



Optimal Recycling System Design: With an Application to Sophisticated Packaging Tools

A.J.D. LAMBERT*, H.M. BOELAARTS and M.A.M. SPLINTER

*Department of Technology Management, Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands; *Author for correspondence (e-mail: a.j.d.lambert@tm.tue.nl)*

Accepted 3 September 2003

Abstract. This paper deals with the mathematical analysis of product-process chains, aimed at the proper design of recycling systems. A modelling method is presented that can be applied to various chains. It is applied to a case in which a producer of sophisticated packaging tools requires insight into the many options of the design of a reuse/recycling chain. This is due to expectations for the near future that are related to extended product responsibility and the enforcement of recycling. Depending on the weight of different criteria and the choice of systems boundaries, optimal solutions can be selected. It turns out that the modelling method acts as a useful decision tool. A major bottleneck is the availability of data from suppliers and customers.

Key words: decision support, life cycle chain, mathematical programming, recycling, reuse

1. Introduction

As a consequence of growing environmental concern, extended product responsibility (EPR) and product stewardship are frequently advocated as a tool for the reduction of the amount of waste that originates from discarded products, see e.g. (Hart 1997; Veroutis et al. 1997). EPR refers to a policy that is designed for integrating the environmental costs throughout the product lifecycle into the way that goods are produced and distributed. The design of appropriate take-back schemes is crucial to EPR. This concept, which was initially introduced by the chemical industry, is presently incorporated in the legislation of about 40 industrialised countries (Wilck 1997) and has been adopted by a score of industrial branches, particularly those that are involved in products for packaging. EPR and product stewardship typically exceed the system boundaries of an individual company and also include the domain of suppliers and customers. Frequently, the customer's customers are involved too and the processes even further downstream are relevant too. This makes these policies embrace a considerable part of the product chain. Consequently, a lot of enterprises face the problem of the design of a strategy to implement product stewardship, which results in a conscious trade-off between environmental advantages and economic benefits. This goes beyond accidental changes in process and product design, or ad-hoc modifications in logistics, as

it encompasses a combination of measures both within the company and in close co-operation with the other partners in the chain. These measures can result in essential modifications in, and additions to, a considerable part of the product's life-cycle. Within this philosophy, reuse and recycling plays a crucial role. Therefore, these subjects are relevant to the many companies in the sequence of processes that are applied to the product during its lifecycle, which is usually called the product chain. In the literature, many ways of describing such a chain can be found. There are flow-oriented approaches that do not focus on the processes, material-product chains, etc.

A detailed design of an optimal reuse/recycling system is often impeded by the absence of satisfactory data on the chain. This results from the fact that usually a chain is considerably truncated. Moreover, appropriate exchange of data is frequently counteracted by an intense competition between the enterprises concerned. Fortunately, mathematical tools are available that can be applied to models of the chain that are on a rather high level of aggregation. These tools are useful for gaining insight into chain behaviour for the assessment of possible chain configurations, and for quantitative evaluation of their respective disadvantages and benefits, e.g. by sensitivity analysis. This provides a basis for a more detailed study and, eventually, a definite decision.

This paper describes a method of quantitative, static product-process chain modelling based on physical flows, being aimed at selection and optimisation of recycling configurations with respect to some definite criteria. Both the structure and the magnitude of the flows can be adapted to various objectives. This enables the selection of a set of near-optimal candidate solutions. The method is explained and, subsequently, applied to a case from practice, which illustrates its possibilities and restrictions. An essential feature of the method is that it includes the possibility for selecting subsystems within the product-process chain, which correspond to a definite real or virtual enterprise. In this way, companies can select the activities that are considered either for being internally carried out or for outsourcing.

