CLEANER PRODUCTION FOR PROCESS INDUSTRIES

OVERVIEW OF THE CLEANER PRODUCTION CONCEPT AND RELATION WITH OTHER ENVIRONMENTAL MANAGEMENT STRATEGIES

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ABSTRACT

Cleaner Production stands for a proactive and preventive approach to industrial environmental management and aims for process- and/or product-integrated solutions that are both environmentally and economically efficient ('eco-efficiency'). Pioneers in the field were large process industries in the USA (since the late 1970's), but it took until the early 1990's before Cleaner Production was generally recognised as a valuable approach for large and medium sized enterprises in all industry sectors. Although the first Australian case studies date from around the same time, the uptake of Cleaner Production in Australia appears to lag behind North America, Western Europe and several Asian countries.

This paper explains the Cleaner Production concept and provides examples of its application from a few selected Australian businesses in the process industry. This evidences that Cleaner Production can achieve significant reductions in environmental impact, in terms of reduced waste and emission generation and in terms of conservation of materials, energy and water, while simultaneously reducing operating costs. The current practice of Cleaner Production for the process industry is reviewed at the three scales at which Cleaner Production can be typically engineered, i.e. macro scale (dealing with industrial systems), meso scale (dealing with plants) and micro scale (dealing with synthesis processes). In each area examples are given of the analytical and diagnostic tools and the improvement and innovation concepts used. It appears that the most innovative developments are taking place at the macro- and micro-scales, outside the traditional domain of Cleaner Production, but with the potential to substantially redesign the structure and operation of the chemicals and materials industries as of the start of the second quarter of this century.

INTRODUCTION

Historically, environmental compliance efforts have focussed principally on treatment of pollution once it has been released from a process (end-of-pipe approach) rather than on prevention or recycling, two approaches that in many cases offer a lower cost means of attaining compliance (e.g. OTA, 1995; UNEP, 1994). End-of-pipe, pollution control, methods often result in increased costs with no appreciable benefits to the firm in terms of enhanced materials or energy efficiency. In contrast, prevention and recycling investments often not only lower energy and material usage but also reduce end-of-pipe treatment costs, resulting in decreased disposal expenditures, possible reduced paperwork, and lower liability and insurance costs. Greater and continued emphasis on prevention and recycling, as endeavoured by the Cleaner Production strategy, can thus lower environmental compliance costs for – process – industries.

Cleaner Production in the process industry is not a new concept (Zosel, 1994). It has essentially been practised since the first chemical processes were utilised in our industrial society. Initially, the industry focused on issues such as yield improvement rather than specifically preventing pollution from entering the environment. However, the consequence of both activities was the same: less material constituting waste streams entering the environment. The application of Cleaner Production technologies and

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practices has already enabled the process industry to reduce and better manage pollution risks associated with wastes and other releases. Industry is now tasked with addressing emerging environmental issues, including the emissions of greenhouse gases, and providing a positive contribution to sustainable development in general. Further and renewed application of the Cleaner Production approach can provide a competitive edge for process industries while addressing those emerging environmental concerns.

This paper addresses the applicability of Cleaner Production for the process industry. It starts with a brief summary of the origins and historic development of Cleaner Production, and then provides an operational definition along with examples of the environmental and financial benefits that different processing industries have achieved by means of the adoption of Cleaner Production. Next, the three application scales of Cleaner Production in the process industry are focussed upon. This will provide an overview of the issues and methodologies for the application of Cleaner Production at the level of industrial production systems, unit operations/plants and materials/products, both for existing projects as well as development of new projects. Finally conclusions are drawn with regard to the continued applicability of Cleaner Production for the process industries.

HISTORICAL PERSPECTIVE

The concept of process industry Cleaner Production as we know it today began to emerge in the mid 1970’s in response to the growing complexity and stringency of environmental requirements. Leading global companies in the process industry, in particular those headquartered in the USA, began to critically assess their approach to environmental issues. The concepts of ‘*pollution prevention*’ and ‘*waste minimisation’* came through as clearly the most economical and environmentally effective means of addressing environmental challenges. A leading pioneer for the preventive approach to industrial environmental management was 3M that launched its Pollution Prevention Pays (3P program) in 1975 (e.g. Zosel, 1990). 3P created a tremendous drive for employee initiated innovation to reduce costs as well as the creation of wastes and pollutants. Box 1 summarises a recent update of the key achievements of this 3P program. Similar corporate pollution prevention programs were in the early days for instance launched by Dow, DuPont, and several others (Freeman et all, 1992).

Box 1: Pollution Prevention Pays (3P) program at 3M (based on DeSimone et all, 1997, pg. 220-233).

The 3P program is an approach that prevents pollution at the source – in the manufacturing processes and products – rather than removing it after it has been created. While the idea itself was not new when 3P was started in 1975, the concept of applying pollution prevention on a company-wide basis and documenting the results had not been done before.

The program’s success has been widely acknowledged. In its first 20 years 3M employees originated 4,450 projects. These have eliminated more than 1.2 billion pounds of pollution to air, land, and water, and significantly cut pollution per unit of production. 3M’s first-year savings alone from these projects totalled more than U$ 750 million.

Some examples:

- A resin spray booth had been producing about 500,000 pounds annually of overspray that required special incineration disposal. New equipment was installed to eliminate excessive overspray. The new design reduced the amount of resin used, saving more than U$ 125,000 a year on a U$ 45,000 investment in equipment.
- A 3M plant developed a new product from the waste stream of an existing product at the plant. The new product is used in industry to contain and adsorb hazardous waste spills. The new product has provided revenue, cut landfill costs, and helped the environment.

Other 3P projects world-wide have ranged from improved control of coating weight at a facility in Wales and the recycling of waste water in a plant in Germany, to a variety of combustion control and heat recovery projects in Japan.

3M ties the success of 3P to five factors:

1. Top management support – which has been present at all times from CEOs and other top managers
2. Employee involvement – by all staff. While the bulk of the ideas has come from process engineers, 3M have had some great ideas from clerical staff, maintenance personnel, sales people, and others.
3. Simplicity – applying for a 3P designation is done on a one-page application form.
4. A reward system – all employees like recognition by their peers and bosses. It makes them feel good about themselves, reinforces reputations, and contributes to career growth.
5. Promotion – 3M did this both internally and externally. It means that new employees are exposed early in their careers, that for older staff it becomes a way of life, and that external recognition builds internal motivation.

Despite the growing number of case studies in the 1980's originating from the process industries in the USA, several studies pinpointed to the lack of industry and government commitment to pollution prevention, and the environmental and financial opportunities that were left unattended (e.g. OTA, 1986; Dorfman, 1992). This incited the first pieces of legislation for waste minimisation (Hazardous and Solid Waste Amendments to the Resource Recovery and Conservation Act (RCRA) in 1984) and pollution prevention (Pollution Prevention Act 1990). Industry, under the umbrella of the Responsible Care Program of the Chemical Manufacturers Association, responded by adopting a voluntary Pollution Prevention code in 1991 (CMA, 1991). This code has since then been replicated by many industry associations around the world (2) (3) and thus became an important vehicle for the implementation of pollution prevention. The Pollution Prevention Code calls for the establishment of a pollution prevention program, compromising 14 management practices: top management commitment; waste and release inventory; environmental impact evaluation; environmental risk education and dialogue; goal setting and release reduction planning; ongoing reductions of wastes and emissions; measurement of progress; pollution prevention education and dialogue; inclusion of pollution prevention into research and development; support for pollution prevention by suppliers, customers and other parties; periodic review of waste management practices; inclusion of environmental aspects in contractor selection; improved engineering controls for early detection of releases; and ongoing program for addressing past operating and waste management programs (CMA, 1991).

Since 1987 pollution prevention started to gain ground in Western Europe, initially in particular in Sweden and The Netherlands, but gradually becoming accepted in most other countries as well (Crul et al, 1991). As pollution prevention was applied outside its traditional domain of the process industry, in manufacturing, service, transport and other sectors, the term Cleaner Production came into being. Cleaner Production embraced a more comprehensive analysis of environmental impacts of industries, including environmental *outputs* (wastes and emissions) as well as environmental *inputs* (consumption of materials, energy and water) and containment of *toxic* materials in consumer goods. Moreover, the term stressed the continuity of the approach, striving for continual improvements of the environmental performance of industrial production. The term Cleaner Production became accepted by the international community under the governance of the United Nations Environmental Program, and was anchored in Agenda 21 for sustainable development adopted at the Rio Earth Summit on Environment and Development in 1992 (UNCED, 1992).

