"INTERACTIONS BETWEEN OPERATIONAL RESEARCH AND ENVIRONMENTAL MANAGEMENT"

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Interactions between Operational Research and Environmental Management

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Abstract: Economic growth is frequently considered to be in conflict with sustainable development and environmental quality. Therefore, a decision maker needs to know how to deal with the environmental issues that come around. This article aims to inform Operational Researchers of the possibilities of incorporating environmental issues when analyzing industrial supply chains and to inform environmental scientists more generally of the value of using OR models and techniques in environmental research.

Keywords: environment, modelling, optimization, pollution control, supply chains.

1 Introduction

In the last few decades environmental problems have received increasing attention. Protection of the environment has become an issue at all levels of society: worldwide (UNCED '92), regional (European Union), national, sectoral and the individual consumer.

Within the field of Operational Research (OR), attention for environmental issues is now growing rapidly. In 1991, a special issue of Transportation Science was devoted to the transportation of hazardous materials. In the same year, van Beek *et al.* (1991) demonstrated how Operational Research can play an important role in visualizing and solving environmental problems. The June 1992 issue of OR/MS Today featured the title "Reflections on OR and the Environment". One of the authors, F.W. Talcott of the U.S. Environmental Protection Agency (EPA), stated:

"*... the opportunities for OR and MS are numerous. Environmental problems are substantial; the costs of dealing with them are imposing. Because our resources - natural and financial - are limited, it is critical that we think smart and plan smart in dealing with environmental issues. Good analysis can pay off.*" (Talcott, 1992)

As early as 1976, a special issue of Computers & Operations Research was devoted to macro economic environmental models. The first examples of the application of OR optimization models to environmental problems appeared in the mid-seventies in journals on environmental issues such as *Environment and Planning* (e.g. Böttcher and Rembold, 1977) and *Water Resources Research* (Das and Haimes, 1979). Later, applications of OR to Environmental Management (EM) appeared also in OR/MS journals such as *Operations Research* (Batta and Chiu, 1988), *European Journal of Operational Research* (Ellis, 1988) and *Management Science* (Bouzaher *et al.*, 1990). Nowadays, literature on a wide variety of environmental problems, using all kinds of OR techniques, can be found in both environmental journals and OR journals.

It is not the purpose of this paper to give an exhaustive review of examples on the interactions between Operational Research and Environmental Management for the simple reason that the area is too large for that. For some specific issues, it is possible to briefly describe previous work. When we arrive at these issues, we refer to reviews and bibliographies. However, most of the work in this area is still very much in development and some applications have only just started. Therefore, we decided to structure this paper around some carefully selected examples of fruitful interactions between OR and EM. We hope that this paper can be an eye-opener on the richness of this area, and that the reader will become aware of the many possibilities to integrate environmental issues in his or her OR discipline.

In the remainder of this paper, we distinguish between two ways of looking at the interaction between OR and EM:

1. *Impact on the supply chain:* Environmental issues play a role in the routine activities of business firms. Decisions on production planning, logistics, location, allocation and inventory control will change due to legal requirements or consumer pressures to reduce waste and emissions. Therefore, there is a need to adapt OR tools such as production planning algorithms, location models and routing heuristics in order to deal adequately with a new situation requiring 'green supply chain modelling'.

2. *Impact on the environmental chain:* The amount of waste and the level of emissions caused by the supply chain result in a number of serious environmental effects, such as global warming and acid rain. Frequently, these environmental problems are international and complex. The interaction between OR and EM can result in a clear formulation of these problems and in new insights in the impacts of alternative policy measures.

This paper is structured as follows. In section 2, some incentives and constraints regarding the interaction between Operational Research and Environmental Management are stated. We explain why, in our opinion, the knowledge of OR will be useful in environmental problem solving, and why incorporating knowledge from environmental management will enrich the working area of Operational Research. Furthermore, a framework is presented to show how environmental issues and business interact in the two ways described above. In section 3, we discuss in more detail the environmental issues in a supply chain. In section 4, some examples are given of OR work that deals with reducing **waste and emissions** in the supply chain. In section 5, we turn to the environmental chain and discuss the effects of business on the environment and the way environmental policy makers try to deal with this. In section 6, some OR work in this area is presented. Finally, section 7 provides some conclusions.

2 Operational Research and Environmental Management

In this section, we indicate why closer interaction between OR and EM may become very fruitful and even necessary. We also show the need to take an integrated chain approach in studying these problems.

2.1 Internalization

Thinking about the environment has evolved from **end-of-pipe control** (reduce waste and emission flows) towards **waste prevention at the source** by redesigning products and processes. This change in attitude poses many questions which OR can help answer. As Kleiner (1991) mentioned: "A recycling operation must deal with the same transport difficulties and storage problems that challenge any distribution system; a landfill is, in effect, like a warehouse whose inventory never shrinks; garbage barges and toxic trains are the environmental equivalents of production-distribution networks".

In line with the shift in attitude from end-of-pipe controls to prevention at the source, laws are changing from strict rules and specific emission controls towards a policy of leaving operational managers more flexibility to decide how to keep pollution within given emission limits (Corbett and Van Wassenhove, 1993). This market-based policy ('bubble policy') treats entire firms as being inclosed in a bubble and allocated to each bubble a specific total pollution limit. This allows firms to decide for themselves where and how to cut back pollution and results in more degrees of freedom for the decision makers to optimize their behaviour.

2.2 Scope

The international nature and the complexity of many environmental problems in relation to supply chains makes it almost impossible to make decisions based on intuition. A quantitative model-based representation of the problem will often be extremely useful.

Although model building can provide insights in the characteristics of a complex problem, it can be very hard to 'solve' such models. Sterman (1991) mentioned that "whenever the problem to be solved is one of choosing the best from among a well-defined set of alternatives, optimization should be considered. If the meaning of best is also well-defined and if the system to be optimized is relatively static and free of feedback, optimization may well be the best technique to use". The latter conditions are rarely satisfied for the economic and ecological systems that are dealt with in Environmental Management. Fortunately, more and more optimization techniques (e.g. multicriteria analysis and dynamic programming) try to overcome these problems. Moreover, discrete and continuous simulation can identify how feedback, nonlinearity and delays interact to produce troubling dynamics that persistently resist solutions.

The complexity of environmental problems is also characterized by the typical difficulty to find a unique quantitative measure for 'being green'. Environmental damage cannot easily be compared with parameters such as costs or time that are 'hard' metrics. However, techniques like 'life-cycle assessment' (SETAC, 1993) should make it possible to compare products based on their environmental profile. Furthermore, environmental regulations are often stated in quantitative terms (e.g. emission standards to air and water).