In the literature, a number of quantitative studies on product chains are presented. These are mainly based on methods from operational research. Many of these studies are on a detailed level of aggregation, as they are focused on topics that are closely connected to reverse logistics, such as allocation of activities, inventory control, and production planning. Other detailed studies are on the level of process design, e.g. optimal disassembly sequence generation (e.g., Lambert 1999). Full chain analysis on a high level of aggregation is practised in methods such as the determination of Gross Energy Requirement (GER) (IFIAS 1973) and Life-Cycle Assessment (LCA) (Guinée et al. 1993a, b). The LCA-method, which is frequently used and internationally standardised, results in a set of values that indicates the environmental impact of a definite unit of a product, while considering its entire life cycle. As the method is principally confined to convergent chains, additional presuppositions should be added to include recycles (Tillman et al. 1994). In particular, system boundaries should be consciously defined in

such cases. Although LCA studies are basically a matter of inventory, also studies have been carried out that combine LCA with optimisation tools, particularly linear programming. In the paper of Azapagic et al. 1995, this has been applied to the chain of thermoplastic materials. This proved a valuable method. Recycling systems, however, were not incorporated in this study.

2. Systems Approach

In industrial ecology, one distinguishes between the ecosystem and a part of the physical world that, to some extent, is used by man (Graedel et al. 1995; Ayres et al. 1996). In studies with an emphasis on economy, this is often called the *economic system* or the *economy*. Although the materials and the energy flows within this system are surely controlled by economic rules, they are also subjected to the laws of physics, such as mass conservation. In this paper, the physical approach plays an important role. Therefore, the term *technosystem* is used throughout this study.

The boundary between the ecosystem and the technosystem is ambiguous to some extent. This can be seen by considering an agricultural field, an ore deposit, or a landfill. Somewhere, however, resource flows can be defined that are entering the technosystem, and waste flows that leave the technosystem. As a matter of fact, the technosystem can be decomposed into subsystems. The relations between subsystems are expressed in flows of material, energy, and information. Material and energy flows are physical flows and are expressed in physical units (kg/s, kW, etc). Economic quantities, such as money, are considered to be information. Subsystems are considered to be transformation processes. This is analogous to the modelling of the ecosystem in purely ecological studies. Exchange of physical flows between technosystem and ecosystem takes place by *extraction* and *discharge*.

The aim of the technosystem is meeting the need for services. To this purpose, physical products are required. These are created from extracted raw materials in *production* processes that increase the value of these materials by a transformation with respect to place, time, and quality. Subsequently, the products provide their services in a *consumption* process, from which they are rejected as discarded products. Finally, these are discharged. Consequently, the technosystem is not principally organised in closed cycles, but rather in a linear way. This is essentially different from the ecosystem, which virtually produces no waste because all matter that leaves the one system (organism, environmental compartment) will be used by the other. The *product-process chain* in the technosystem is depicted in Figure 1. The processes are represented by the rectangles, and the products by the arrows. Each of these processes needs additional materials and energy flows (utilities) and generates process waste, emissions, and residual energy. These are, however, not indicated here because this study is focused on product waste. For both environmental and economic reasons, discharge is preceded by waste processing. This is aimed at reducing the harmfulness of the waste. Examples of such processes are: separation, confinement, and neutralisation.

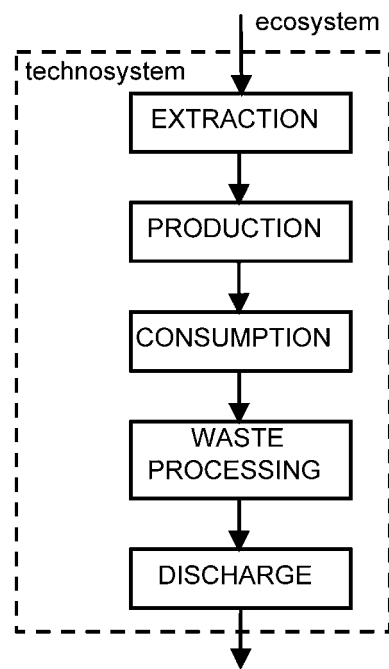


Figure 1. Aggregated linear product-process chain.