Victoria pioneered Cleaner Production in Australia since the early 1990's with industry support programs and awards (VicEPA, 1996). Between 1994 and 1996, Environment Australia implemented a National Cleaner Production Demonstration Project covering 10 medium scale industries from different industry sectors. Moreover, an audit manual was developed and a National Cleaner Production Centre established at RMIT University. Since completion of this national demonstration project efforts have concentrated on the development of a national Cleaner Production strategy (ANZECC, 1998) and disseminating information (Environment Australia, 1999). In recent years the States - in particular Victoria, New South Wales and South Australia – have played a key role in actually promoting Cleaner Production in industry, through combinations of:

- *industrial partnership programs*: provision of financial and/or technical assistance to selected businesses for the identification, evaluation and implementation of Cleaner Production practices and technologies;
- *award programs*: recognition for industry best practice in Cleaner Production through awards, and compilation and dissemination of industrial case studies;
- *industry codes:* development and distribution of sector specific Cleaner Production guidelines.

Two recent surveys monitored the current level of awareness and implementation of Cleaner Production in Australian industry. Holmes et all (1999) surveyed a cross section of industries in New

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[2] The Plastics and Chemicals Industry of Australia (PACIA) operates an Australian Responsible Care Program. This does not have a specific Pollution Prevention or Cleaner Production Code, although several of the management practices from the US CMA are covered by PACIA Responsible Care Codes of Practice for Manufacturing and Waste Management (see: http://www.pacia.org.au/code.html).

[3] A similar program for the oil and gas industry has been developed at the global level by the Exploration and Production Forum (E&P Guiding Principles) (see: http://www.eandpforum.co.uk/).

South Wales, Victoria and Queensland. 153 companies responded (response rate of 16 per cent). 85 per cent of the respondents claimed to have implemented Waste Minimisation in the past, 45 per cent Cleaner Production and 5 per cent Eco-Efficiency. However, few respondents explicitly merge productivity and environmental issues, as is the core of Cleaner Production and Eco-Efficiency, as only few companies reported that environmental management issues had a significant influence on their production strategies. The adoption of preventive environmental management practices was found to lag behind the general advance of the environmental management function. Companies are increasingly looking at moving beyond compliance, but not necessarily by means of preventive environmental management strategies like Cleaner Production and Eco-Efficiency. Greene (1999) interviewed 53 companies from across Australia that are recognised as industry thought-leaders on environmental management. The results showed that 85 per cent of the companies was aware of Cleaner Production. The responses however also indicated that companies that have employed Cleaner Production methods have not moved from use on one project or problem to comprehensive use in all operations.

The surveys confirm the generally perceived slow progress in the actual implementation of Cleaner Production in Australia’s industry. Australia can make a quantum leap in Cleaner Production in the next couple of years. The Federal Government has set the stage for Cleaner Production, and States are in the process of developing (or strengthening) and implementing their own strategies, based on different combinations of both traditional environmental management policies and more innovative economical and technology policies (Van Berkel, 2000 a).

CLEANER PRODUCTION CONCEPT AND BENEFITS

Pollution Prevention is generally regarded as the fourth stage in the development of environmental management strategies (following the dispersion, control and recycling strategies). Cleaner Production succeeds the pollution dispersion, control and recycling strategies, by preventing and/or minimising the creation of wastes and pollutants. Cleaner Production precedes the sustainable development strategy, which emerged as an environmental management strategy but can no longer be regarded as strictly environmental, given its focus on integrating, rather than balancing, objectives regarding economic growth, social equity and environmental protection and resource conservation (e.g. Rowledge et all, 1999). Cleaner Production is at the transitional stage between pollution prevention and sustainable development. It goes beyond pollution prevention by explicitly incorporating conservation of materials, energy and other natural resources, and by strengthening the value-adding aspect of processes. It is however not a sustainable development concept, since it does not explicitly aimed at integration of social equity objectives.

Cleaner Production is generally defined as ”*the continuous application of an integrated preventive environmental strategy to processes, products, and services to increase eco-efficiency and reduce risks to humans and the environment* “ (UNEP, 1994; ANZECC, 1998)). Cleaner Production aims at progressive reductions of the environmental impacts of processes, products and services, through preventative approaches rather than control and management of pollutants and wastes once these have been created. It is an integrated approach, since it includes all relevant environmental aspects and impacts, and is not confined to one environmental impact category like most end-of-pipe technologies. Moreover, it serves economic and ecological efficiency (‘eco-efficiency’) and contributes to realisation of the environmental risk reduction and management objectives for humans and the environment.

For production processes, Cleaner Production aims in particular at conserving raw materials and energy, eliminating toxic raw materials, and reducing the quantity and toxicity of all emissions and wastes before they leave the process. In the case of products, Cleaner Production aims at reducing the environmental impact along the life cycle of a product, from raw materials extraction to its ultimate disposal. Finally, for services, Cleaner Production entails the incorporation of environmental concerns into designing and delivering services. Cleaner Production requires changing attitudes, responsible environmental management and evaluating technology options.

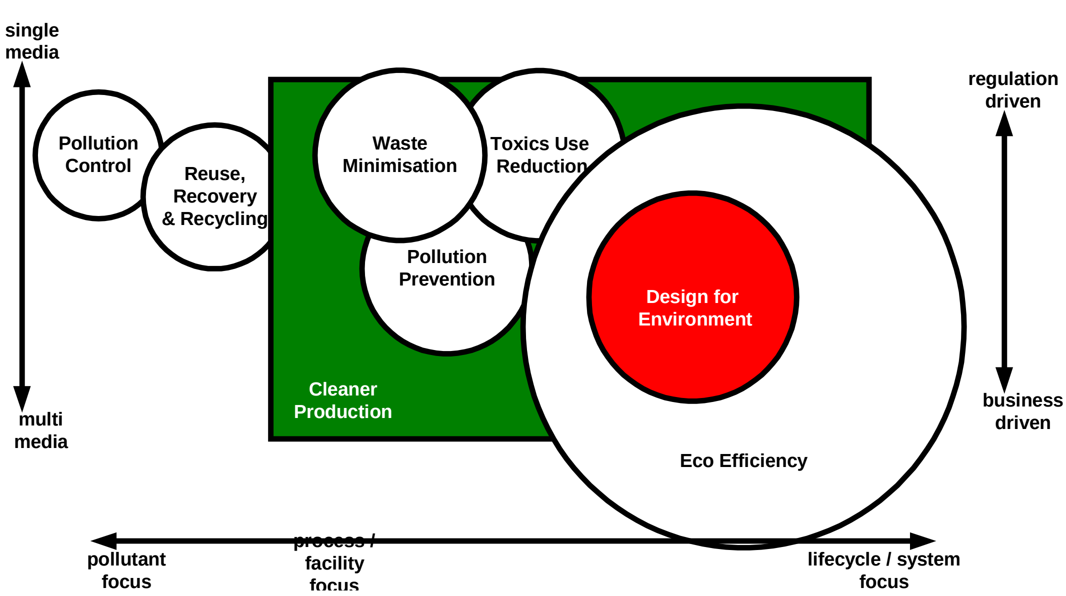
Cleaner Production is related to several other environmental management concepts (Van Berkel, 1997). Figure 1 shows relative positions of key environmental management concepts, regarding:

- *environmental impact categories* covered, in particular whether only one environmental impact category is targeted (‘single media’) or several (‘multi media’);

- primary *motivation* driving the respective environmental management strategy: a division is made between environmental regulation or corporate self responsibility as the key drivers;
- *reactive* versus *preventive* approaches; whether the environmental strategy addresses waste and pollution once it has been generated or aims to avoid waste and emissions in the first place;
- *focus*: whether the environmental management concept centres on waste streams, production facilities or product life cycles.

Cleaner Production may be regarded as a common denominator for the most frequently used preventive approaches. The older preventive approaches are waste minimisation, pollution prevention and toxics use reduction, and each of these tends to focus on one key environmental impact, hazardous waste, toxic substances or pollution respectively. The newer preventive approaches explicitly target reduction of environmental impacts along the product's life cycle, by focusing on product design (in case of design for environment) or on new approaches for value adding activities (in case of eco-efficiency). The overlap of Cleaner Production is highest with Eco-Efficiency. This term has been developed and promoted by the World Business Council for Sustainable Development (WBCSD), and is receiving growing support internationally (e.g. OECD) and nationally (e.g. Environment Australia). According to the WBCSD Eco-Efficiency is '*reached by the delivery of competitively priced goods and services that satisfy human needs and bring quality of life, while progressively reducing ecological impacts and resource intensity throughout the life cycle, to a level at least in line with the earth's carrying capacity'* (DeSimone, et al, 1997)). The WBCSD identified seven components of Eco-Efficiency: reduce material intensity of goods and services; reduce energy intensity of goods and services; reduce toxic dispersion; enhance material recyclability; maximise sustainable use of renewable resources; extend product durability; increase the service intensity of goods and services. Implementation of these seven Eco-Efficiency components will most often call for practical changes that fall under either of the five generic prevention practices under the Cleaner Production umbrella, and, vice versa, implementation of either of these five generic prevention practices will generally also achieve at least one, if not several, of the seven Eco-Efficiency components. Eco-Efficiency and Cleaner Production are truly complementary concepts, with Eco-Efficiency focusing on the strategic side of business ('value creation') and Cleaner Production on the operational side of business ('production'). In the remaining of this paper, Cleaner Production can therefore be substituted with Eco-Efficiency and vice versa.

