reporting format. Most commercially available LCA software programs (in particular CMLCA, EMIS, GaBi, KCL-eco, Regis, SimaPro, TEAM, and Umberto) are now able to import and partly even to export EcoSPOLD files. Most of the European databases that have been developed are only available through one of the many LCA software programs available (usually for a fee), with relatively few databases provided on a national, publicly available basis.

In its communication on Integrated Product Policy, the European Commission concluded that Life Cycle Assessments provide the best framework for assessing the potential environmental impacts of products currently available. In the document, the need for more consistent data and consensus LCA methodologies was underlined. It was therefore announced that the Commission will provide a platform, called The European Platform of Life Cycle Assessment, to facilitate communication and exchange of life-cycle data and launch a co-ordination initiative involving both ongoing data collection efforts in the EU and existing harmonization initiatives. The Platform is planned to provide quality assured, life cycle based information on core products and services as well as consensus methodologies. The project started in mid-2005 and is planned to run until mid-2008.

Americas

Canada

The Canadian Raw Materials Database project was begun over 10 years ago, although it was only made publicly-available from 2001 until 2004. The database contains life cycle inventory cradle-to-gate data for basic materials, as provided by industry associations and their contractors. The data reflect as closely as possible Canadian production, except that in some cases the Canadian data have been averaged with US production data in order to protect proprietary information concerning Canadian suppliers. The materials covered include steel (EAF and integrated), aluminum, six separate plastics, glass (recycled and virgin), paper, and softwood lumber. The data were available in pdf format at no cost to the public. The website is still online but it has not been possible to access the data since 2004. The continuation of the project has not been determined.

USA

LCI data is available from a fair number of sources in the USA, from work done at various universities and research organizations, and by various government departments, consultants and industry organizations. However, not until 2001 was a collaborative project to develop a publicly available LCI database for the USA realized (more specifically, the database contains cradle-to-gate or gate-to-gate data that can be used in completing an LCI). This project received start-up funding from the General Services Administration (GSA) and the US Department of Energy (DOE), and the database is hosted by the National Renewable Energy Laboratory (NREL). The data, a user guide and project development guidelines can be downloaded from their website. There are currently 73 data modules in the NREL database that are available for downloading.

Latin America

There is much activity now occurring in Latin America on LCA. An LCI database development project for Argentina was launched at the Universidad Tecnologica Nacional (Mendoza), but due to the present economic situation in Argentina, there is no current funding for the project. In Chile, work is being done to develop electricity data representative of Chilean conditions.

Professor Armando Caldeira Pires and his team are developing a Brazilian database, as well as conducting a South American project to develop a standardized LCI database for metals (although Mexico is not receiving funds for this project they are also participating). Colombia has also started a national LCI database. Mexico also started database development, first funded and helped by AIST in 2002, for electricity and metals, and then continued with other important sectors such as fuels, chemical substances, some building materials and waste treatment. Last year the Mexican Center for LCA and Sustainable Design was started; the Center now manages the databases, and is working together with government and industry to officially launch a project which will allow the database to grow.

Brief Descriptions

American Center for Life Cycle Assessment

The ACLCA (www.lcacenter.org) was formed in 2001. Its mission is to build capacity and knowledge of LCA. ACLCA is a part of the Institute for Environmental Research and Education (IERE).

American Iron and Steel Institute (AISI)

The North American steel industry is heavily involved in efforts to evaluate the life cycle impacts of steel products using internationally accepted methodologies. These studies integrate life cycle inventory data, life cycle impact assessments, and risk assessment into an overall life cycle evaluation. This life cycle impact assessment is currently being peer-reviewed and is being broadened from a site-specific to an industry-wide basis. The study addresses all relevant environmental issues, including resource depletion, for the full life cycle of a steel product from mining of raw materials through the manufacturing and use phases of the product and ultimate disposal or recycling of the material used in the product.

American Plastics Council (APC)

APC is collecting unit process data for all steps from raw material acquisition through production of resin or precursor. Inventory data for 9 polymers and 4 polyurethane precursors are being collected. The final data will be submitted to the US LCI Database.