For reasons of resource conservation and waste reduction, it is desirable that the materials and the energy remain as long as possible within the technosystem in which they are used during a longer time, and more than once. By doing so, a definite amount of materials or energy can provide a maximum service to the users. Measures that are advocated for attaining this goal in the production and consumption phase are (Stahel 1994): Clean production techniques, enhancement of durability, product life extension by good operation, adequate maintenance, and repair. In the post-consumer phase, a hierarchy of measures including product remanufacturing, module or parts reuse, and materials recycling is recommended. Passing through a next phase in this sequence means a further decrease of the functionality of the original product.

This idea can be included in the model. Particularly for complex products, the typical structure of the production chain is a sequence that consists of materials production, parts production, and assembly. The first two phases correspond to the process industry and the manufacturing industry, respectively. Next to consumption, a more or less reverse sequence is completed, aimed at product remanufacturing, part reuse, and materials recycling. This reflects an idealised case, in which first the complete product is tested, if possible remanufactured, else considered for parts reuse, etc. In practice, these phases are often only partially passed through. A typical sequence in a reuse/recycle chain consists of the processes: disassembly, shredding, separation, and final treatment. Figure 2

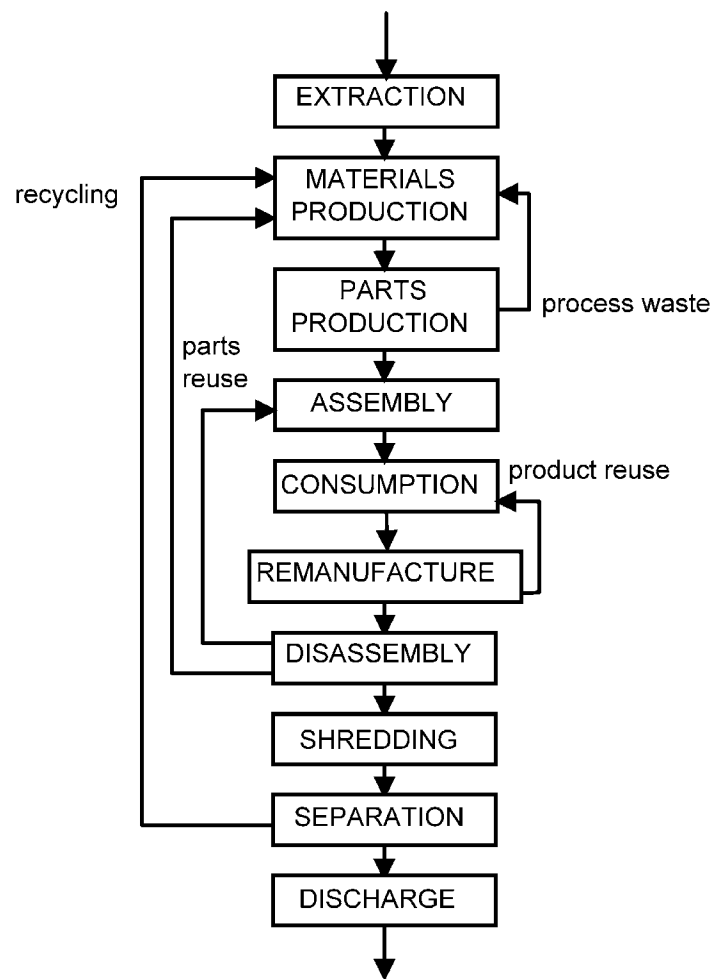


Figure 2. Product-process chain for complex products, including reuse and recycling.

indicates an idealised scheme of these processes, and the related principal material flows. Here, the flows of remanufactured products, parts, and materials are indicated. In practice, various departures from this scheme are possible. Moreover, in realistic cases such a chain is strongly interconnected with other parts of the technosystem by the exchange of products and materials. Descriptions of the recovery systems for complex products and the associated management problems can be found in Thierry et al. (1995), Krikke (1998), and Krikke et al. (1998).