Figure 1: Cleaner Production in relation to other preventive environmental management concepts (modified from Van Berkel, 1997).



Cleaner Production aims at making more efficient use of natural resources (raw materials, energy and water) and reducing the generation of wastes and emissions at the source. This can be achieved in various ways. A division in five prevention practices is most common (e.g. USEPA, 1992).

1. *Product modifications* change the product characteristics, such as shape and material composition. The lifetime of the new product is, for instance, expanded, the product is easier to repair, or the manufacturing of the product is less polluting. Changes in product packaging are generally also regarded as product modifications.

2. *Input substitution* refers to the use of less polluting raw and adjunct materials and the use of process auxiliaries (such as lubricants and coolants) with a longer service lifetime.

3. *Technology modifications* include for instance improved process automation, process optimisation, equipment redesign and process substitution.

4. *Good housekeeping* refers to changes in operational procedures and management in order to eliminate waste and emission generation. Examples are spill prevention, improved instruction of workers and training.

5. O*n-site recycling* refers to the useful application of waste materials or pollutants at the company where these have been generated. This could take place through re-use as raw material, recovery of materials or useful application.

Table 1 contains both low and medium/high cost examples of each prevention practice for the process industry.

Table 1: Illustrative Cleaner Production options for process industry (adapted from CMA, 1991; Allen, et al, 1997).

Type of prevention practice	Typical low/no cost examples	Typical medium/high cost examples
1. Product Modification	• High solids paint and inks to reduce solvent use in production and product application • Environmentally preferred packaging (e.g. less or reusable packaging, recyclable materials)	• Develop premium products for longer service lifetime (e.g. coolants, lubricants) • Develop 'greener' products that are safer to the customer and pose fewer risks to the environment
2. Input Substitution	• Use biodegradable detergents and cleaners • Use higher purity materials	• Replace toxic catalyst by less toxic catalyst • Replace non renewable material by renewable material • Make use of renewable energy
3. Technology Modification	• Installation of appropriate process instrumentation to measure and optimise process conditions • Use mechanical tank wall wipers to scrap product from tank walls after a product batch has been emptied (e.g. paint, resins, etc.)	• Better mixing design of reactors to reduce by product generation • Adopt alternative synthesis pathway to avoid toxic by-product or toxic process intermediary • Convert from batch to continuous processes • Develop more selective catalyst
4. Good Housekeeping	• Training employees in proper material storage and handling procedures • Spill and leak detection and prevention programs • Use spill and drip trays to recover losses from manual material transfer operations	• Maximise batch sizes, and follow with a similar product that may not require equipment cleaning between batches. • Dedicated equipment for large volume products
5. On Site Recycling	• Use counter-current washing, heating, etc. • Dry-clean equipment before hosing down and reuse recovered material	• Rinse with compatible solvent and store solvent for reuse in make up of next batch of compatible product • Heat recovery from hot process streams

Businesses that decide to adopt Cleaner Production generally find that this makes good business sense.

- Nowra Chemical Manufacturers is a small-scale formulator of speciality chemical products, located in Nowra (NSW). The production takes place in large mixing tanks, and cleaning of mixing tanks results in wastewater to be neutralised on site and creating sludge difficult to dispose of. Over 1995-1996, the company participated in the National Cleaner Production Demonstration Project, conducted on behalf of Environment Australia. A solid waste reduction plan was developed and pilot tested. The tank rinse flows are now collected and treated separately, in order to avoid the unwanted chemical reactions between chemicals contained in different rinse flows that created the sludge. The environmental benefits are outstanding; sludge generation is reduced by 2/3, whereas chemicals and energy are being conserved. A total of A$ 25,000 dollars was invested, and the annual savings were projected to be A$ 27,500. In addition the space requirement for waste handling was reduced, allowing the company to install additional production equipment in its existing premises (Environment Australia, 1996).

- Another Cleaner Production example is the scrubber liquor-recycling project at the Superphosphate Manufacturing Plant of CSBP in Kwinana. The scrubber liquor is now collected and premixed with around 10% of the incoming phosphate rock and then fed into the main reactor where superphosphate is formed. The remaining 90% of the phosphate rock is still being pre-mixed with sulphuric acid. The investment for the recovery project was A$ 1.55 million with projected annual savings mounting up to around A$ 400,000. The scrubber liquor recycling is by far the cheapest option to minimise the phosphorous and fluoride emissions and thus remain in compliance in the future. The environmental benefit comes from ending the discharge of the scrubber liquor. The phosphorous and fluoride load of the waste water of the entire site have been reduced by respectively 80% and 97%, and the pH has increased significantly to a neutral range. The phosphorous contained in the scrubber liquor is recovered, giving rise to an increase of the overall product yield, which however could not yet be substantiated, since the scrubber recycling was introduced in conjunction with other process modifications (Van Berkel, 1999).

- Alcoa operates an alumina refinery in Kwinana. Alumina hydrate scale builds up over time in the vessels and pipework, and these therefore have to be cleaned regularly. In the early days, hydrate scale was manually jack hammered off, and the waste scale was disposed of in a landfill. More recently, jack hammering was replaced by high pressure water blasting. Using water blasting, part of the scale could be reprocessed in the digestion plant. The Cleaner Production project identified by staff was to remove the hydrate scale in situ, by dissolving it in concentrated caustic. Once dissolved it can be directly reused in the process. All 214 tanks have been equipped with in situ caustic washing systems. The scale to be reprocessed is reduced by around 90 %, avoiding the crushing and reprocessing of 18,000 TPA scale. Moreover, the consumption of 20,500 m3/yr of drinking water for water jet cleaning is now avoided. The total capital outlay was A$ 790,000. Taking all direct costs and benefits into consideration, Alcoa calculated a pay back for the project well within 1.5 year. Moreover this Cleaner Production project created on average 8 % extra precipitation capacity. This extra precipitation capacity contributed to achieving an overall yield improvement of 2% (Van Berkel, 2000 b).

The examples illustrate that investments in Cleaner Production generally have attractive economics. These attractive economics are achieved through:

- *reduction of expenditures on input materials, energy and water*: Cleaner Production options can reduce the material-, energy-, and/or water-consumption per unit of product produced, and hence savings are made on the costs of these natural resources;

- *reduction of expenditures on waste (water) treatment*: the amount and pollutant load of the various process waste streams (including solid waste, wastewater, air emissions) is reduced, and hence expenditures for treatment and disposal of waste and emissions are reduced;

- *increase of production revenues*: Cleaner Production most often increases the efficiency of the production processes, resulting in higher levels of production output, and thereby increase revenues; and/or

Figure 2: Cleaner Production can be engineered at macro-, meso- and micro-scales (source: Allen et all, 1997).

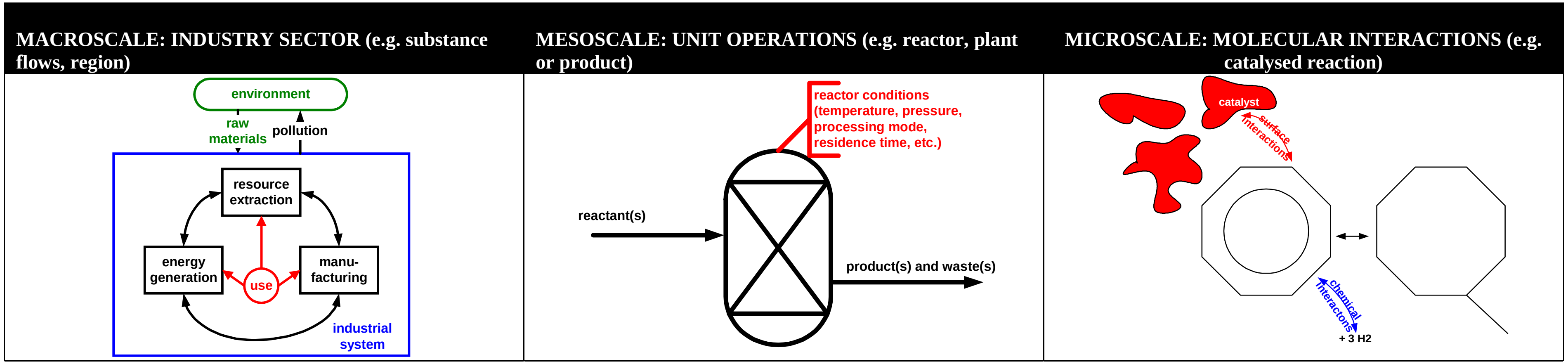


Table 2: Overview of Cleaner Production concepts and example tools (4).