Association of LCA in Latin America (ALCALA)

ALCALA was formed in April 2005 and a workgroup was established to determine different tasks for the Association to address. While ACLCA is still in the planning stage, the following topics are being discussed: objectives, adequate legal structure, communication and promotion.

Australian LCA Society (ALCAS)

ALCAS is a professional organization for people interested in practice, use, development and interpretation of LCA. The purpose of the society is to promote and foster the responsible development and application of LCA methodology in Australia and internationally with a view to making a positive contribution to Ecological Sustainable Development (ESD) and to represent the Australian LCA community in the international arena. It is a not- for- profit organization with individual and corporate members from industry, government, academia and service organization.

Australian Life Cycle Inventory Data Project

Life Cycle Inventory Data Research Program is a research program with the principal aim of developing Life Cycle detailed data inventory resources for Australia. Life Cycle Inventory (LCI) is the second stage of life cycle assessment, but it is often the most resource intensive stage, so the better general data which are available, the easier the LCI development becomes. The Centre for Design's LCA resources are published in spreadsheets, and are also available in the SimaPro LCA software. Most of the data currently developed by the Centre and provided to the public had been developed from secondary data.

Boustead Model 5.0

Created by Boustead Consulting, the Boustead Model is an extensive database, in which data such as fuels and energy use, raw materials requirements, and solid, liquid and gaseous emissions are stored. It also includes software which enables the user to manipulate data in the database and to select a suitable data presentation method from a host of options.

CIRAIG

CIRAIG (Centre interuniversitaire de référence sur l'analyse, l'interprétation et la gestion du cycle de vie des produits, procédés et services) was created in 2001 with the goal of joining the strengths of Quebec and Canadian universities in the field of Life Cycle Management (LCM) and Life Cycle Assessment (LCA) and making them available to companies and governments. The CIRAIG is also an official partner of the UNEP/SETAC Life Cycle Initiative.

CRMD

The Canadian Raw Materials Database (CRMD) is a voluntary project involving a cross-section of Canadian materials industries to develop a database profiling the environmental inputs and outputs associated with the production of Canadian commodity materials. The database uses the techniques of life-cycle inventory (LCI), consistent with the method of life-cycle assessment (LCA). The purpose of the database is to provide Canadian life-cycle inventory data: - to small and medium-sized manufacturers, converters, formulators and other users to support their voluntary efforts in improving the environmental performance of their products, consistent with principles of pollution prevention and – to participating industries to support their internal improvements. Industry associations are participating on a voluntary basis with Environment Canada as chair. Participating materials industries are: aluminum, glass, plastics, steel and wood.

Ecoinvent Database v1.2

A reference work for life cycle inventory data including the areas of energy, building materials, metals, chemicals, paper and board, forestry, agriculture, detergents, transport services and waste treatment. Data are based on the production and supply situation in the year 2000. The datasets are available on the level of unit process raw data as well as on the level of cumulative results. The ecoinvent data v1.2 comprises more than 2700 datasets with global/European/Swiss coverage. About 1000 elementary flows are reported for each dataset, including emissions to air, water and soil, mineral and fossil resources and land use. Furthermore, several actual and widespread impact assessment methods, namely the cumulative energy demand, climate change, CML 2001, Eco-indicator 99, the ecological scarcity method 1997, EDIP 1997, EPS 2000 and Impact 2002+ are implemented. The ecoinvent data v1.2 is available together with EMIS, GaBi, Regis, SimaPro, and Umberto and is importable into CMLCA, KCL-eco, and TEAM.