Some environmental management issues deal with behaviour. These issues do not easily lend themselves to OR modelling. In addition, environmental decisions are often made by politicians not familiar with, and indeed sometimes suspicious of, mathematical modelling. The review by de Melo and Câmara (1994) shows how policy makers can be successfully involved in the development of models for the optimization of regional wastewater treatment systems. Moreover, Operational Research models can be used as a rational tool in otherwise irrational and emotional debates on environmental issues.

2.3 Framework

The shift from effect-directed control towards prevention and the increasing acknowledgement of the complexity and international character of environmental problems are open invitations for the increasing interaction between OR and EM.

The interaction between OR and EM can be rather straightforward in the sense that an end-of-pipe approach (e.g. an emission standard) can be incorporated in a classical OR production-distribution model as an additional constraint. In this way, effect-directed approaches involve adjustments to classical OR models.

Preventive approaches acknowledging the complexity and international character of environmental problems require more fundamental thinking, the development of new models and the use of different techniques. They provide a great challenge to OR.

In any case, the shift from end-of-pipe environmental policy towards integrated waste and emission prevention suggests an integrated chain approach to the interaction between OR and EM. Our paper is therefore structured accordingly. We illustrate this shift in policy within the context of both the supply chain and the environmental chain (Figure 2.3) and point out opportunities for OR.

Figure 1 about here

The *supply chain* contains the extraction of raw materials (e.g. agriculture, refinery), manufacturing, distribution and use of goods. Waste, generated in each component of the supply chain, is collected at the end of the chain. In general, changes within the supply chain are necessary to reduce the amount of waste and emissions, and the use of non-renewable resources. In sections 3 and 4, we explore the incorporation of environmental issues when analyzing supply chains. We structure the discussion around a hypothetical shift from an effect-directed approach towards waste prevention at the source, and the corresponding development of OR as a tool in green supply chain modelling.

The supply chain causes emissions in the *environmental chain*. The emissions and waste are transported and transformed and result in water, air and soil pollution with damaging effects to the environment. In addition, the supply chain's need for resources extracts non-renewable and scarce resources from and places a burden on the environmental chain. In sections 5 and 6, we focus on the development of OR as a tool for analyzing and solving environmental problems on a large scale. The discussion deals again with a shift from local end-of-pipe policies towards an integral approach in order to prevent environmental problems.

3 Green supply chain management

During each step in the supply chain, from the extraction of raw materials to processing steps, consumption and then waste treatment, emissions take place that can be a threat to people, plants, animals and ecosystems. New decisions are necessary to decrease emissions and waste flows. Legal requirements and changing consumer preferences increasingly make suppliers and manufacturers responsible for their products, even beyond their sale and delivery. To comply with these new regulations, producers have to apply cradle-to-grave product management covering the entire supply chain. Figure 3 presents potential environmental actions in a supply chain in more detail.

Figure 2 about here

The first actions, quite easy to apply, have been effect-directed (end-of-pipe) such as *waste* *treatment*. Somewhat more integrated are waste-directed and emission-directed adaptations in technology such as *reuse of materials and packaging* and *recovery of products*. The most integrated approach is source-directed and deals with *adaptation of raw materials*, *product redesign* and *process changes*.

Barry *et al.* (1993) introduced a five-stage outline for analyzing environmental issues throughout the product life-cycle. This outline is used here to discuss the potential environmental actions in Figure 3 in more detail. First, the use of fewer raw materials is discussed. This is followed by a discussion of the manufacturing stage covering process and product changes, distribution issues (less transport, redesign of locations and reverse logistics), the use of products, and finally, the treatment of waste.

Raw materials

Considering raw materials, green objectives may be to minimize the use of materials whose acquisition is environmentally damaging and to maximize the use of recycled materials and renewable resources. In addition, preference can be given to suppliers which operate in an environmentally responsible manner. General Motors, for example, has embarked on an ambitious program in material acquisition. Its WE CARE (Waste Elimination and Cost Awareness Reward Everyone) program involves cooperation with suppliers and includes specific measures to reduce inbound packaging materials, encourage their reuse and increase their recycling ability (Barry *et al.*, 1993).

Manufacturing

In manufacturing, both process and product design can be improved. In process design, the goals are to reduce waste, minimize pollution, use resources efficiently and find substitutes for hazardous materials. In product design, the purpose is to design not only for cost-effective assembly but also for disassembly and recyclability. Europe's automobile manufacturers and their suppliers are considering ways to increase the use of recycled parts. BMW and Volkswagen, for example, have set up pilot plants to examine reusability of current models and to develop design requirements for new models (Kleiner, 1991).

Distribution

Reverse distribution planning is necessary for collecting packaging and used products. In Germany, consumers have the legal right to return product packaging to retailers for recycling and reuse (Töpfer Law, '91). As a reaction, retailers developed the Duales System Deutschland (DSD). This dual system collects used packaging and sorts it by type of material. These materials are then transported to industries that have a license to make the materials valuable (Cairncross, 1992).

Use

Efficient use means minimizing energy or other resources consumed by the product, increasing the product's durability and lifespan, and minimizing the pollution the product emits during use. Consumers should also be provided with instructions for using the product efficiently, with a minimal impact on the environment. The Dutch electricity firms' 'efficient light bulb' action includes humoristic ads and television shows to change consumer behaviour (NEPP2, 1993).

Disposal

Infrastructural measures are necessary to collect and sort waste. In addition, hazardous materials should be collected safely. According to the Office of Technology Assessment (USA), American industry generates approximately 250-275 million metric tonnes of industrial chemical wastes annually. Most of the waste is dumped in landfills and could be quite hazardous (Anandalingam and Westfall, 1988).

The production-distribution-consumption process is a classic source of well-known Operational Research applications such as production planning and scheduling, network optimization and routing, inventory control, etc. These applications can be scrutinized to see how environmental issues can be effectively integrated and how this integration influences model structure and solution methods.

4 Integration of environmental issues in supply chain modelling

In order to classify the literature on green supply chain modelling, we structure the discussion around the shift from effect-directed environmental policy towards integrated waste prevention as mentioned in section 2. As a first phase in the integration of environmental issues in supply chain modelling, the end-of-pipe approach to *waste management* is discussed in section 4.1. In this phase, only distribution and disposal will be subject to changes. In an intermediate phase we consider all environmental issues concerning recovery management of used products (section 4.2). Here, manufacturing is also subject to changes due to the supply of used products. Finally, we discuss the source-directed approach which encompasses the complete supply chain (section 4.3).

4.1 Waste management

Optimization approaches with respect to waste treatment focus on two problems: *(i)* locating sites for the storage of (hazardous) waste and *(ii)* transporting waste to the chosen destination in the safest possible way. These problems have appeared in the OR literature for quite a long time. As early as 1977, Böttcher and Rembold (1977) studied the optimal location of facilities in a regional system of solid-waste and waste-water disposals.