Approach	Analytical and Diagnostic Tools	Improvement and Innovation Concepts	Application Areas
Macro Scale: Industrial Ecology			
Diagnosis of material and energy flows through – parts of the – industrial society	Material Flow Analysis Ecological Accounting	System Innovations guided by e.g.: • The Natural Step • Factor X	Industrial Symbiosis Sustainable Technology Development
Meso Scale: Eco-Efficiency			
Diagnosis of material and energy efficiency of products, services and processes	Life Cycle Assessment Cleaner Production Assessment	Eco-Efficient Products and Processes, guided by e.g.: • Life Cycle Design Principles • Eco-Compass	Equipment Design and Operation Process Selection and Design
Micro Scale: Green Chemistry			
Diagnosis of material and energy efficiency of synthesis pathways and process routes	Atom Economy	Greener synthesis pathways and process routes, guided by: • Green Chemistry Principles	Development of Chemical Synthesis Pathways

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[4] This table is meant to provide an overview of the Cleaner Production field, and the listings of analytical and diagnostic tools, improvement and innovation concepts and application areas are therefore by no means complete. Example tools, concepts and applications are provided with a view to illustrate the applicability of the Cleaner Production framework for the process industries. Additional information on tools and application areas can for instance be found in Van Berkel, 1996; Van Berkel et al, 1997 b; c; Allen, 1997)

- *better product quality:* the application of Cleaner Production normally improves the level of control over the various production processes, which normally will increase the overall product quality level.

From an engineering point of view, it is important that Cleaner Production can be engineered at three levels; macro-scale; meso-scale; and micro-scale (Allen et all, 1997). The scope of each of these three scales is presented in figure 2. At the *macro-scale*, the flows of materials in our industrial economy, from natural resource extraction to consumer product disposal are analysed, with a view to identify improvement opportunities in areas like dematerialization, design for reuse and recycling, substitution of toxic or other hazardous and scarce materials, and reuse of waste streams from one process or product system as input for another process or product system ('industrial metabolism'). This macro scale is also referred to as Industrial Ecology. The *meso-scale* is concerned with the study of Cleaner Production at the level of the – chemical – manufacturing process. Cleaner Production options at this meso-scale could for instance entail process optimisation, substitution of process technology and equipment, better operation and maintenance practices and better production planning. This meso scale application of Cleaner Production coincides with the Eco-Efficiency concept. The *micro-scale* deals with molecular interactions. Cleaner Production is here achieved by means of alternative catalyst systems, alternative process chemistry and use of alternative feedstock for processes. This is also known as 'Green Chemistry'. Table 2 lists the eminent analytical tools, improvement concepts and application areas for Cleaner Production at each of these three scales. These are further explained in the remainder of this paper.

CLEANER PRODUCTION AT MACRO SCALE: INDUSTRIAL ECOLOGY

Following the flow of materials in our industrial economy, from raw material acquisition to product and waste disposal, provides a perspective that is essential for the most effective practice of Cleaner Production. Such analyses can help to identify whether materials currently regarded as wastes in one industrial sector could be viewed as raw materials in another sector. These studies also reveal what types of processes and products are responsible for waste generation, and identification of the sources of waste is the first step toward their prevention.

Cleaner Production at this macro-scale is often regarded as *Industrial Ecology* ([5]). Industrial Ecology is inspired by natural ecology, and applies natural ecology principles and mechanisms for the study of industrial societies and the identification of options to reduce human induced impacts on the environment. It is an emerging concept for promoting environmentally sound manufacturing and consumption. It aims to balance industrial development with the sustainable use of natural resources including energy, materials and the capacity of the environment to assimilate wastes and render valuable services. It is best characterised by the holistic view it employs to study, assess and improve the utilisation of natural resources, materials, energy and the assimilative capacity of the environment in an industrial society (e.g. Graedel et all, 1995).

Analytical and diagnostic tools

The most prominent macro-scale analytical tool is Materials Flow Analysis. Materials Flow Analysis intends to support the development of a proper understanding of the societal metabolism of materials and thereby contribute to more sustainable production and consumption. Materials Flow Analysis analyses and quantifies material flows in – parts of – the industrial production and consumption system. It provides insight into the volume, the structure and the regulating mechanisms of anthropogenic material flows. In essence, Materials Flow Analysis refers to accounts in physical units (usually in terms of tons) compromising the extraction, production, transformation, consumption, recycling and disposal of materials. A recent example of Materials Flow Analysis was performed for the iron and steel industry in the United Kingdom. The study found that the overall exergy (available energy) consumption had declined in the sector almost twofold from 700 to 380 PJ p.a. between 1954 and 1994, indicating a similar reduction in resource consumption. Contrary to the overall decline, the

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[5] Elsewhere, four different approaches to Industrial Ecology were identified: material specific; product specific; regionally-focused and actor specific (Van Berkel et al, 1997a). The material-specific and regionally-focused approaches are dominant, and fall in the macro-scale application of Cleaner Production, whilst the product specific and actor-specific approach are largely confined to North America and would better fit to the meso-scale.

amount of waste steel and transportation exergy consumption due to the import of raw materials has increased significantly (Michaelis et all, 2000).

The principles of Material Flow Analysis are also used in the various indicators for Ecological Accounting, that characterise the material intensity and/or efficiency of products and services, or even of the national economy. Examples are *ecological footprints* and *ecological rucksacks*: both are attempts to estimate the environmental capital requirements of an economy, taking into account the impacts of technological advance and trade (OECD, 1995).

- The concept of *ecological footprints* redefines the carrying capacity as the area of productive land and water required to support a defined economy or population at a specified standard of living, wherever that land may be located. In the context of industrialised economies, thriving on imported energy, materials, food and animals feedstocks, a large part of their ecological footprint is remote, i.e. felt in other countries. As population numbers, and/or standards of living in rich countries increase, the remote land area required to support their economies rises. This phenomenon is described as 'appropriated' carrying capacity.

- *Ecological rucksacks* are concerned with the total weight of material flows involved in the production of a particular good. Thus, the real ecological weight of e.g. a motor car includes the weight of its constituent materials (metals, glass, plastic, etc.) plus the weight of soil, rock and wastes removed or created during the extraction and processing of those materials. This materials extraction phase often occurs outside the consuming country; ecological rucksacks, like footprints, are concerned with displaced environmental impacts.

While the ecological footprint concept is principally concerned with the psychological distancing and environmentally damaging effects of trade, ecological rucksacks take a more technical standpoint, focusing on the need to monitor and reduce the volume of materials flows by means of eco-efficient measures (particularly dematerialization and materials reuse) and lifestyle change (OECD, 1995).

Simpson et al (2000) present the results of a recent ecological footprint analysis for Australia. The data used are from 1991-1992, and since only a few key materials were considered (excluding for instance sea products), the analysis should be regarded as a conservative proxy measurement. The results indicate that the average Australian appropriates 5.96 hectares of ecologically productive land in his/her consumption of goods and natural resources. The consumption and transport of food compromises the largest portion (45 per cent) of Australia's ecological footprint, due mainly to the area of pasture required for supporting the consumption of meat products. The consumer goods category compromises 22 per cent of the total, with significant contributions from the pastureland use category (through consumption of wool products), forests (wood furniture and paper and cardboard) and energy embodied in the goods consumed. For comparison purposes, Australia shares the third place in terms of largest ecological footprint with Canada (at 6.03 hectare/person), behind New Zealand (at 6.82 ha/person) and USA (at 7.44 ha/person). The current ecological footprint of an average Australian is 3.4 times higher than of the average global citizen and even 4.6 times higher than what is regarded as a fair earth share. Moreover, it is about 10 times higher than the ecological footprint of the Indian subcontinent.

Improvement and innovation concepts

Several improvement concepts are being used at the macro scale. Their common goal is to identify opportunities for quantum leaps in the resource efficiency of services and products, in closing materials cycles and in reducing overall material flows through society, by means of '*system innovations*'. Such system innovations are typically the result of technological innovations in different areas, complemented by new business concepts and strategies, new forms of collaboration and ownership among technology developers and owners, producers, consumers and the community in general.

A first example of an improvement concept is *The Natural Step*. It is a framework for sustainable business, originating from a consultation process aimed at identifying points of consensus regarding the definition of sustainability. This led to the formulation of four non-overlapping criteria for sustainability – also called the '*system conditions*'. These state that in order for a society to be sustainable, nature's functions and diversity should not be systematically (e.g. Natrass et all, 1999):

1. Subject to increasing concentrations of substances extracted from the Earth's crust;
2. Subject to increasing concentrations of substances produced by society, or
3. Impoverished by overharvesting or other forms of ecosystem manipulation, and
4. Resources are used fairly and efficiently in order to meet basic human needs world-wide.

The Natural Step has been a very effective strategy tool for a number of large corporations to develop and implement innovative environmental management strategies, such as the carpet lease approach by Interface and product recovery and down-cycling by Nike (Natrass et all, 1999).

Another emergent, macro scale improvement concept from the 1990's is the *Factor X* reduction in resource use, with *X* being between 4 and 50 (Reijnders, 1998). This factor *X* is qualitatively similar to the concepts of dematerialization and eco-efficiency, but has a quantitative edge. The factor *X* may refer to a product (such as an automobile), a service (e.g. transport over a certain distance at a certain speed), an area of need (e.g. clothing), a sector of the economy (e.g. energy supply and demand) or the economy as a whole. The lower value proposed for *X* – a multiple of four – refers to near-term possibilities for improvement; the higher values indicate longer-term improvement potential. Factor 4 is symbolised as doubling wealth while halving resource consumption. A factor 10, reflecting a tenfold reduction of the material flow per unit of service to be realised over a period of 30-50 years, stems from the scenario of halving environmental impacts while achieving equity of access to resources. Factors in the range of 20 to 50 are used in sustainable technology development programs.