EDIP Database

The EDIP database contains a large number of LCI data and supports the EDIP LCA methodology. Some of the data are aggregated, but others exist as system-plans, which makes it easily to modify by, for example, changing the type of electricity into regional or marginal. The EDIP materials data are well updated, a part having the same origin as in other databases, but others like paper, wood/furniture, textiles and electronics are unique for EDIP. Data for production processes are generally older, but some are quite unique (e.g., data for machining processes). EDIP also contains data for recycling and waste treatment, and for a large number of transport processes (different types of trucks, ships, trains and flights under different utilization and transport modes). The database was developed from 1991 to 1996. Since then, two major updates have been made, one in 2001 and the latest in 2003. The EDIP database is available together with the GaBi software from the Danish LCA Center or directly from the software developer PE.

eiolca.net

Created by the Green Design Institute of Carnegie Mellon, this web site allows users to estimate the overall environmental impacts from producing a certain dollar amount of a commodity or service in the United States. The database first was made publicly available in 1999; since then two major and several minor updates have been conducted. In 2006, the website had its 800,000th "user" (i.e. user of the model, not web page hits). The web-based model provides rough guidance on the relative impacts of different types of products, materials, services, or industries with respect to resource use and emissions. The latest version is based on the 1997 industry benchmark input-output accounts compiled by the Bureau of Economic Analysis of the U.S. Department of Commerce. It incorporates emissions and resource use factors estimated for all 491 sectors of the U.S economy, using publicly available electricity and fuel consumption data compiled by the U.S. Census Bureau, the U.S. Departments of Energy and Transportation, and environmental databases created by the U.S. EPA. The model estimates the following environmental effects:

Conventional Air Pollutants Emission (CO, NO_x, PM_{10}, SO_2, VOC and Pb)

Toxics Release Inventory (TRI) Emissions

Greenhouse Gas Emissions

Electricity and Fuel Use

EPD Norway

In Norway NHO established a Norwegian EPD-program in 2000, in line with ISO/TR 14025 and following R&D-projects. In 2002 the program was further formalized as a Foundation owned by NHO (Confederation of Norwegian Business and Industry) and BNL (Confederation of Norwegian Construction Industry). Representatives of the Federal Pollution Control Authority, the Directorate of Public Construction and Property, as well as from process, energy, and furniture industries are represented on the board, in addition to NHO and BNL. In addition to a close cooperation between the Scandinavian EPD-programmes, an international member organization GEDnet (Global Environmental Declaration Network) has been founded. GEDnet has arranged several seminars especially aimed at developing countries on how EPDs etc are developed. Presently about 49 EPDs are presented on the registry.

European Copper Institute

The copper industry has responded to the market need for consistent and accurate data on copper production by developing up-to-date life cycle data for its tube, sheet and wire products. The information has been prepared in cooperation with recognized life cycle practitioners, using international methodologies (ISO standards), leading software (GaBi), and proprietary production data collected from across the copper industry. These data are now available through a variety of channels, including the Institute's website.

European Platform for LCA

The European Commission initiated the Platform for LCA mid-2005 with the intent of promoting life cycle thinking in business and policy making in the EU. The focus of the effort is on underlying data and methodological needs. The Platform is planned to provide quality-assured, life-cycle based information on core products and services as well as consensus methodologies (http://lca.jrc.it).

Franklin US LCI Database

This database contains North American inventory data for energy, transport, steel, plastics, and processing. The data were collected by Franklin Associates, Ltd., a division of ERG (Eastern Research Group). The fully documented and licensed database is available from SimaPro.

GaBi 4

GaBi (Ganzliche Bilanzierung) is a tool for creating life-cycle-balances. GaBi supports the user with handling a large amount of data and with modeling of the product life cycle. GaBi calculates balances of different types and assists in aggregating the results. The contained data sets are based on the experience of cooperation with industry, patent and technical literature. It is one of the most extensive databases in the world. The software and the database are independent units. In addition to the standard databases (lean and professional), GaBi offers extension databases from different branches e.g., metals, renewable raw materials, building materials, intermediate products, energy carrier, textile processing and many more. Additional datasets are available on request.