We classify the literature on waste treatment into three groups: *(i)* papers dealing with routing and scheduling, *(ii)* papers dealing with location and *(iii)* papers dealing with both location and routing. The state-of-the-art article by List *et al.* (1991) surveys papers spanning risk analysis, routing and scheduling, and facility location. For the purpose of this review, it is sufficient to highlight some issues.

4.1.1 Routing of hazardous waste

For hazardous wastes, the routing problem is of the 'many to few' type, because there are a limited number of treatment and disposal sites. Batta and Chiu (1988) suggested two single objective formulations for hazardous waste routing. In both formulations, the criterion includes the size of the population potentially impacted by an accidental release of hazardous waste. The authors also mention the difference in risk between network nodes and network links by assigning penalties to nodes and considering different accident probabilities for different links in the network. Unfortunately, single objective models fail to capture the trade-off between transportation risk and transportation costs. Therefore, multi-objective models have been developed using e.g. bi-criterion methods or goal programming. These algorithms focus on finding a set of non-dominated routes explicitly representing the available trade-offs between criteria (List and Turnquist, 1994).

4.1.2 Locations for waste disposal

Most location problems attempt to minimize some distance function. However, in the case of waste disposal the (un)desirability of a specific site often has a higher priority than costs (Not-In-My-Back-Yard-syndrome). Consequently, such facilities tend to be located near the outskirts of cities with maximum distance to people. Erkut and Neuman (1989) give a review of single criterion undesirable facility location. Again, multiple criteria are almost inevitable: potential sites are selected using criteria such as safety, size, distances, investment costs and operating costs. A recommended and often used method to select sites is multiple criteria analysis. Vuk *et al.* (1991) apply the PROMETHEE method to select the location for the disposal of communal waste in Slovenia. Anandalingam and Westfall (1988) use multi-attribute utility theory to select waste disposal alternatives.

4.1.3 Location and routing of waste

The disposal of hazardous waste at sites remote from its production requires shipment of waste across a transportation network. The location and routing problem becomes one of choosing where to open disposal sites, how to assign sources to disposal sites and how to route the waste flows from each source to its assigned destination.

If the only objective is to minimize cost, the problem can be modeled as a simple plant location model. Revelle *et al.* (1991) combine a shortest path algorithm with a zero-one location program and the multi-objective weighing method to solve the two-criteria problem of minimizing transportation costs and perceived risk.

Bloemhof-Ruwaard *et al.* (1992) consider the problem of how to design an efficient (minimum cost) distribution structure which simultaneously takes into account the location of plants and disposal sites, the coordination of the flow of goods between plants and customers and the flow of waste between plants and disposal sites. Risk related to the transport of waste is not covered in this paper.

In summary, these end-of-pipe approaches to waste management are mostly concerned with managing risk (accidents during transport, exposure at sites) and with the strategic aspect of selecting appropriate locations. For OR modelling this often leads to multiple objective, analytic models, typically closely related to traditional routing and location models which have been studied for a long time.

In all these models environmental concerns only affect distribution and waste disposal. Below, we introduce the recovery of used products which involves a much more integrated approach to green logistics since the return flows affect production planning and scheduling decisions.

4.2 Product Recovery Management

Traditionally, manufacturers did not feel responsible for their products after consumer use. The bulk of used products were dumped or incinerated with considerable damage to the environment. Today, consumers and authorities expect manufacturers to reduce the waste generated by their products.

Product recovery management is defined as the management of all used and discarded products, components, and materials for which a manufacturing company is legally, contractually, or otherwise responsible (Thierry *et al.*, 1993). Product recovery management offers several options to handle products after consumer use: repair/reuse, refurbishing, remanufacturing, cannibalization and recycling. Each of the options involves collection, reprocessing and redistribution of the used products. The main difference is in the degree of reprocessing. Figure 4.2 demonstrates the degree of required disassembly. The choice of the 'best' product recovery option in a practical case depends on environmental regulations, technological capabilities, costs, etc.

Figure 3 about here

Uncertainties in product recovery problems occur with respect to time, quality and quantity of returned products (Flapper, 1993). The supply of used products may be highly irregular as it is influenced by e.g. alternative uses, loss of products (e.g. car accidents) and the general economic situation. Forecasting the quantity and quality of used products will therefore be hard. The varying quality of the returned product requires screening and sorting, which complicates the modelling and analysis of product recovery problems. However, these issues may have a tremendous effect on production planning and inventory control and represent a challenging research agenda.

As an illustration of such research, we discuss some examples of how classical models can be adjusted for remanufacturing, one of the options of recovery management. Salomon *et al.* (1994) reviewed the literature on production planning and inventory control models with remanufacturing. For example, consider a *periodic review* model with return flows of used products which can either be disposed of or remanufactured to an 'as new' condition. At the beginning of each planning period t, decisions are taken with respect to *(i)* the number of products disposed of in period t, *(ii)* the reorder quantity in period t, and *(iii)* the number of products remanufactured in period t. The objective is to minimize total expected costs over the entire planning horizon. Kelle and Silver (1989) formulate the problem as a chance-constrained integer program. They suggest an approximation procedure which contains a transformation to the well-known Wagner-Whitin model and they solve this transformation using a dynamic programming algorithm. *Continuous review* models have also been used for remanufacturing problems. Muckstadt and Isaac (1981) present a control strategy with respect to order points and order quantities where returned products will be remanufactured. An approximation procedure, based on Markov-chain models, determines values for the order points and order quantities. Heyman (1977) analyses a model where incoming returnables are disposed of whenever the inventory position reaches a predefined disposal level. Recently, models have been formulated in which remanufacturing and disposal decisions are considered simultaneously (van der Laan *et al.*, 1994).

4.3 Source-directed product management

Examples in this section deal with environmental impacts associated with a product over its entire life cycle. They differ from the above examples which focus solely on waste disposal and product recovery.

For some years now, people have been developing techniques for assessing environmental impacts of products and processes 'from cradle to grave'. Such techniques require a lot of environmental data. One of the most promising techniques is *Life Cycle Assessment (LCA)* defined as a process to evaluate the environmental burdens associated with a product, process or activity by identifying and quantifying energy and materials used and wastes released to the environment (SETAC, 1993, p. 3). The knowledge obtained from LCA studies is a valuable input to green manufacturing models.

Pirila *et al.* (1994) studied emission oriented production planning in the Finnish pulp and paper industry. Their production planning model is a large multiple period linear program. Integration of environmental impacts within this model leads to alternative strategies, including process choices, recovery of waste products, etc.

Haasis (1994) studied production planning and control of less emitting production systems. The methodologies used are based on dynamic programming, priority based heuristics and neural networks (machine learning).