Application areas

The exchange of wastes, by-products, and energy among closely situated firms is perhaps the best-known application of Industrial Ecology principles. By doing so an industrial area is transformed into an 'industrial ecosystem' or 'industrial symbiosis' because of the many links among the firms. A classical example of how an industrial ecosystem can develop is found at Kalundborg in Denmark. At the core of this industrial system is the Asnaes Power Station (coal fired) which provides steam to the Statoil Refinery and Novo Nordisk pharmaceutical plant. Vice versa Statoil Refinery provides fuel gas and cooling and waste utility water to the Asnaes Power Station. The adjacent Gyproc Wallboard plant utilises fuel gas from the refinery, and scrubber sludge from the power station. The fly ash from the power station is further processed as cement and road aggregate. Waste heat, both from the refinery and the power station was initially provided to greenhouses, but this has recently changed to provide waste heat to fish farms and district heating. Finally, sulphur from the refinery is shipped to the Kemira Acid Plant, while Novo Nordisk's Pharmaceutical plant provides treated sludge as fertiliser to neighbouring farms. The environmental benefits from the industrial symbiosis are summarised in table 3.

Table 3: Environmental benefits from industrial symbiosis at Kalundborg (source: Ehrenfeld et all, 1997).

Annual resource savings through interchanges	
• Water savings	Statoil – 1.2 million cubic meters from Asnaes (Novo Nordisk – 0.9 million cubic meters available but not yet utilised)
• Fuel savings	Asnaes – 30,000 ton of coal (about 2 % of throughput) by using Statoil fuel gas About 19,000 tons of oil use by using fuel gas from Statoil in Novo Nordisk's boilers and Gyproc dryer fuel Community heating via waste steam from Asnaes
• Input chemicals	Fertiliser equivalent to Novo Nordisk's sludge (about 800 tons nitrogen and 400 tons phosphorous) 2,800 tons sulphur 80,000 tons of gypsum
Wastes avoided through interchanges	
• Fly-ash and clinker	200,000 tons fly-ash and clinker from Asnaes (diverted from landfill)
• Scubber sludge	80,000 tons of scrubber sludge from Asnaes (diverted from landfill)
• Sulphur (as H2S)	2,800 tons from fluegas from Statoil (diverted from air emissions)
• Waste water sludge	1,000,000 tons from Novo Nordisk (diverted from sea disposal)
• Sulphur (as SO2)	1,500-2,500 tons SO2 avoided by substituting coal and oil (diverted from air emissions)
• Greenhouse gases	130,000 ton CO2 avoided by substituting coal and oil (diverted from air emissions)

The current system is the result of a dynamic evolution over about four decades. The 'twinning' between the three key process industries (power station, refinery and pharmaceutical plant) is generally regarded as the critical success factor at Kalundborg, since each provides large volume waste streams with valuable by-products on a continuous basis (Ehrenfeld et all, 1997). It the absence of the co-location of two or preferably even more major process industries it may not be possible to develop a significant industrial symbiosis. Manufacturing industries, often the largest segment at any industrial estate, typically produce comparatively small volumes of mono material waste streams (resulting from cut of from input materials) and a mixed waste stream comprising of production rejects, packaging and other production waste. The mono-material stream is most valuable for reuse or downcycling in other industries, but is only available in smaller quantities, often with large fluctuations in volume over time, and are generally only valuable to industries in the same sector. These factors make it difficult to achieve positive economics for symbiosis on mono material streams within any given industrial estate. The mixed waste stream from manufacturing industries is not fundamentally different from the general municipal waste stream, and likewise it has limited potential and economic value for direct reuse by industries. In sum, it may not be easy to design ex ante industrial symbiosis at the scale of the Kalundborg system. However, at a more modest scale, it may well be possible to develop symbiotic relations between companies, as for instance proved by the experience of the Business Council for Sustainable Development in the Gulf of Mexico (Mangan, 1998).

An emerging application area is Sustainable Technology Development. Such programs are generally inspired by concerns about the dominant incremental way of industry-based or industry-co-funded research and development. It is argued that this incrementalism is not likely to yield in time the system innovations that will deliver the quantum leaps in eco-efficiency mandated by Factor X and alike considerations (e.g. Vergragt et all, 1994; Weaver et all, 2000). Innovations in the innovation processes itself are therefore needed, e.g. by expanding the innovation networks that guide and steer research and development, by imposing challenging long term environmental objectives, and utilising a backcasting approach ([6]). The Sustainable Technology Development Program in The Netherlands, aimed to demonstrate how such innovations in the innovation processes can lead to new perspective on R&D priorities. The development of a methodology and establishment of a series of case studies were at the core of this research program. The five case studies conducted, were: nutrition; transport/mobility; buildings and urban spaces; services provided by water; and services provided by materials and chemicals. In each case study critical technology innovations were identified for reaching a factor 20 quantum leap in eco-efficiency within a 50-year time frame. The critical innovation areas identified for chemical industry were (Weaver et all, 2000) ([7]):

- *C-1 chemistry*: this is critical for using organic materials (in particular biomass waste) as feedstock for the chemical industry. It is essentially the chemistry based on molecules with one C atom. The vision is to extract all high valuable materials from plant biomass (e.g. oils, fibres, etc.), then convert the remaining biomass waste into C-1 forms and synthesise bulk quantities of industrial organic chemicals from those C-1 forms. Breakthrough innovations are needed in the conversion and synthesis areas. With regard to conversion, three emerging technologies provide promising prospects: advanced gasification (with oxygen enriched air or pure oxygen, to produce pure synthesis gas, as input for synthesis of methanol or ammonia); flash pyrolysis (short heat treatment to depolymerise cellulose, but not breaking it down to C-1, resulting in a bio-oil containing C5-C10 fragments); and hydro-thermal upgrading (production of biocrude – equivalent to crude oil - from biomass with a high temperature and high pressure treatment). All three offer production routes to at least the ten largest bulk industrial organic chemicals, from biomass of any type and not just from selected parts of biomass, such as starches or sugars.

- *New chemical engineering approaches in fine chemistry*: only about 20% of the known reactions can be used at a commercial scale for the fine chemistry, due to lack of specific engineering

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[6] Forecasting refers to the projection of future events and conditions on the basis of current trends, whereas backcasting starts with a desired state of affairs at a particular point in the far future (~25-50 years) and develop alternative paths (including required technological breakthroughs) that can be taken from the present to reach that state.

[7] Two other priorities were identified in the case study on 'services from chemicals and materials', i.e. cascade use of biomass (subsequent winning of several valuable materials from plant biomass) and structural materials from natural fibre composites (e.g. as lightweight structural materials for the transportation sector). These two however have only limited impact for chemical engineering, and are therefore not further covered here.

approaches (including unit operations, plant architecture etc.) for the fine chemicals sector. The alternative to the current continuous production architecture – 'borrowed' from the bulk chemicals sector – would be to base fine chemistry around batch production in quasi-laboratory-scale conditions that could support the leaner and cleaner reactions for fine chemicals synthesis that have been proven at laboratory scale

CLEANER PRODUCTION AT MESO SCALE: ECO-EFFICIENCY

Cleaner Production at the macro scale is useful in identifying resource inefficiencies in current industrial – production and consumption systems – and outlining possible system innovations, with a typical medium to far future timeline. This needs to be complemented with short-term improvement and innovation starting from today's product, services and processes aimed to make those more '*eco-efficient*'. This can involve: reducing the material intensity of goods and services; reducing the energy intensity of goods and services; reducing toxic dispersion; enhancing the material recyclability; maximising the sustainable use of renewable resources; extending the product durability; and increasing the service intensity of goods and services (DeSimone et al, 1997).

It can be argued that at this meso scale Cleaner Production is essentially a combination of 'best practice' in terms of process engineering, industrial design and operational and strategic management. Provided such 'best practice' implies that environmental and resource efficiency considerations are truly considered and integrated right from the start in product and process design, engineering and management, it would be an acceptable starting point to equal meso scale Cleaner Production to best practice. However, in daily practice, this is far to often not yet the case, and it remains therefore useful to distinguish Cleaner Production from best practice, notwithstanding the fact that implementation of Cleaner Production will generally heavily rely on tools and systems that basically stem from the engineering, design, management and accounting disciplines.

Analytical and diagnostic tools

At least a dozen or so common engineering and management tools are regularly used for analytical and diagnostic purposes for the meso scale implementation of Cleaner Production. These include for instance: material and energy balance, PINCH analysis (for energy and water), concurrent engineering, fishbone analysis, quality circles, cost benefit analysis, flowsheeting, mass exchange network analysis, etc. Such common tools are supplemented with specific Cleaner Production tools.