GEMIS

Global Emission Model for Integrated Systems (GEMIS) is an LCA program and database for energy, material, and transport systems. It is available at no cost (public domain). The basic version 1.0 of the computer program GEMIS was developed in 1987-1989 as a tool for the comparative assessment of environmental effects of energy. The GEMIS database offers information on fossil fuels, renewables, nuclear, biomass, and hydrogen. GEMIS includes the total life-cycle in its calculation of impacts (i.e. fuel delivery, materials used for construction, waste treatment, and transports/auxiliaries). The GEMIS database covers for each process:

- efficiency, power, capacity factor, lifetime
- direct air pollutants (SO_2, NO_x, halogens, particulates, CO, NMVOC)
- greenhouse-gas emissions (CO_2, CH_4, N_2O, SF_6, all other Kyoto gases)
- solid wastes (ashes, overburden, FGD residuals, process wastes)
- liquid pollutants (AOX, BOD_5, COD, N, P, inorganic salts)
- land use.

German Network on Life Cycle Inventory Data

The German Network on LCI data was initiated in 2001 in a joint effort of the Federal Ministry for Education and Research and the research center Forschungszentrum Karlsruhe (FZK). The network aims to supply continuously updated and reviewed LCI data sets. Within a funded research project, data sets in core areas (metals, energy, transportation, and building materials) are supplied and methodological aspects are consistently harmonized. First outputs are expected in 2006. Within the network major German software and data providers as well as industrial and scientific stakeholders are organized to reach consensus and realize this novel infrastructure for LCI data supply.

GREET 1.7

Sponsored by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE), Argonne has developed a life cycle model called GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation). The model covers production of various transportation fuels and vehicle technologies using the fuels. GREET includes more than 85 fuel production pathways and more than 70 vehicle/fuel technology options for evaluation. For this purpose, GREET contains extensive data for transportation fuel production and use in particular, and production and use of energy products in general. GREET was developed as a multidimensional spreadsheet model in Microsoft Excel. A graphic user interface (GUI) program was developed for users to interact with GREET model to conduct simulations. This public domain model is available free of charge for anyone to use. The first version of GREET was released in 1996. Since then, Argonne has continued to update and expand the model. The most recent GREET version is GREET 1.7 beta version. For a given vehicle and fuel system, GREET separately calculates: - consumption of total energy, fossil fuels, and petroleum; emissions of CO_2-equivalent greenhouse gases; and emissions of five criteria pollutants (VOC, NO_x, CO_2, SO_x, and PM_{10}).

IDEMAT 2005

IDEMAT is a powerful tool for material selections in the design process. IDEMAT provides a database with technical information about materials, processes and components in words, numbers and graphics, and puts emphasis on environmental information. With IDEMAT you can lookup and compare information about materials, processes or components and you also can let IDEMAT search for materials that match your criteria.

International Iron and Steel Institute (IISI)

In 1996 IISI launched a comprehensive data collection project, known as the IISI Worldwide Life Cycle Inventory (LCI) Study for Steel Products — in order to gather the data necessary for initiating or participating in LCA's. This exercise has subsequently been updated for 1999/2000 data for steelmaking operations. An integral part of the project was the development of a common worldwide methodology for collating and evaluating steel product LCI data. Since this innovative project was completed the results have been communicated to external audiences undertaking LCA studies for steel-using products, and to steel producers active in benchmarking and in other environmental improvement programmes. An ongoing programme is underway at IISI to further improve the electronic database resulting from the study.

International Stainless Steel Forum (ISSF)

ISSF has undertaken a commitment to provide the best possible information to the industry stakeholders in the area of LCA, delivering transparent and authoritative data on the production of stainless steel from its raw materials. Raw material LCI data have been provided by ICDA, NiDI and IMOA, using the same methodology and standards. The experience gained from the life cycle studies at Eurofer, and the IISI, has been extended in order to produce an LCI for global stainless steel. The datasets involved in this study cover major stainless producers in Europe, Japan, Korea, and North America with a focus on global averages for the production of austenitic and ferritic grades (flat products). The data collection phase also covered long products, duplex grades, and stainless steel from scrap and ore based steel making. The ISSF global LCI data for stainless steel products are available to LCA practitioners on request.