3. The Modelling Method

Models for production systems including recycling are reviewed in Fleischmann et al. (1997), Carter et al. (1998), and Fleischmann et al. (2000). As these reviews

are mainly focused on reverse logistics, chain optimisation is only casually taken into account. In LCA (Guinée et al. 1993a, b), no optimisation is included and complex production chains including recycles are not supported. Recycling chain optimisation by mathematical programming has been carried through by Hoshino et al. (1995). Here, a dynamic optimisation model has been applied to a rather simple chain for discrete products, which is a two-source model and includes the reuse of parts. This model is principally logistically oriented with an emphasis on inventory control. Methods like this, however, do not optimise the complete chain, but rather optimise the proper operation of an already existing reuse or recycling system.

In this paper, a method is described that deals with the design problem of more complex recycling systems. This proceeds, however, at the cost of detailed information on the dynamic behaviour. Therefore, we restrict ourselves to static analysis. A strict application of the product-process chain concept is crucial here for properly determining the network structure of the model. A traditional example of static modelling of physical flows in production systems is that of crude oil refinery operation. Here, an optimisation takes place according to the strongly varying market conditions, such as crude oil supply and the demand of various products (kerosene, gasoline, etc.), which results in changing process performances and product revenues. Linear programming (LP) or related techniques are applied here. On the basis of LP, more extensive parts of a product chain, including recycling, can be modelled, as has been demonstrated by Starreveld et al. (1994), who applied this method to the plastics recycling system, in which the authors investigated the influence of a charge on landfill on the production chain. This model is based on the conventional refinery models, but it is extended with some materials recovery processes. Several other papers on product chain modelling have been published, such as a study on the pulp and paper chain (Bloemhof-Ruwaard et al. 1996), and one on general by-product flows (Bloemhof-Ruwaard et al. 1994). Here, the emphasis is on logistic aspects, such as transportation between and allocation of the production facilities. Other authors follow a service-oriented approach, the so-called material-product (M-P) chain orientation. As physically completely different products can satisfy a unit of service, substitution is enabled in these models. This strongly influences the environmental performance corresponding to the meeting of this service. Therefore, some variables in the model are expressed in units of service or items of the corresponding product. As other variables are expressed in material flows, a conversion should take place somewhere in the model. One of the objectives of M-P chain studies is a quantitative approach to the consumption and emission of one or more definite, environmentally harmful materials, e.g. zinc (Kandelaars and Van den Bergh 1997). In a M-P network the materials and products are considered as nodes, and the arcs represent processes. In our study, the *product-process chain* approach is used. This is a network approach in which the nodes are processes. These are connected by directed arcs that represent the physical flows.

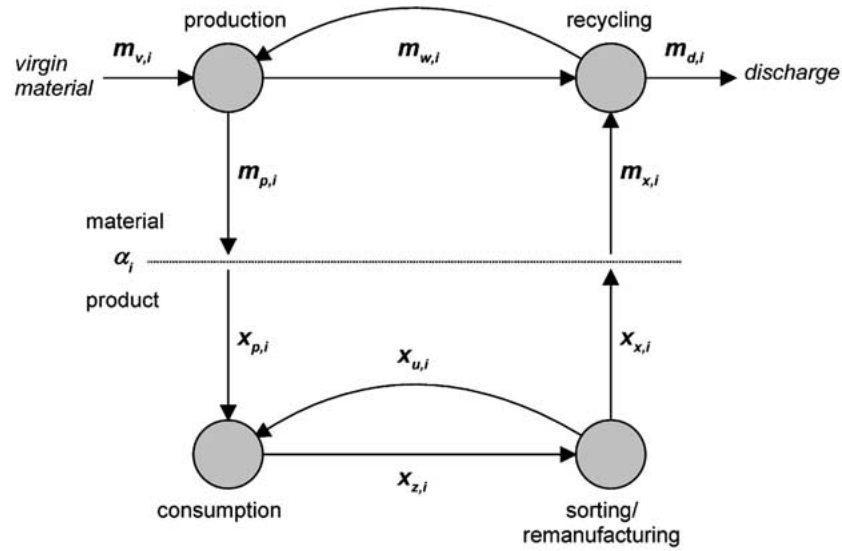


Figure 3. Material-product chain with reuse and recycling.