An example specific diagnostic tool is a Cleaner Production assessment. This is essentially a systematic procedure for the identification and evaluation of Cleaner Production options for a production facility. The Cleaner Production assessment is also supposed to contribute to changes in management and information systems that can sustain the implementation of Cleaner Production options upon completion of the assessment. Such Cleaner Production assessment is most often divided into five phases (Crul et al, 1991; Van Berkel, 1996):

1. *Planning and Organisation:* this includes obtaining management commitment, setting aims and establishing a proper project organisation for conducting the Cleaner Production assessment.

2. *Pre-assessment*: the prime objective is the selection of one - or a few - audit focuses. This requires a preliminary identification and evaluation of the Cleaner Production potential at the plant level. While doing so, a first inventory of obvious options is made as well as a preliminary estimate of the waste generation costs.

3. *Assessment:* this consists of the in-depth evaluation of the selected audit focus(es) in order to develop a comprehensive set of alternate Cleaner Production options. This requires a quantification of the volume and composition of the various waste streams and emissions as well as a detailed understanding of the causes of these waste streams and emissions.

4. *Feasibility Studies*: these now have to prove whether or not each of the options is technically and economically feasible and whether each indeed creates net environmental benefit.

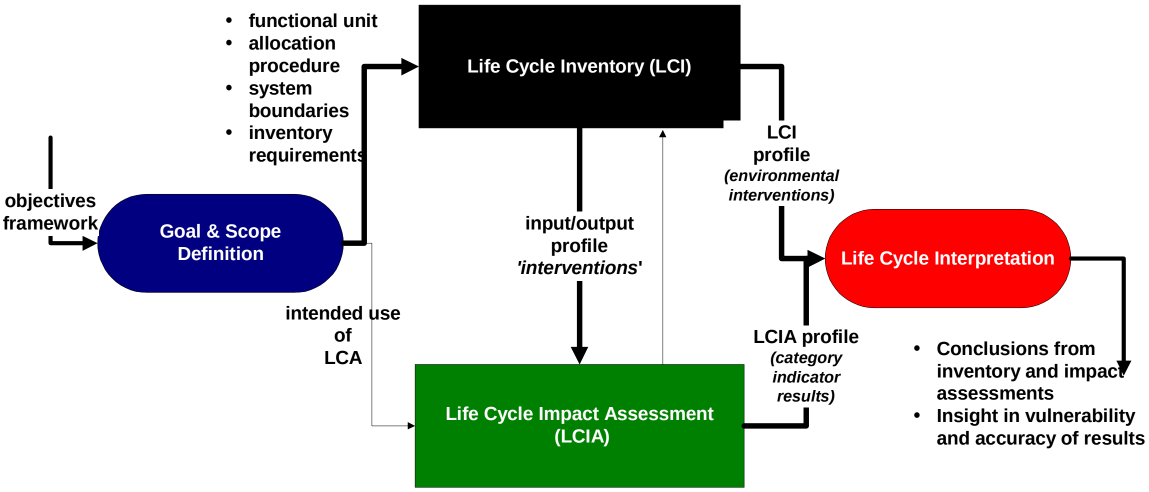
5. *Implementation and Continuation*: the feasible prevention measures are implemented and provisions taken to assure the ongoing application of Cleaner Production. This includes an ongoing program requires monitoring and evaluation of the Cleaner Production results achieved

Several attempts have been pilot tested to streamline this comprehensive Cleaner Production assessment procedure, whilst still maintaining its potential to identify innovative sets of Cleaner Production opportunities. Sectorial Cleaner Production blueprints and Cleaner Production indicators are examples of potentially successful abridged assessment procedures (Van Berkel, 1994). In general, however, abridged Cleaner Production methods fail to elicit a learning process in the audited companies (De Bruijn et al, 2000).

An analytical tool specific for the implementation of Cleaner Production at the meso scale is Life Cycle Assessment. At the operational level, Life Cycle Assessment, or - more precisely - an environmental assessment of a product life cycle - is best described as a systematic approach to quantify and assess the environmental problems caused by a product (or service or process) over its entire life cycle. The product life cycle starts with the extraction and processing of the product raw materials, to product manufacturing, product distribution, consumption, and reuse, recycling and disposal. The execution of Life Cycle Assessment is governed by a series of international standards (ISO 14040-14043) (ISO, 1997-2000). The development of Life Cycle Assessment methodology is largely driven by various working groups under the umbrella of the Society for Environmental Chemistry and Toxicology (SETAC; e.g. Udo de Haes et all, 1999 a; b).

A Life Cycle Assessment comprises of four parts; goal and scope definition; life cycle inventory assessment; life cycle impact assessment; and life cycle evaluation (see figure 3). The *Goal and Scope Definition* establishes the functional unit, the allocation procedure, system boundaries, and requirements for inventory data. The *Life Cycle Inventory Analysis* deals with the collection and synthesis of information on physical material and energy in- and outputs in the various stages of the product life cycle. The input and output data collected for individual process steps are then summarised by input and output category, to compile the environmental input output profile, or Life Cycle Inventory, profile for the product life cycle being studied. In the Life Cycle Impact Assessment these environmental input and outputs are assigned to environmental impact categories, and characterisation models used to calculate the contribution of each of these inputs and outputs to category indicators. This leads to a Life Cycle Impact Assessment Profile of category indicator scores for all environmental impact categories. Finally, the Life Cycle Evaluation deals with the interpretation of the results from both the Life Cycle Inventory Analysis and Life Cycle Impact Assessment. It includes the identification of significant issues and the evaluation of results.

Figure 3: Structure of Life Cycle Assessment (modified from ISO 14040).



The application of Life Cycle Assessment in Australia still appears to be in its infancy as compared to for instance Western Europe and Northern America. General methodological issues (in particular pertaining to system boundaries, allocation rules and streamlining approaches) and availability and quality of data hamper the application of Life Cycle Assessment in general. In the case of Australia, however, this is further compounded by the need to develop a Life Cycle Impact Assessment methodology customised to Australian conditions and collect the necessary environmental data for conducting such Life Cycle Impact Assessment.

Improvement and innovation concepts

Different concepts are being used to drive the identification of improvement and innovation options for Cleaner Production at this meso scale. Their common goal is to contribute to more eco-efficient products, services and processes, starting from existing products, services and processes. Doing so most often calls for the simultaneous use of specific Cleaner Production concepts and common engineering and management tools. The list of prevention practices and eco-efficiency objectives discussed in the section on Cleaner Production concept and benefits can be regarded as the most elementary improvement and innovation concepts for Cleaner Production at the meso scale (De Simione et all, 1997).

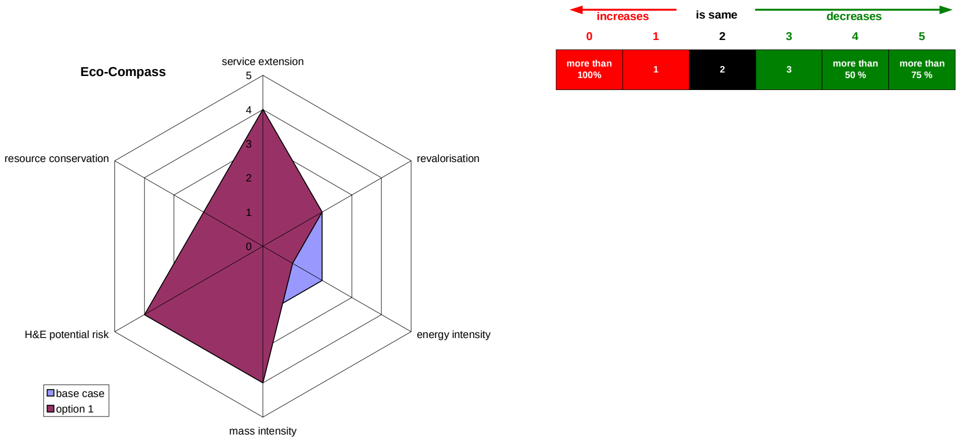
An example of an improvement concept for products, is the set of 13 Life Cycle Design Principles developed by Beherendt et all (1997). These are summarised in table 4. The table clearly reflects that improvement concepts for products are largely geared towards product architecture and functionality. Even though material selection is being considered in principles 3, 6 and 8, the framework does provide only limited guidance for environmental improvement and innovation in the materials and chemicals industries.

Table 4: Life Cycle Design Principles (source: Beherendt et all, 1997).