IPU

The Institute for Product Development is a non-profit organization situated in the Technical University of Denmark which carries out industrial research and development of products, processes, manufacturing systems, and organizations. IPU co-manages the LCA Center Denmark.

IVAM LCA Data 4.1

The IVAM database is a database to be used for environmental life cycle assessment (LCA) with SimaPro software. The database is an integration of various public databases, such as APME and ETH, and data from individual case studies performed by IVAM. It consists of about 1500 processes, leading to more than 350 materials. The data can be used for LCA applications in various sectors. Next to general background processes it consists of foreground processes especially in the sectors of Building and Construction, Food and Waste management.

Korean LCI

The Korean National Cleaner Production Center (KNCPC) is constructing an LCI database for Korean industries with the support of Ministry of Commerce Industry and Energy. The database is based on the request from industries through a series of surveys and is accessible through KNCPC's website.

LCAit

LCAit was developed by CIT Ekologik in 1992. It was the first software for LCA with a graphical interface on the market. Since then, LCAit has been widely used for the environmental assessment of products and processes.

MIET 3.0

MIET (Missing Inventory Estimation Tool) was developed by CML. It is substantially improved over the previous version by using additional data sets and the most up-to-date data sources. In contrast to MIET 2.0, a less aggregated assessment of the environmental interventions associated with the production of commodities and services is possible. In MIET 3.0, 480 commodities and services are considered while in MIET 2.0, only 91 commodities and services are distinguishable. In addition, the environmental intervention database module has been improved and contains information on generation of 1344 environmental interventions. MIET 3.0 is incorporated in the latest version of the Simapro software of Pré Consultants and is available as a stand-alone software package from Enviro Informatica under the name CEDA 3.0 (Comprehensive Environmental Data Archive).

Nickel Institute

The Nickel Institute, whose members represent over 70% of current world production, generates and communicates knowledge required to support safe and sustainable production, use and reuse of nickel. It was established on January 1, 2004. The Institute provides a single membership and management structure for activities previously undertaken by the Nickel Development Institute (NiDI) and the Nickel Producers Environmental Research Association (NiPERA). NiPERA is an independently incorporated division of the Nickel Institute, continuing as a well-respected provider of peer-reviewed, published information on the human health and environmental science of nickel. The Nickel Institute continues the use-related technical work of NiDI, but focuses more on nickel issues related to stewardship and sustainable development, especially the generation and use of knowledge about the full life cycle impacts of nickel. The nickel database has been in place since 2001 and includes complete and open cradle-to-gate data.

PlasticsEurope

Formerly The Association for Plastics Manufacturing in Europe (APME), PlasticsEurope generates eco-profiles that are a periodically updated in a databank and provide extensive information on the main types of plastics, from cradle to the production plant gate (as delivered ex-plant: powder or pellets). To prevent as far as possible any misunderstanding or misuse of the data, it is highly recommended to first read the methodology document published on the website. The area covered is Europe (data collected from the APME members' European plants). Data on the consumption and recovery of plastics used in the main application sector of packaging, building and construction, automotive and electric and electronics are published annually. Indicative data are also provided for typical European plastics conversion operations.

REGIS

REGIS, a product of Sinum AG, is an LCA software tool that was developed in close cooperation with the Swiss Association for Environmentally Conscious Management and has consistently applied this methodology regarding the handling of system boundaries. Regis is the most used software tool for corporate ecobalances and the improvement of the corporate environmental performance according to ISO14031 in the German speaking part of Europe. Regis works with the ecoinvent database.

SimaPro 6

SimaPro stands for "System for Integrated Environmental Assessment of Products." In addition to product assessment, its generic setup allows for expanded use to analyze processes and services as well. First released in 1990, SimaPro is a proven, reliable and flexible tool used by major industries, consultancies and universities; nearly a thousand user licenses have been sold in 50 countries. To get started, SimaPro comes inclusive of several inventory databases with thousands of processes, plus the most important impact assessment methods. PRé Consultants is reseller of the new ecoinvent database, an up-to-date database with 2500+ processes. The SimaPro software can be run in various languages (English US, English UK, Italian, Spanish, French, Danish, German and Dutch). Databases, help and manuals are only available in English. A fully Japanese version of SimaPro is available through the Japanese partner Yamatake.