Bloemhof-Ruwaard *et al.* (1994) studied product mix problems at a large multinational food company. The products in this case study are spreads, usually consisting of a mix of several fats. LCA was used to assess the environmental impacts of these fats. These impacts were then converted into a single environmental index for each fat using the Analytic Hierarchy Process (AHP) (Saaty, 1980). This environmental index was used in the product mix models. Two types of linear programming product mix models were considered: one with a classical cost minimization objective and a constraint on environmental impact, and one with an environmental impact minimization objective and a constraint on costs. Results indicate that the environmental impact could be improved considerably at the expense of only a slight cost increase of the product mix.

At this point, two issues remain to be resolved. First, LCA studies are still pretty complex and expensive. Second, the LCA data involve all sorts of environmental effects which should somehow be combined into a single environmental index in order to be useful in an OR decision model. The practical link between LCA and OR models provides a challenging research issue: how to design LCA studies that quickly yield relevant environmental impacts and how to combine these impacts meaningfully into inputs for OR models.

5 OR tools in environmental policy

In the previous sections, the focus was on environmental actions within the supply chain with the objective to control the amount of waste and the use of non-renewable inputs. In the next two sections, the focus will be on the damaging effects that inputs and outputs of the supply chain can have on the environment.

Once pollutants have left the supply chain, they are emitted to air or water, or appear as waste on or in soil. In each of these environmental compartments chemical transformations take place, e.g. the formation of sulfuric acid from SO_2 in air, causing acid rain. Next, the pollutants are transported through media like air, surface water and groundwater. Most air pollutants are then deposited on soil or water and cause detrimental effects to the environment (e.g. nitrates formed in the air from NO_x cause eutrophication of surface water). Finally, the deposited pollutants lead to reduction and damage of the primary resources. From this description, it will be clear that the environmental problem can also be described as a chain (see Figure 1).

In recent years, environmental policy has shown some major shifts. First, it changed its focus from compartments (air, water, soil) to issues (acid rain, climate change, etc.). For example, in the Netherlands the following key problems are now the focus of environmental policy (see NEPP2, 1994):

- Change of climate (global)
- Depletion of ozone layer (global)
- Smog (continental)
- Acidification (continental)
- Eutrophication (fluvial)
- Dispersion of toxic substances (regional)
- Drying out of soils (regional)
- Disposal of solid waste (local)
- Disturbance of the environment by noise or odour (local)

Second, traditional end-of-pipe abatement policies are gradually being replaced by an integrated approach. Table 1 shows the evolution in Dutch environmental policy according to Cramer (1991, p. 87).

Table 1: Development of Dutch environmental policy (Cramer, 1991)

Period	Characteristics
Seventies:	Approach to 'clear away' (end-of-pipe). Emphasis is on local problems, especially site decontamination of soil pollution;
Eighties:	Policy evolves towards prevention. Effort is on pollution control of regional problems (mainly water pollution);
Nineties:	The ideas of sustainable management and integral chain management develop; global orientation of policy. The intention is to use an integrated approach that can cope with the transboundary issues of air pollution.

In Figure 5, the environmental chain shows the pressure of economic activities on the environment and society's response in terms of measures. These measures include traditional end-of-pipe techniques (e.g. flue gas desulfurization), new low waste technologies (e.g. low NO_x burners), decrease of production (e.g. energy conservation), mitigation (e.g. liming of acidified lakes) and adaptation (e.g. acid rain resistant tree species). A major challenge for environmental policy both at the local and the national level is to make an optimal selection of measures from a large set of options. It is here that OR can play a useful role (see section 6). In order to enhance understanding of the (links in the) environmental chain, the different components of the chain are briefly discussed below.

Figure 4 about here

Production, consumption

Broadly speaking, the three main sources of waste are agricultural waste, industrial waste and domestic refuse (Kharbanda and Stallworthy, 1990). For agricultural waste, the major environmental problems are eutrophication, acidification and use of pesticides. Industrial waste poses by far the biggest problem because of its nature and the vast variety of materials that have to be handled. Much industrial waste consists of hazardous chemicals, often highly toxic, that can damage the health of human being and the quality of ecosystems. Domestic waste contains not only reusable materials such as glass, paper and food waste, but also an ever-increasing amount of hazardous waste such as mercury from batteries and PCBs in old TV sets. Consumers often claim to take into account the environment while shopping. However, domestic waste generation seems to be unaffected until now.

Waste and emissions

The location of disposal sites and incinerators has a large influence on the possible effects of waste disposal. The problem of locating these sites requires difficult pollution-cost tradeoffs. Emissions to air and water are in most cases treated via end-of-pipe techniques. For some air pollutants international agreements on reduction of emissions have been reached in Europe (SO_2, NO_x, VOC) and North America.

Dispersion

The environmental effects of emissions and waste disposal depend largely on the distribution and movement of damaging components. The chemical behaviour of air pollutants varies greatly, while meteorological conditions determine the dispersion. In order to detect contamination and air pollution, remote geophysical techniques are increasingly being used to monitor the environment (air or surface).

Effects

Environmental effects of emissions and waste disposal have been found in many species and ecosystems (e.g. fish damage due to acid rain, reduced crop growth due to enhanced ozone levels). Further, at very high levels of concentration some pollutants cause human health effects. Although reduction of the pollutant sources is most effective, in some cases actions are taken to mitigate the effects (e.g. liming of acidified lakes in Scandinavia). In recent years the effects of emissions on the environment have been studied in a new way. Rather than focusing on effects of a single pollutant on a single species, indicators of effects have been used. In 1986 the concept of *critical loads* for acidification has been introduced as the highest deposition of a compound that will not lead to long-term harmful effects on ecosystems (Nilsson, 1986). In studies on climate change a similar concept was proposed by Swart (1994). This change in focus is in line with the trend toward issue-driven integrated environmental policy which was signalled before in Table 1.

Resources

Some, certainly not all, pollutants affect the resources needed for production and consumption. Examples are the reduction of forest growth and fish populations. In cases where it would take a very long time to recover the quality of the environment adaptive measures have been taken. An example is plantation of acid rain resistant tree species in the so-called Black Triangle in Europe (Germany, Poland and the Czech Republic). Another example of adaptation can be found in several studies on climate change (e.g. change in agricultural practices, see Parry *et al.*, 1988).

In the various parts of the environmental chain applications of OR can be found, some dating back to the 1980s. With the change in environmental policy from single pollutant/single effect policies to integrated policies on issues (climate, acid rain and the like) the demand for OR is growing. This is caused by both the larger number of options available to reduce environmental effects, and the increased complexity of systems and models. In the next section, a selection of OR work for the environmental chain is presented.

6 Integration of Operational Research in Environmental Management

In this section, some examples of the use of Operational Research for solving environmental problems or for environmental policy making are presented. The use of OR techniques in environmental problem solving is also described in a 'guided tour' by Debets and Van Wassenhove (1992), covering water and air pollution and waste (chemical, nuclear).

The scale of environmental problems has shifted over the last few decades from the local and regional level to a continental (acid rain) and global (climate change) level. An integral approach to environmental problems has become necessary in order to arrive at good preventive abatement measures.