Principle	Explanation
1. Achieving environmental efficiency (optimal functioning of products)	Includes the formulation of new ways to fulfil customer needs. It calls for a focus on needs and demands of customers, and can be achieved by dematerialization, resource cascading and design of green product systems.
2. Saving resources	The reduction of energy and material use in the production of a product by miniaturisation, up cycling (refurbishment) and use of recycled materials.
3. Using renewable and sufficiently available materials	Alternatives for the current materials choice for products can be found by replacing non-renewable with renewable materials, by replacing scare by less scarce materials and miniaturisation and recycling for scare materials.
4. Increasing product durability	Increased product durability can mainly be achieved by devising products with a long life span, by using a product system design that is technologically adaptable and by designing for maintenance.
5. Designing for product reuse	Reuse of products can be facilitated with modular design, easily accessible product components, wear-resistant design, corrosion protection, and standardisation of components and connecting elements.
6. Designing for material recycling	Adopting practices that allow for the easy recovery of materials from scrapped products, at a quality level which approaches the quality of virgin material, facilitated through the selection of recyclable materials, minimisation of material variety, compatibility of material combinations and material marking.
7. Designing for disassembly	Quick and damage free disassembly is a precondition for obtaining reusable components and reusable materials. This benefits from product structure geared to disassembly, easily accessible, and low number of connecting elements.
8. Minimising harmful substances	This includes both the substitution of harmful substances by less harmful substances as well as allowing for the easy removal of harmful substances.
9. Applying environmentally sound production processes	Provide product designs that can be made with Cleaner Production technologies and practices, that consume minimal quantities of material, energy and water, and reduce the generation of waste and emissions during product manufacturing.
10. Minimising environmental impacts of products during consumption	Incorporate environmental impact during the use stage in the product design, and address for instance the consumption of materials, energy and other auxiliaries for product operation and maintenance.
11. Using environmentally friendly packaging	This includes minimisation of material consumption for packaging as well as use of environmentally preferred materials, and introduction of packaging reuse.
12. Enabling environmentally sound disposal of non recyclable materials	Of particular concern are ensuring the proper disposal of hazardous materials and safeguarding that biodegradable materials are being composted instead of incinerated or landfilled.
13. Implementing environmentally sound logistics	The transport intensity of product distribution and delivery is a major environmental concern as is the amount of secondary packaging used for distribution purposes.

Another innovation concept has been proposed as the *Eco-Compass* (Fussler et all, 1996). It was developed at Dow to identify and evaluate improvement projects and as a creative method to envision a sustainable future and back cast from it. This will shed light on the necessary innovations, which will move current products, services and processes to sustainability. The Eco-Compass has six poles or dimensions, which are intended to encompass all significant environmental issues. Two are largely environmental; i.e. health and environmental potential risk; and resource conservation. The other four are of business as well as of environmental significance, i.e.: energy intensity; materials intensity; revalorisation (of waste) and service extension. The latter measures the ability to deliver greater service from given inputs, for example by improving durability. The Eco-Compass is a tool to compare new options to a base case. A screening of the life cycle data of the base case and the new options leads to a score (0 to 5) for each dimension. The base case is by definition scored 2 on all dimensions, and the new options are scored relative to this bases case. A score of 5 reflects a factor 4 or more environmental improvement (reflecting a decrease to 25% or less of the base case). Likewise a score of 4 reflects a factor 2 or more environmental improvement. In case of poorer environmental performance, the option receives a score of 0 or 1, with 0 reflecting a worsening of the eco-efficiency by a factor 2 (reflecting a 100% increase or more to the base case). The result can be graphically displayed in a hexagon, and the closer a product option gets to the hexagon shape, the better its environmental performance (as illustrated in figure 4).

Figure 4: The Eco-Compass: a tool to envision sustainable product and process innovations and compare those with the base case (source: Fussler et all, 1996).



Application areas

The most developed application area of meso scale Cleaner Production in the process industry is for equipment design and operation. This has resulted in a substantive body of knowledge of Cleaner Production options for different – sets of – unit operations (as summarised in for instance: CMA, 1993 and Allen et all, 1997). As an illustration of this application area, table 5 summarises key Cleaner Production options, both design and operational related, for reactors, heat exchangers and sampling.

A more recent meso scale application area is process selection, design and optimisation. This is part of Research and Development, in particular the process conception, where possible production routes are being identified and screened. This precedes the application of Cleaner Production to equipment design and operation. The application in process selection and design was initially predominantly qualitative, through for instance the development of lists of Cleaner Production ideas by commonly encountered resource efficiency problems in reaction pathways and process routes (e.g. CMA, 1993). However, more recently quantitative tools, in particular Life Cycle Assessment, are being used for process selection, design and optimisation (Azapagic, 1999). As an environmental tool for process management Life Cycle Assessment has two main objectives. The first is to quantify and evaluate the environmental performance of a process from cradle to grave and so help decision-makers to choose a more sustainable option among alternatives. Another objective is to provide a basis for assessing potential improvements in the environmental performance of the system. Two main problems are associated with these objectives of Life Cycle Assessment. First, in many cases there will be a number of options and

Table 5: Key Cleaner Production options for selected process equipment (adapted from CMA, 1993).

Design Related	Operational Related
Reactors	
• Static mixing • Add baffles • Change impellers • Add distributor • Provide separate reactor for converting recycle streams to usable products	• Add ingredients with optimum sequence • Allow proper head space to reactor to enhance vortex effect • Optimise reaction conditions (temperature, pressure, etc.)
Heat Exchangers	
• Use intermediate exchangers to avoid contact with furnace walls and tubes • Use staged heating to minimise product degradation • Use scraped wall exchangers in viscous service • Use falling film reboiler, piped recirculation boiler or high flux tubes • Use lowest pressure steam possible • Use welded tubes or double tube sheets with inert purge • Mount vertically • Use super heat or high pressure steam in place of a furnace	• Select operating temperatures at or near ambient temperature • Use lower temperature steam to lower temperatures • Monitor exchanger fouling to process conditions • Use on line tube cleaning techniques • Monitor leaks
Sampling	
• On line in situ analysers • System for return to process • Closed loop • Vent to header • Drain to sump	• Reduce number and size of samples required • Sample at lowest possible temperature and pressure

possibilities for improvement and it may not always be obvious which of them represents the optimum solution. Therefore some kind of system optimisation will be necessary. Secondly, there may exist more than one optimum solution for improving the system's performance, in which case the issue becomes that of choosing the best compromise option from a number of optimum solutions. Initial case study work proves that Life Cycle Assessment can be integrated in a Multi Objective process optimisation routine. There are examples from the minerals and processing industries that demonstrate the potential benefit of doing so. The efforts now focus on systematic integration of Life Cycle Assessment in Multi Objective process selection and optimisation models. This could yield in a new tool, tentatively a Life Cycle Process Design tool (Azapagic et all, 1999).

CLEANER PRODUCTON AT MICRO SCALE: GREEN CHEMISTRY

At the micro scale Cleaner Production investigates synthesis pathways and process routes with a particular focus on the complete utilisation of starting materials, on process requirements, including physical process conditions and consumption of reagents, and on potentially hazardous intermediate and by-products. The overall aim is to develop synthesis pathways and process routes that are intrinsically cleaner than the ones they replace, because of lower waste and by-product generation, lower consumption of materials and energy and fewer hazardous chemicals – all measured by unit of produced material.

In its earliest applications, Cleaner Production at the micro scale focused in particular on the systematic design of substitute materials, such as alternatives for hazardous solvents or biodegradable products, and molecular analysis of reaction pathways (see e.g. Allen et all, 1997). Over the last decade, the scope expanded, and the field is now probably best known as green chemistry. Green chemistry, environmentally benign chemical synthesis, alternative synthetic pathways for Cleaner Production, benign by design: these phrases all essentially describe the same concept. Green Chemistry is the utilisation of a set of principles that reduces or eliminates the use or generation of hazardous substances in the design, manufacture and application of chemical products (Anastas et all, 1998). Green Chemistry is not complicated although it is often elegant.

Analytical and diagnostic tools

Green Chemistry generally uses standard chemical and engineering analytical and diagnostic tools that are not the specific result of the attention for Cleaner Production. These include for instance the application of group theory for the search for alternative chemicals, and molecular-level reaction pathway synthesis, for reducing the use of toxic precursors and reducing the formation of unwanted by-products (Allen et all, 1997). Perhaps the only analytical tool that has been significantly progressed by Green Chemistry considerations is the use of concept of '*atom economy*'.

The classic evaluation of the effectiveness and efficiency of a synthesis is yield. '*Yield*' also totally ignores the use or generation of any undesired products that are an intrinsic part of the synthesis. It is possible, and very often the case, that a synthetic pathway, or even a synthetic step, can achieve 100% yield and generate waste that is far greater in mass and volume than that of the desired product. This is true because the calculation is based around the mole concept of moles starting materials versus moles of product. If a mole of starting material produces a more of desired product, the yield is 100% and the synthesis is deemed perfectly efficient by this calculation. This same transformation, however, could produce one or more moles of waste for every more of product. Each mole of that waste could be many times more the molecular weight of the desired product. Therefore a 'perfectly efficient' synthesis according to the percentage yield calculation could generate significant amounts of waste and this would be invisible using only this evaluative equation. It is because of this discrepancy that the concept of atom economy is used. 'Atom economy' is an assessment in which one looks at all of the reactants to measure the degree to which each of them is incorporated into the final product (Anastas, 1998).