SPINE@CPM

SPINE@CPM is the Swedish national LCA database developed and maintained by IMI, Industrial Environmental Informatics at Chalmers University of Technology for the Swedish national competence center CPM (Centre for Environmental Assessment of Product and Material Systems).

The database contains more than 500 well documented and manually reviewed datasets. The database is available in two versions: SPINE@CPM in the SPINE format, and LCI@CPM in the ISO/TS 14048 format, where the data has been translated into the ISO/TS 14048 format. LCI@CPM is a web portal for LCI information. The portal provides the possibility to: search for specific LCI-data in the database; purchase LCI-data sets; and, convert SPINE data sets into ISO/TS 14048 automatically. The portal also provides other tools for information management for LCA.

In the database you can find detailed information on all types of goods, transportation, electricity, heat and fuel production, raw material production for (e.g., polymers, metals, chemicals, and building materials) as well as some manufacturing processes such as metal processing, and waste management alternatives. Some of the data sets in the database are reported as full flow-charts where each included process or transport is separately stored in the database.

Thai LCA Network

The Thai LCA Network was formed in 2000. It is a web-based forum to disseminate information and promote collaboration on LCA.

Thai National LCI Database Project

The Thai National LCI Database project is a 3-year project starting from 2005 with the aim of developing LCI database for Thailand with partial technical support from Japanese government through the Green Partnership Plan.

Tool for Environmental Assessment and Management (TEAM)

TEAM is Ecobilan's LCA software that allows users to build and use a large database and to model any system representing the operations associated with products, processes and activities. TEAM enables users to describe any industrial system and calculate the associated LCI and potential environmental impacts according to the ISO 14040 series. TEAM comes with a Starter Kit database of over 300 modules to use in the construction of almost any system. These modules cover the range from fuel production to transportation and from chemical production to plastic molding. The modules provided in the Starter Kit are a subset of those available in the Ecobilan Group's general catalogue of data, referred to as DEAM (Data for Environmental Assessment and Management).

Umberto

Created by ifü Hamburg GmbH, Umberto serves to visualize material and energy flow systems. Data are taken from external information systems or are newly modeled and calculated. Graphic interface allows complex structures to be modeled: the production facilities in a company, process and value chains, or product life cycles. Flows and stocks can be valuated using standard or individual performance indicators. Scaling per unit of products or per period is possible. Based on the material and energy flows the real costs of processes, materials being used, or waste materials that have to be disposed can be analyzed and displayed. The user can create individual projects with each project characterized by a freely definable and expandable list of products, raw materials, pollutants, forms of energy, etc. - all referred to as materials. They are administered in a hierarchically structured material list.

US LCI Database Project

In May 2001, the National Renewable Energy Laboratory (NREL) and its partners created the U.S. Life-Cycle Inventory (LCI) Database to provide support to public, private, and non-profit sector efforts to develop product LCAs and environmentally-oriented decision support systems and tools. Since the goal is to make the creation of LCIs easier, rather than carry out full product LCIs, database modules provide data on many of the processes needed by others for conducting LCIs. Therefore, the modules do not contain data characterizing the full life cycles of specific products. The database provides cradle-to-gate or gate-to-gate data, depending on the product or process, for commonly used materials, products and processes following a single data development protocol consistent with international standards. The resulting consistent and coherent LCI datasets for basic processes make it easier to perform life cycle assessments, and increase the credibility and acceptance of the results. The data protocol is based on ISO 14048 and is compatible with the EcoSpold format. The data are available in several formats: a streamlined spreadsheet, an EcoSpold format spreadsheet, an EcoSpold XML file, and a detailed spreadsheet with all the calculation details.