As in section 4, we classify the examples according to the shift from local end-of-pipe policies towards integrated policies in order to prevent environmental problems. Three categories are described: local problems that deal with soil pollution and disturbances, emission control on regional level and the rather recent integrated approach dealing with global problems.

6.1 Local orientation

Part of the environmental policy of a central government of a country concerns the decontamination of polluted soils. The source of this pollution is usually a *local* point e.g. a landfill site, a gas station or an industrial district. For each case of soil pollution, several clearance variants are known. Usually, the monitoring of decontamination projects will be decentralized. Operational Research can play a role in allocating a central budget to the local authorities so as to obtain the 'best' overall environmental effect, as described in Corbett *et al.* (1993). This case can be generalized to any problem to evaluate various budget allocation policies to combat some kind of environmental problem (see also Hordijk, 1988). Corbett *et al.* (1993) emphasize that the issue is not so much that the environmental effect measure be precise but rather that all regions agree on a reasonably accurate and easy-to-determine environmental measurement system for budget allocation purposes. The objective is to maximize the beneficial environmental effects of the selected projects, subject to *(i)* budget constraints for each region and the overall budget, *(ii)* storage limitations on the waste generated in each region, and *(iii)* labour supply conditions in each region. The resulting mixed integer programming model is too large to solve optimally. Therefore, the authors propose a two-step heuristic procedure:

- In the first step, local authorities specify the maximum environmental effect they expect to achieve for different levels of budget allocated to them.
- In the second step, the central authority determines which budget allocation leads to the highest total environmental effect.

Technically, the information from the first step consists of a matrix containing the attainable environmental effects for each area and each budget allocation. This matrix can be transformed into an acyclic graph. The objective of the second step is then to find a path through the graph maximizing total cumulative environmental effect. This can be done using a dynamic programming recursion formula. The corresponding budget allocation can then be derived by backtracking via the optimal path.

This budget allocation approach can also be used for reduction of noise disturbances. Traditionally, the central government typically controlled the measures for noise disturbance. Recently, policy makers advised decentralisation in order to give regions their own budgets and responsibility to reduce the disturbances (Vellekoop, 1994). These budget allocation problems illustrate the usefulness of decomposition, a common approach in OR.

6.2 Regional orientation

We discuss three categories of mathematical models that deal with regional problems: *(i)* lake eutrophication models, *(ii)* non-point sediment pollution control models, and *(iii)* detection models.

6.2.1 Eutrophication

Eutrophication, the increased presence of nutrients, and its consequences has been one of the most serious lake water quality problems over the last decades. One of the major features of eutrophication is that although the consequences become manifest within the lake, the causes (increased use of nutrients) and most of the possible control measures have their origin in the region.

Models developed with the aim of analyzing eutrophication can be classified into two groups:

- dynamic simulation models to describe the phenomena (e.g. Orlob, 1983)
- optimization models with the objective to determine the 'optimal' combination of alternative control measures (e.g. Loucks, 1981).

Somlyódy and Wets (1988) develop a framework for optimal design strategies for controlling water quality of eutrophic lakes. They combine descriptive simulation models and management optimization models. The first step of their method is to decompose the complex system into smaller, tractable units leading to a hierarchy of simulation models. This step is followed by aggregation, to preserve and integrate only the issues that are essential for the higher level of hierarchy. Only aggregate models are incorporated in an optimization model at the highest level of the hierarchy. This approach can be very useful in coping with complexity.

6.2.2 Nonpoint source pollution

Sediment deposition affects water quality. A major source of sediment deposition is soil erosion from cropland. This is called a nonpoint source of pollution because it is difficult to track discharges back to a specific source. Public officials must determine whether to implement uniform policies, or measures that implement abatement measures selectively. Bouzaher *et al.* (1990) outline a model that can assist controlling agencies by revealing costs and pollution loads due to alternative selective and nonselective policies and can help local and regional environmental quality officers identify how and where selective actions can be taken in the most cost-effective manner. The controlling agency's problem can be viewed as a 0-1 knapsack problem with additional generalized upperboundary constraints. It has been solved using dynamic programming.

6.2.3 Detection

OR has been used to optimize monitoring networks in order to maximize the probability of detection in the face of uncertainty. Meyer and Brill (1988) coupled a simulation model of contaminant transport and a facility location model to generate optimal locations for monitoring wells. Modak and Lohani (1985) studied the problem of optimal number and configuration of ambient air quality monitors given an acceptable level of uncertainty. Their approach is based on location models using spatial correlation analysis.

6.3 Global orientation

The primary reason for the shift from local and regional problems toward continental and global problems is the recognition of the fact that emission in one country may affect environmental quality in other countries. In this paragraph we discuss a group of models dealing with acidification (section 6.3.1) and a model dealing with the greenhouse effect (section 6.3.2).

6.3.1 Acidification

Acid rain is not a new phenomenon. According to Stam *et al.* (1992), over 300 years ago an English nobleman already suggested the theory that sulphur originating from smoke by burning coal turns silver black and destroys iron and stone. Since the first World Conference on Environment and Human Development (Stockholm, 1972), efforts have intensified in order to avoid the negative impacts of sulphur oxide and nitrogen oxide pollution, especially at the local and regional level.

As early as 1980, Lesuis *et al.* (1980) extended a classical economic Input-Output model for the Netherlands with energy and environmental sectors. The thus enlarged model has been put into an LP framework and used to explore various scenarios for the reduction of emissions of SO_2 and their effects on the Dutch national economy. But it is only in recent years that various mathematical models have been developed to cover the acidification process from the sources of emission to the impacts on the environment. These models emphasize the transboundary aspects of air pollution and embody optimization, simulation and often a combination of both. A review is given by Ellis (1988).

One of the integrated assessment models is the RAINS (Regional Acidification INformation and Simulation) model (Alcamo *et al.*, 1990, Hordijk, 1988). Characteristic for these models is that they are based on a set of submodels describing pollution generation and control, atmospheric transport and deposition, and environmental impacts (i.e. the processes in the environmental chain of figure 5). RAINS (or its submodels) can be used as input to procedures for optimizing the reduction of emissions. These procedures can be based on linear programming with single or multiple objectives (Ellis, 1988), nonlinear multiple criteria modelling (Stam *et al.*, 1992) or stochastic programming (Batterman and Amann, 1991). An example of the use of RAINS in its LP mode is presented by Amann *et al.* (1991). In this study the authors use linear optimization to arrive at a cost optimal solution for a Europe wide reduction of the emission of SO_2. Starting from maps of current deposition and critical loads for acid rain in Europe, a least cost solution is found to reduce the gap between deposition and critical loads. In recent international discussions on acid rain the results of optimization runs with the RAINS model have served as basis for the negotiations. The final Protocol on the reduction of SO_2 signed by 27 nations in June 1994 is largely based on one of these runs.