In Figure 3, a translation of a M-P network to a product-process chain has been performed. The advantage of a product-process chain is the straightforward generalisation and extension to complex systems. The model represents a system that satisfies an externally defined demand for a service by a number of product types (with index i), each containing a definite amount of material. When there is an emphasis on two or more different materials, an extra index n (for the material) and an additional set of constraints should be introduced. These constraints represent the ranges according to which the composition of the different product types can vary. Kandelaars and Van den Bergh (1997), e.g., consider the substitution of two product types (gutters) that provide the same service (rainwater collection), but that consist of two different types of material (zinc and PVC, respectively), each of which causes a different environmental impact. In our paper, however, the substitution between similar products is considered that differ in surface treatment and in the presence of some minor quantities of additives. Therefore, we restrict ourselves to one material and account for the environmental impact by adding an environmental cost, expressed in EcoPoints (see Goedkoop and Spriensma 2000), to each product and each process (see Table I).

In Figure 3, those flows are depicted that are related to a definite product. Two subsystems can be discerned here: one for the materials and the other for the products. The material flows m_i are in kg/yr and the product flows x_i are in units/yr. Conversion factors α_i (in kg/unit) convert material flows into product flows. Apart from the index i , the other indices that appear in the figure are: v for virgin material, p for product, u for reuse, c for recycle, w for waste, z for end-of-life products, d for discharge, and x for return flow from the product to the materials circuit.

Table I. Process costs in the base case

Process	Costs (\$/kg)	Environmental impact (10^{-6} EcoPts/kg)	Gross energy requirement (MJ/kg)
Reel production	5.38	560	15
Wrapping	0.32	20	0.12
Unwrapping	0.32	50	0.31
Materials recovery	0.5	200	5
Incineration	0.06	1800	-20
Disposal	1	500	0.1
Spraying	6	4000	2
Coating	7	3000	2
Cleaning/sorting	1.37	50	0.05
Cleaning	1	40	0.05
Internal shredding	0.95	150	3
External shredding	1.1	100	2

Figure 3 shows that the system can be divided into two subsystems, the one with flows m expressed in kg/yr includes materials recycling, the other with flows x expressed in units/yr includes product reuse. For each product type i , four nodes are discerned here, which correspond to production, consumption, sorting/remanufacturing, and recycling respectively. It has been assumed here that the remanufacturing costs considerably exceed the sorting costs, which is the reason why costs have been put proportional with the throughput of the remanufacturing process, which equals the output $x_{x,i}$. A balance equation can be formulated for each of the nodes that are discerned in Figure 3:

$$\begin{aligned}
 m_{v,i} + m_{c,i} &= m_{w,i} + m_{p,i} \\
 m_{w,i} + m_{x,i} &= m_{d,i} + m_{c,i} \\
 x_{p,i} + x_{u,i} &= x_{z,i} \\
 x_{z,i} &= x_{u,i} + x_{x,i}.
 \end{aligned} \tag{1}$$

For avoiding unnecessary complexity, the product loss that is caused by the different processes (apart from recycling) has been neglected in these equations. The costs and the environmental load of upstream activities, such as virgin material production, are included in the characteristics of the virgin material. These values are established outside the system under consideration. They are entering the model via expression (5) that will be treated in advance. The influence of the upstream activities thus touches the optimal mix of recycled and virgin materials or the optimal mix of different materials in the case of product substitution.