APPENDIX H:

SUNCOR ENERGY POLICY ON LIFE CYCLE VALUE ASSESSMENT (LCVA)

APPENDIX H:

SUNCOR ENERGY POLICY ON LIFE CYCLE VALUE ASSESSMENT (LCVA)[7]

Scope and Purpose

This policy guidance & standard (PG&S) applies to Suncor Energy Inc. and its subsidiaries world-wide (collectively “Suncor” or “Company”). References in this document to “Suncor Personnel” include directors, officers, employees, contract workers, consultants and agents of Suncor. The purpose of this standard and guideline is to support Suncor’s vision as a Sustainable Energy Company.

Definitions

Life-cycle: The complete system of a product/process from cradle to grave, including extraction and processing of raw materials, manufacturing and construction, operation and maintenance, and disposal, recycling or retirement (includes complete chain, including activities upstream and downstream of Suncor’s direct operations.)

Life-cycle thinking: A primarily qualitative consideration of important environmental and economic impacts throughout the life-cycle of a product or process (any quantification efforts that are undertaken are limited to easily available data on areas of impact recognizing practicality limitations).

Life-cycle value assessment methods: Systematic identification, quantification, assessment and documentation of the important environmental and economic impacts and opportunities for design improvements throughout the life-cycle (recognizing practicality limitations – assessment is selective and prioritized).

Guidance & Standards

As a sustainable energy company, Suncor will continue as a highly successful and caring business enterprise in both the near and long term.

We will achieve this by being leaders in the provision of energy solutions that meet or exceed the environmental, economic and social needs and expectations of our customers and other stakeholders, while contributing to the ability of future generations to meet their needs. Suncor has defined six characteristics for success in achieving its sustainability vision, one of which is Integrated Decision-Making. The operational characteristics of Integrated Decision-Making directs that Suncor will:

- Integrate environmental social and financial considerations in business decision-making (this includes furthering understanding and use, as appropriate, of various tools including

7 Available at http://www.suncor.com/default.aspx?ID=1246.

eco-efficiency concept, life cycle thinking and life cycle value assessment methods (LCVA), EH&S performance indicators/targets, and EIA/SEIA).
- Make business and operating decisions which result in:
  - Continuous improvements in the eco-efficiency of Suncor's operations and products.
  - The environmental impacts of Suncor's operations and products being managed within the carrying capacity of local and global eco-systems.

Suncor will proactively apply life-cycle thinking and adopt life-cycle value assessment methods in business decision analysis to ensure that:
- Decision-makers understand the full life cycle costs and benefits of decisions, and
- Project teams have optimized the design eco-efficiency of their proposals Proactive application of life-cycle thinking and LCVA methods will make Suncor a more sustainable energy company that continuously improves the eco-efficiency of its operations and products through:
- Better decision based on more complete environmental and economic analysis.
- More eco-efficient design of processes and operations based on consideration of opportunities to reduce costs and environmental impacts and improve net value.

Both outcomes result from systematically identifying economic and material inputs and outputs and assessing their impacts across the life-cycle of a process or product.
Proactive application of life-cycle thinking and LCVA methods at Suncor will result in:
- Reducing the risk of unintentional shifting and environmental impacts created by Suncor decisions in direct operations to upstream or downstream activities;
- Reduced business risk from hidden socio-economic or environmental liabilities, and/or regulatory or stakeholder expectations;
- Improved economic grounding for financial analysis (i.e., full cost-benefit analysis);
- Early environmental data and qualitative issue scoping to assist in formal environmental impact
- Assessment and stakeholder consultations, when these are required (e.g., regulatory applications);
- More accurate "green" or eco-efficient purchasing decision, or system/technology selections.

Implementation

Proactive application of life-cycle thinking and LCVA methods will be fully integrated into Suncor decision analysis by December 31, 2001 (3 year implementation plan).
Business units and growth teams will develop specific goals (measurable), local application guidelines and implementation/action plans to support and ensure compliance with the corporate standard and guideline. It is expected that major capital projects (e.g., >$25 M capital) will include appropriate levels of LCVA analysis early on in implementation.
Local business unit application guidelines will be developed through local management committees. Expectations for application and use of life-cycle thinking and LCVA methods will likely differ between business units (decentralized model).