6.3.2 Climate Change

A rising amount of CO_2 in the earth's atmosphere can lead to an increasing absorption of heat radiation energy and consequently to an increase in temperature and a shift in wind and rainfall patterns. This is commonly referred to as the enhanced *greenhouse* effect. Not only carbon dioxide, but also N_2O, CH_4, H_2S and aerosols contribute to the global warming effect. The temperature increase could cause melting of the ice caps and consequently a rise in sea levels. Eventually, ecosystems will be threatened.

One of the models built to gain insight into the greenhouse problem is IMAGE, an acronym for Integrated Model for the Assessment of the Greenhouse Effect (Alcamo, 1994). The greenhouse problem is modelled by means of dynamic simulation based on non-stationary Markov chains.

IMAGE can be used as input for optimization routines for developing and improving climate change response strategies (Janssen, 1993). In order to cope with the narrowness of pure optimization and the slowness of a large simulation model, a meta version of IMAGE was combined with a local search optimization of response strategies for CO_2 reduction.

7 Concluding remarks

The growing attention for environmental issues within the field of Operational Research is in concordance with some trends in society:

- the shift from corrective policies towards prevention (internalization);
- the expanding scope of environmental policy both in content and in area (scope).

These trends cause a natural opportunity for the interaction between OR and EM. However, issues like complexity, measurability and the social character of environmental problems may impose roadblocks to this interaction.

Our examples from literature exploring the interaction between Operational Research and Environmental Management were classified using a framework consisting of two approaches:

- the supply chain approach: integration of environmental issues in supply chain modelling
- the environmental chain approach: integration of Operational Research tools in Environmental Management.

Supply Chain

Within the supply chain, environmental actions can be taken in each link from raw materials to waste disposal. To classify examples of the incorporation of environmental issues, the shift from end-of-pipe correction to source-directed prevention was used.

Examples of end-of-pipe waste management modelling have appeared in the OR literature for quite a long time. These models are mostly characterized by the strategic aspect of choosing locations for disposal units. The models have a close relation with traditional models. A new aspect in these models is the description of risk.

Product recovery management can have a large impact on the supply chain. It affects production planning, inventory control and distribution. Integration with traditional planning and control models (e.g. MRP) is less obvious due to the uncertainties in time, quality and quantity of the supply of used products.

There are at present very few attempts at using a 'cradle to grave' modelling approach. Methods to assess environmental impact of products and processes appear to be essential to these models. The combination of life cycle assessment studies with OR models and techniques is a wide-open area of research.

Environmental Chain

Within the environmental chain, the production and consumption element is the cause of pollution. Other elements in the chain are the atmospheric processes and the environmental impact on soil, water, air and ecosystems. Within each of these elements, OR modelling has turned out to be useful.

The scale of environmental policy to control pollution has shifted from the local and regional level to a continental and global level. This shift has two consequences which have both influenced the use of OR. The first consequence is a more integrated approach to environmental policy and management, in which a manifold of abatement strategies is available. To make an optimal selection between these strategies, OR tools are increasingly being used. A second consequence is that models describing these larger systems are much more complex. This can be seen as another cause for the increased demand for tools from OR.

Until recently, local problems like polluted sites and noise disturbance were typically handled at a central level. Nowadays, policy tends towards decentralization and allocation of budgets to local authorities. This development can be supported using the well-tested decomposition approach of Operations Research.

Models for regional problems like eutrophication have to overcome the typical complexity of these problems. An approach combining simulation and optimization has proved to be quite successful, especially when it is possible to decompose the complex system into smaller tractable units.

For global problems, we conclude that an integrated assessment model is the only way to cover the complex system of causes, emissions, transportation, effects and control policies. Optimization appears as a submodule of the larger modelling system. The added value of OR consists of the evaluation (efficiency) and improvement (effectiveness) of emission and waste reduction scenarios.

General conclusions

In general, we conclude that the first phase in the shift from corrective policy towards preventive policy generates a rather straightforward use of all kinds of Operations Research applications both in the supply chain approach and in the environmental chain approach.

The intermediate phase in this shift probably describes the actual state-of-the-art of exploring the interaction between OR and EM. More complicated and adapted models (and methods) are necessary to cope with recovery management in the supply chain approach and with regional problems in the environmental chain approach.

The final stage in the shift will probably be reached in the near future. OR has to integrate with related sciences to be able to use tools like life cycle assessment, economic input-output modelling and systems analysis. Without this natural extension, it will be hard to motivate that OR is a suitable science to cope with 'cradle to grave' approaches in supply chain management and with the global problems in the environmental chain.

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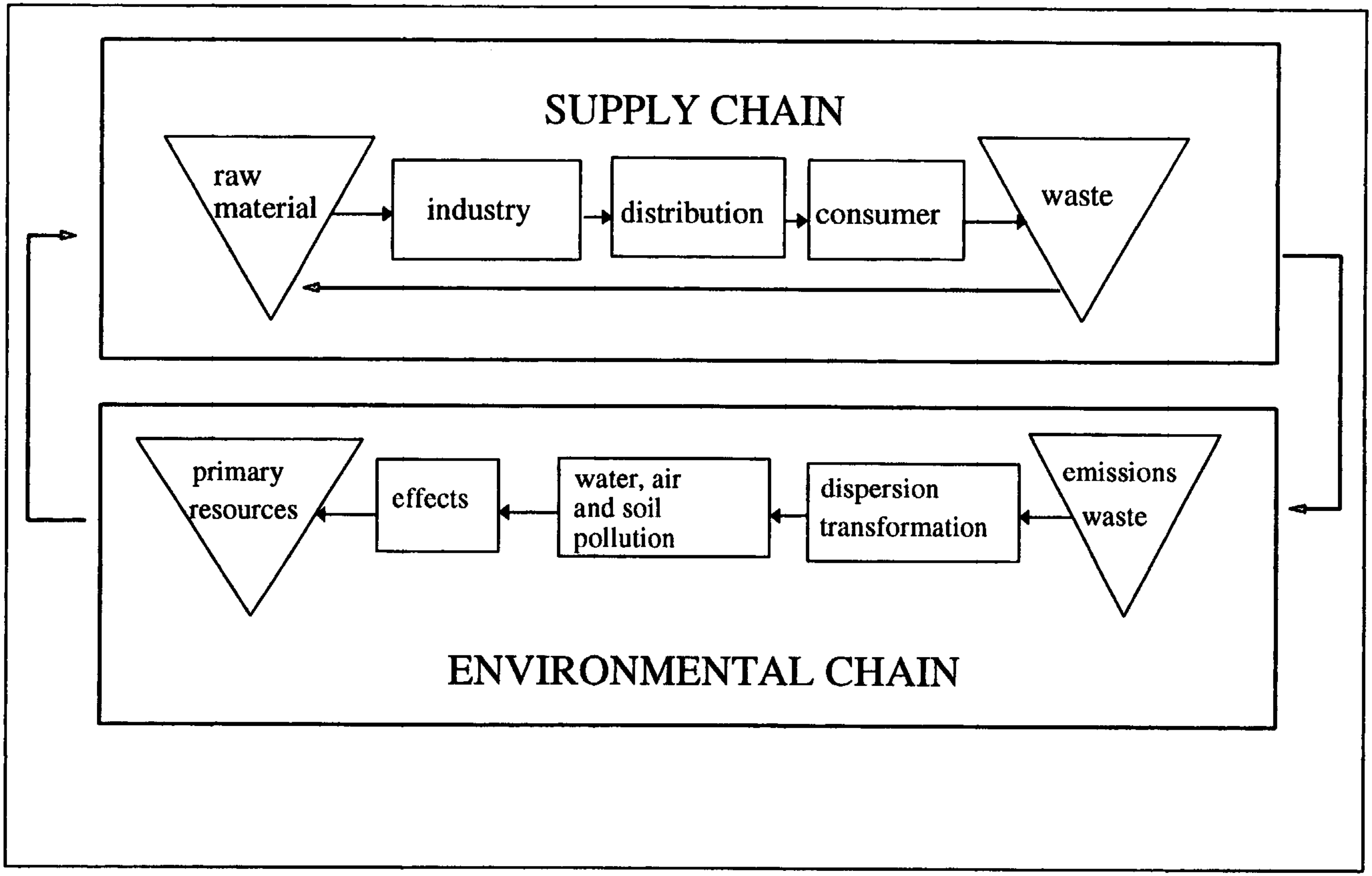