Therefore if all the reactants are incorporated into the product completely, the synthetic pathway is said to be 100% atom economical. The standard synthetic transformation types can be evaluated generically to determine the intrinsic atom economy of each type. Rearrangement and addition reactions are in principal atomic economical, whilst substitution and elimination reactions are by definition not atomic economical, with the level of atomic economy depending on the size of the group that has been substituted or eliminated.

Innovation and improvement concepts

The leading innovation concept for Green Chemistry is a set of twelve principles that has emerged from practical work and is generally expected to be guiding the future development of this field. As illustrated in box 2, the principles are rather diverse. Each of these provides specific direction to avoid specific resource efficiency problems commonly encountered in sets of synthesis pathways (e.g. energy requirement (principle 6), minimal use of auxiliary substances (principle 5), (bio)degradability (principle 10) and catalytic reagents in preference to stoichiometric reagents. The principles only

Box 2: "Twelve Principles of Green Chemistry" (source: Anastas et all, 1998).

1. It is better to prevent waste than to treat or clean up waste after it is formed.
2. Synthetic methods should be designed to maximise the incorporation of all materials used in the process into the final product.
3. Wherever practicable, synthetic methodologies should be designed to use and generate substances that pose little or no toxicity to human health and the environment.
4. Chemical products should be designed to preserve efficacy of function while reducing toxicity.
5. The use of auxiliary substances (e.g. solvents, separation agents, etc.) should be made unnecessary wherever possible and, innocuous when used.
6. Energy requirements should be recognised for their environmental and economic impacts and should be minimised. Synthetic methods should be conducted at ambient temperature and pressure.
7. A raw material or feedstock should be renewable rather then depleting wherever technically and economically practicable.
8. Unnecessary derivatization (blocking group, protection/deprotection, temporary modification of physical/chemical processes) should be avoided whenever possible.
9. Catalytic reagents (as selective as possible) are superior to stoichiometric reagents.
10. Chemical products should be designed so that at the end of their function they do not persist in the environment and break down into innocuous degradation products
11. Analytical methodologies need to be further developed to allow for real-time, in process monitoring and control prior to the formation of hazardous substances.
12. Substances and the form of a substance used in a chemical process should be chosen so as to minimise the potential for chemical accidents, including releases, explosions, and fires.

address the design of alternative synthesis routes. As for instance illustrated by Pereira (1999) this needs to be complemented with best practice in reaction engineering – the quantification of the engineering aspects of chemically reactive systems – in order to enable, and most likely accelerate, the development and commercialisation of the greener synthesis pathways to industrial systems.

Application areas

Green Chemistry, or micro-scale Cleaner Production, is applied in the development and evaluation of synthesis pathways and chemical products. Its application results generally fall in either of the following six categories.

1. *Alternative feedstocks/starting materials*: using a less hazardous feedstock or using renewable feedstocks (such as agricultural and biological feedstocks for organic synthesis and replacement of heavy metal catalyst by e.g. light). An example can be found in the production of commodity chemicals from glucose. Using biotechnological techniques to manipulate the shikimic acid pathway (responsible for making many of the aromatic compounds in nature), compounds such as hydroquinone, catechol and adipic acid, all of which are important, large volume chemicals, can be synthesised. The traditional starting materials for these substances is benzene, a known carcinogen. By using glucose instead of benzene, this biosynthetic pathway – using genetically modified E. Coli - can help to minimise the use of toxic reagents, and the synthesis can also be conducted in water instead of organic solvents (Anastas et all, 1998; pg. 94).

2. *Alternative reagents*: systematic evaluation of alternative reagents for the same net chemical transformation to select and use the most efficient reagent for carrying out the transformation. Monsanto developed for instance a non-phosgene synthesis pathway for isocyanate - precursor for polyurethanes – by substituting carbon dioxide for the phosgene traditionally used (Anastas et all, 1998; p. 100);

3. *Alternative solvents*: once it has been determined that a transformation cannot be executed in a solventless system, the chemist must select a solvent system. While traditional organic solvents are well known, characterised, and utilised, alternatives such as aqueous systems, ionic liquids, immobilised solvents, dendrimers and amphiphilic polymers, and supercritical fluids are increasingly applied in synthesis. Carbon dioxide surfactant technology, or ‘soapy CO2’, uses liquid/supercritical CO2 in place of less acceptable organic chemicals. This technology involves the development of surfactant systems for CO2 in order to expand the use of liquid and supercritical CO2 to enhance its solvating power for large, hydrocarbon-based molecules. In addition to polymerisation processes, soapy CO2 can be used as a cleaning and extraction medium (replacing halogenated hydrocarbons) as well as solvent/medium for organic reactions (Anastas et all, 1998; p. 105).

4. *Alternative product/target molecule*: if function is the primary motivation for the synthesis (as for instance for pharmaceuticals) molecular manipulation that preserves efficacy of function while mitigating toxicity or other hazards becomes the goal of Green Chemistry. In designing the safer chemicals one identifies the undesirable, toxic portion of the molecule and lessens or eliminates its toxicity, while maintaining the function of the molecule. PolyAcrylic Acid (PAC) is for instance an important anionic polymer used in many industrial applications. Unfortunately it is not biodegradable, so in most cases, these polymers end up in waste treatment facilities. An economically viable, effective, and biodegradable alternative is Thermal Poly-Aspartate (TPA). The production involves a dry and solid polymerisation, converting aspartic acid via polysuccinimide to polyaspartate. The reaction is extremely efficient and waste free, and no organic solvents are involved during the conversion. A catalyst can be used during the polymerisation that allows lower heating temperature to be used. The resulting product has improved performance characteristics, lower colour and biodegradability (Anastas et all, 1998; p. 112).

5. *Process analytical chemistry*: real time measurement of reaction conditions during chemical synthesis, coupled with the ability to alter the reaction depending on the outcome of the analyses. On line Gas Chromatography quantitative analysis can, for example, be applied to monitor alkylation of 1-butene/isobutane. This process replaces the traditional hydrofluoric

and sulfuric acid catalysts, with a solid-acid catalysts, such a HY zeolite, sulphated ziconia or Nafion. Coke retention in the pores of the catalyst is minimised through the use of supercritical CO2 as solvent. In-line monitoring supports and facilitates the solid-acid catalysed process and also uses non-toxic reagents and benign solvents (Anastas et all, 2000; p.19).

6. *Alternative catalysts*: use of new catalysts to remove the need for large quantities of reagents that would otherwise have been needed to carry out the transformations, and would ultimately have contributed to the waste streams. Several heterogeneous catalysts can be used in the condensation of acetone to methylisobutyl ketone (MIBK). Nickel on alumina, palladium zirconia, nickel and nibium, and ZSM-5 with palladium all have demonstrated effectiveness with various degrees of conversion and selectivity, in catalysing the condenstation of acetone to MIBK. The catalytic process eliminates the stoichiometric amount of base typically utilised, as well as the formation of undesirable over-condensation products (Anastas et all, 2000; p. 19).

CONCLUDING REMARKS

Cleaner Production is not longer a whim of our times or of environmentalists only. It is rooted in the process industry, with the first successes already 25 years old. At the international level, Cleaner Production has been progressively embraced by industry, government and the community alike, starting from the mid 1980’s. And evidence continues to emerge that the environmental, technical and financial benefits can continue to increase over time for companies adopting Cleaner Production, even after the first batches of Cleaner Production opportunities – generally referred to as the ‘low hanging fruits’ - have all been implemented. Compared to developments in Western Europe, Northern America and even several Asian countries, the uptake of Cleaner Production in Australia appears to be slow, despite the fact that recent surveys consistently show that Australian businesses consider themselves aware of Cleaner Production and related preventive environmental management strategies.

This paper focused on the application of Cleaner Production in the process industry. The relationship between Cleaner Production and other environmental management strategies was briefly addressed, and a few examples from Australian process industries that successfully implemented Cleaner Production were reviewed. Next developments in Cleaner Production for the process industry were focussed upon for the three general scales at which Cleaner Production can be engineered, macro-scale (or Industrial Ecology), meso scale (or Eco-Efficiency) and micro scale (or Green Chemistry). Each level has its own set of analytical and diagnostic tools and employs a different set of improvement and innovation concepts, with the macro scale primarily aiming at system-innovations, the meso scale primarily at eco-efficient products, services and processes, and the micro scale primarily at chemical synthesis pathways that are more efficient and/or involve less hazardous substances.

At the general level it is remarkable that Cleaner Production started at the meso scale and the macro and micro scale probably only took off with at least a decade delay. However, at present it appears that most of the innovation in Cleaner Production takes place at the macro and micro scale in research and development related to Sustainable Technology Development (macro level) and Green Chemistry (micro level). Both fields aim at break-through innovations that could provide the quantum leaps, or factor improvements, in the resource efficiency of products and services. Thereby both fields have the potential to redefine the way the chemicals and materials industry will operate as of the second quarter of this century. Although Cleaner Production at the meso scale is almost by definition incremental, it should not be neglected. Those businesses that are leading with regard to the meso scale implementation of Cleaner Production will be best prepared for the challenges posed from the other two scales and be in the best position to benefit from the business opportunities that these are likely to create.

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