The following conversion relations are added:

$$\begin{aligned} m_{p,i} &= \alpha_i x_{p,i} \\ m_{x,i} &= \alpha_i x_{x,i}. \end{aligned} \quad (2)$$

It is assumed here that the new and reused products, and the new and recycled materials, are perfect substitutes. This is justified by the selection process, which prevents reuse and recycling of the products and materials that do not meet the specifications (represented by $x_{x,i}$ and $m_{d,i}$ in Figure 3).

The demand d is externally imposed on the system. It is expressed by the relation:

$$d = \sum_i (x_{p,i} + x_{u,i}). \quad (3a)$$

The model is completed by the following proportionality relations:

$$\begin{aligned} m_{w,i} &= c_{w,i} (m_{v,i} + m_{c,i}) \\ m_{c,i} &= c_{c,i} (m_{w,i} + m_{x,i}) \\ x_{u,i} &= c_{x,i} x_{z,i}. \end{aligned} \quad (4)$$

In these relations, $c_{w,i}$, $c_{c,i}$ and $c_{x,i}$ are dimensionless constants with values between 0 and the theoretical maximum of 1. Here, $c_{w,i}$ is usually a technically determined parameter, and the coefficients $c_{c,i}$ and $c_{x,i}$ are calculated from the flows, which act as decision variables. Consequently, only the first of the equalities (4) is effectively a constraint, the other two are rather definitions of constants. However, $c_{c,i}$ and $c_{x,i}$ are usually subjected to additional constraints, such as lower bounds (due to legislation) and upper bounds (due to technical restrictions). This is different from the original approach, in which both the flow variables and the coefficients act as decision variables.

As an objective function, the total system costs in \$/yr can be used:

$$\begin{aligned} obj = \sum_i & (\kappa_{v,i} m_{v,i} + \kappa_{d,i} m_{d,i} + \kappa_{p,i} (m_{v,i} + m_{c,i}) + \\ & \kappa_{c,i} (m_{x,i} + m_{w,i}) + k_{u,i} x_{u,i}). \end{aligned} \quad (5)$$

Here κ and k are specific costs in \$/kg and \$/item, respectively. The production costs include both materials costs and process costs. Thus a distinction because those costs has to be made. Materials costs are assigned to materials flows that cross the system boundary. In this case, these flows include virgin materials and final waste (represented by the factor $\kappa_{v,i}$ and $\kappa_{d,i}$ respectively). Process costs refer to the processes that are included in the system. These costs involve capital, labour, energy, knowledge, etc. We assume that these costs are allocated proportionally to the material throughput of the process. This assumption can be justified by the observation that the time that a process is required is approximately proportional to the throughput. An additional assumption is that the process costs are the

same for virgin and recycled materials. This is a consequence of the assumption of perfect substitution between these materials. Product prices are not included in the model, as these are determined by the interaction of supply and demand, which is external to the model. Therefore, the price has been assumed as externally imposed to the model. Apart from this, a producer aims for the minimization of the production costs for a given amount of marketable products. In more complicated cases, different production costs can be introduced. The terms on the right half side of expression (5) represent material costs, costs of final treatment of waste, production costs, recycling costs and reuse costs, respectively. Non-linearities are introduced if κ and k depend on the size of the flows. This usually occurs in reuse and recycling processes. Because of the structuring of the model, additional flexibility can be obtained, which enables modifications such as the introduction of different technologies.

The process-product approach involves a physically and process-oriented modification of the MP-chain, in which the rather artificial separation between materials and products has been removed, as all flows can equally be considered to be material flows. Processes are treated as subsystems. To all subsystems the full mass balance is applied, making no fundamental distinction between the production, consumption, waste treatment, and discharge processes that are present within the system. Consequently, the demand can be decomposed into a linear combination of material flows:

$$d = \sum_i (x_{p,i} + x_{u,i}) = \sum_i \frac{m_{p,i} + m_{u,i}}{\alpha_i}. \quad (3b)$$

Although the given example is simple, extension to deliberately complex system structures proceeds straightforwardly. Additional constraints, e.g. on capacity of production processes, can be added. The problem is solved using linear programming (LP) or non-linear programming (NLP) algorithms. If desired, binary variables can be attached to the flows, which can be useful in penalty functions, e.g. for complexity. In this case mixed-integer (MIP) problems can be formulated.