Figure 1: Framework

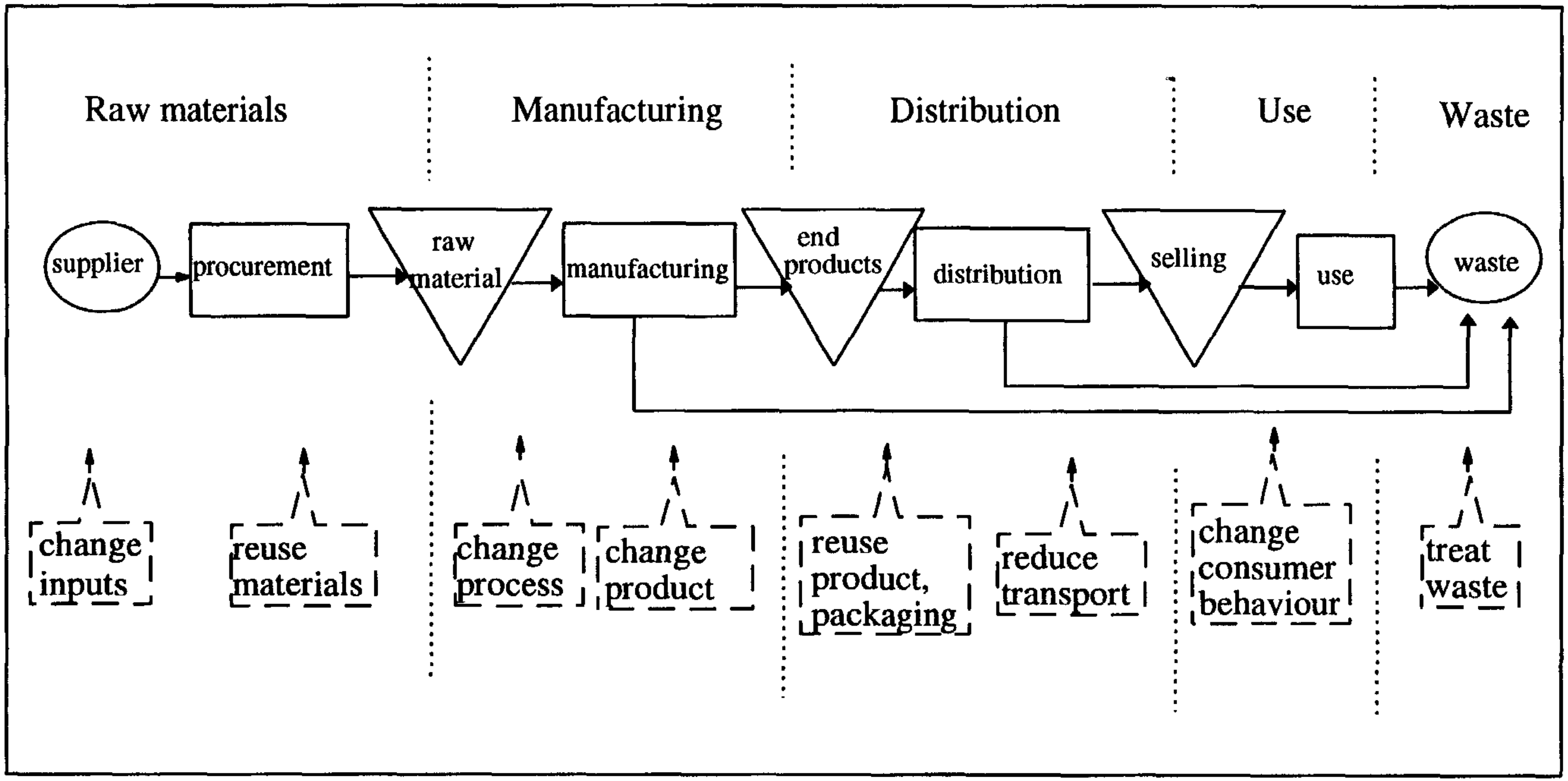

Figure 2: Green supply chain

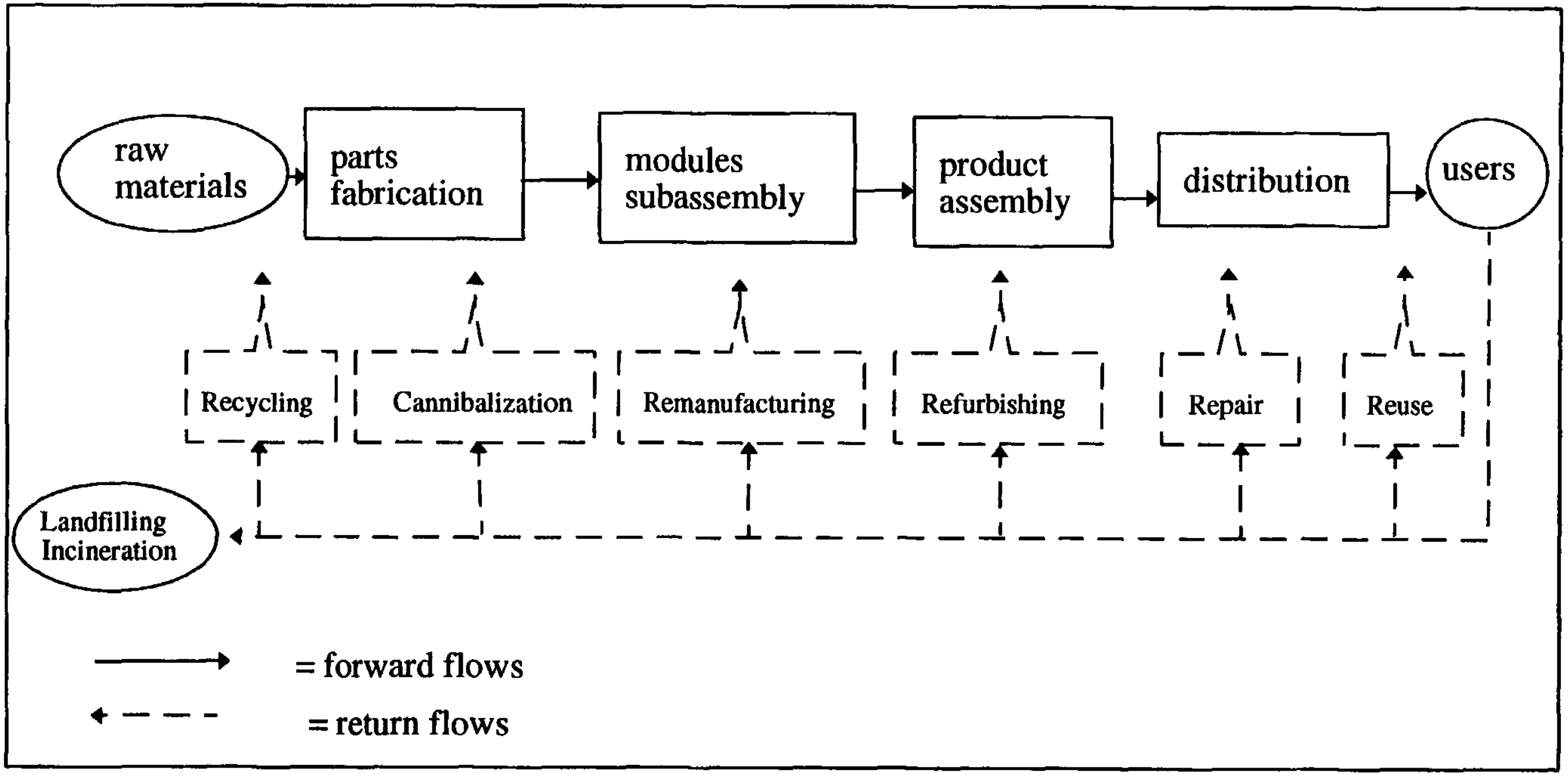