It is envisioned that a small number of LCVA experts/practitioners will reside across Suncor with resident experts in the business units themselves, but “doers” largely drawn from consultants and EPC contractors working with Suncor.
It is important to establish implementation momentum for local and senior LCVA champions within the business units to be identified and proactive in early implementation.
Corporate office has a coordination/integration/facilitation role, including:

- Development and maintenance of generic support tools including a LCVA information Clearinghouse (e.g., library of studies, contacts, references, emissions database, general info for staff/users, etc.), “How To” Guidebook, and general LCVA models
- Development and maintenance of generic education and training materials/processes (note: business contractors
- General advocacy and information exchange among groups including general communications planning Prior to full implementation, the Corporate Director EHS and Director Planning & Strategy will have certain transitional responsibilities including reporting annually on Suncor’s progress towards the policy objective. After full implementation, policy stewardship rests solely with Corporate Finance.

Ongoing use of LCVA methods in Suncor requires additional resources in front end project planning and analysis. Piloting activity has qualitatively demonstrated that this investment is recovered quickly through improved design, lower net costs, improved project value and reduced risk. Consistent quantification of net benefits and budget planning is an important element of initial implementation planning.

Responsibility

- Long-term policy stewardship (Sr. Vice-President & CFO)
- Corporate integration, central support, policy interpretation/application support and transition stewardship and management (Vice-President Sustainable Development)
- Local implementation (EVP’s/Managing Directors for business units, VP Planning and Corporate Development for corporate growth teams)

Exceptions

None

Richard L. George
PRESIDENT AND CHIEF EXECUTIVE OFFICER
July 14, 2005

APPENDIX I:

PETRO-CANADA'S POLICY ON THE USE OF LIFE CYCLE ANALYSIS

APPENDIX I:

PETRO-CANADA'S POLICY ON THE USE OF LIFE CYCLE ANALYSIS[8]

Making Decisions Based On Life-Cycle Value Assessment

Life-Cycle Value Assessment (LCVA) is a business analysis and decision-making methodology that helps employees, project teams and business units identify, examine and balance the social, environmental and financial implications of projects and product purchases. The LCVA is a key method by which our employees integrate and balance social, environmental and business decisions.

The tool is based on the premise that good information enables better decisions. LCVA covers the full life-cycle of a new or existing project, from upfront planning and material and equipment selection, through to final decommissioning and reclamation. Through the process, new ideas and opportunities emerge to improve technical designs, to reduce environmental pollutants and other impacts and to increase efficiencies.

LCVA Background

We adopted the LCVA planning methodology in 1997 in consultation with the Pembina Institute for Appropriate Development (Pembina). We continue to work with Pembina in the development of the LCVA process, tools and training programs to fit our broad base of assets.

LCVA was integrated into the project delivery model in 2003 and incorporated into our TLM standards in 2004. In addition, in the last few years LCVA methodology has been updated to better fit our diverse assets and projects.

LCVA Usage

The level of LCVA analysis is guided by consideration of both the number of potential social and environmental issues and the dollar value of the decision. Petro-Canada has increased the number, scope and scale of projects assessed because the process is so flexible.

In 2005, assessments ranged from the Fort Hills upgrader location selection to service station activities, and from solutions for waste disposal to water use. Increased use of LCVA requires increased employee understanding and awareness of the methodology and tools. In 2005, training sessions were held and courses were introduced for employees in the Downstream business. The LCVA process was also incorporated into the Downstream economic evaluation guidelines.

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[8] Available at http://www.petro-canada.ca/en/about/753.aspx#decisions.

In 2006, an LCVA overview will be added to the upstream economic evaluation guidelines, LCVA "train the trainer" courses (designed by Pembina) will be held and more Petro-Canada personnel will be made aware of the benefits to projects and decisions.

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