Production, consumption, recycling and discharge processes are considered equivalent. Costs are connected to both products and processes, which is visible in Tables I and II. If a particular system is considered, the profit that results of this system is composed of the revenues of the outgoing flows, reduced by the costs of the incoming flows as well as transformation costs. Flows that are internal to the system are neutral to the revenue of this system, but they nevertheless influence the profits by increasing the transformation costs, which are proportional to the material flows passing through the process. This plays a role in internal recycling, in which internally generated waste flows are reused internally. Therefore, they do often not appear in waste statistics, although they are unfavourable for the company's performance.

An enterprise can consist of a group of processes. In reuse and recycling problems, virtual enterprises can also be defined, i.e. a group of different enterprises that

Table II. Product values in the base case (\$/kg). The figures between brackets have been taken from Figure 5. The values exclude added products such as SMDs

Product	Revenue (\$/kg)
Polystyrene specialty (1)	2.10
Primary reels (2)	7.85
Coated secondary reels (3)	7.85
Sprayed secondary reels (4)	7.85
Collected reels for reuse (6)	0.45
Collected reels for recycling (7)	0.40
Discarded reels for external processing (8)	0.40
Secondary materials from externally processed reels (10)	1.00
Reels for lower grade reuse (13)	3.00
Rejected reels for external shredding (15)	0.50
Cleaned reels for external shredding (17)	0.50
Useful materials from internal shredding (18)	1.55
Useful materials from external shredding (19)	1.55

are closely co-operating in a definite field but that are geographically separated. In the product-process chain approach, such extended enterprises can easily be defined. In the next section the method that is described here is applied to a product chain that is characterised by a complicated network of suppliers and customers. Virtual enterprises are visible there in Figures 4 and 5. The demand for product responsibility urges the producer to be involved in the design of a product recovery chain, which involves decisions such as the choice for product redesign, product remanufacturing, internal or external reuse, and materials reuse. This study demonstrates both the possibility of applying a general approach to a particular case, and offers the producer an insight in the consequences in different choices that can be made.

4. Case: Packaging and Product Carriers

4.1. GENERAL

Packaging materials give rise to a substantial share in the generation of waste. As an example, figures from the Environmental Protection Agency (EPA) in the USA for 1990, show a relative share to municipal solid waste of 10% for containers (bottles and cans), 8% for boxes and 9% for other packaging materials, adding up to a total amount of 43 Megatons/year. Apart from this, a considerable amount of packaging remains in industry or is collected by the wholesale or the retail trade companies and thus remains within the business-to-business circuit. Also in 1990, for example, 45% of the boxes was recycled via a separate circuit without reaching the consumer