Figure 3: Product recovery management (Thierry et al., 1993)

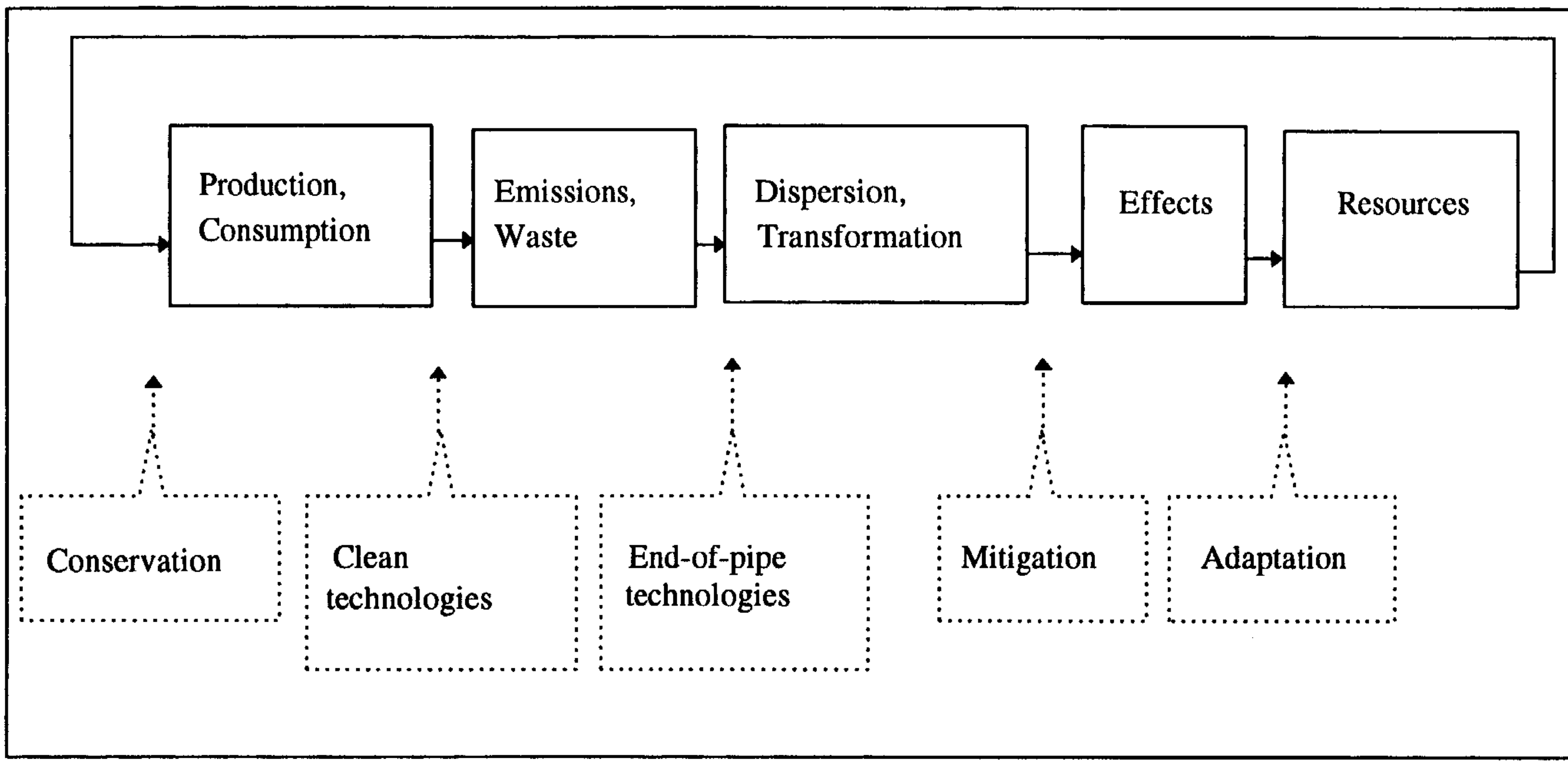

Figure 4: Environmental chain