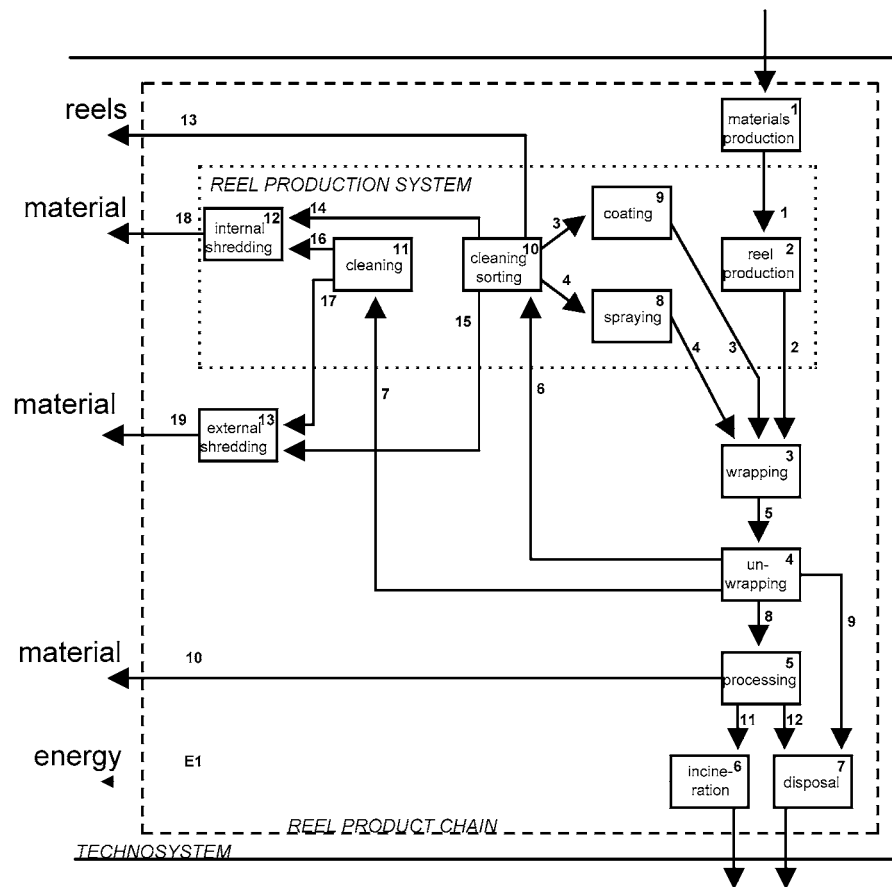


Figure 5. The model structure.

Surface Mounted Devices (SMDs). The reels look similar to film reels but the technical specifications are quite different. This will be explained in the subsection 3.2. The reels are made of polystyrene and they are produced in a variety of sizes and types. A typical reel has a diameter of 330 mm and a tape width of 12 mm. Such a reel has a mass of 100 g. Besides that, smaller reels with a diameter of 180 mm are produced. A typical reel can be loaded with about 10,000 SMDs that are mounted on tape, which represent the greater part of the value of a wrapped reel. The revenues of the reels are typically \$4.-/kg. The world production of reels is about 10,000,000 kg/yr and it is rapidly growing. The company where the research has been carried out, is a medium player in the global market. Because the customers and the customer's customers are globally distributed, the amount of waste is not well documented, but most of the reels are used once only and end up in a landfill. Reel producers want to anticipate regulation that possibly makes them responsible for the costs of the discarded reels and they attempt to take even advantage of expected changes in this field.

4.2. CHAIN STRUCTURE AND CONSTRAINTS

SMDs are mounted on tapes, which in turn are wrapped to reels by the SMD producer. Wrapped reels are shipped to producers of Printed Circuit Boards (PCBs) that mount them on PCBs by means of pick-and-place machines. The emptied reels are left and an adequate way of reusing or recycling these reels must be investigated. Reels are produced by reel producers by moulding from granulate which is a polystyrene specialty. Because of the demanding reel requirements, their specifications are strict, including dimensional, anti-static, mechanical, and visual properties. Reuse of reels for carrying SMDs as well as recycling of the material is particularly impeded by the anti-static requirements. Nevertheless, reel producers are faced with a challenge of designing a recycling system to meet likely future take-back obligations. The producer wants to convert such a challenge into an opportunity, by creating additional added value to his products or services for example. Therefore, changes in processes and products might be required, and additional processes might be introduced. The question arises to what extent outsourcing should be applied.

To address these problems, the following phases should be carried out:

1. Inventory
2. Model design
3. Optimisation
4. Evaluation

The inventory phase involves a survey of the relevant processes and the collection of quantitative data such as costs, environmental impact, and technical constraints. In the model design phase, the model structure is determined, with all possible processes included. Next, one or more optimal solutions are calculated, according to different optimisation criteria. Finally, these solutions are studied in more detail or, if necessary, rejected. Subsequently, a more detailed study can be made on one or more feasible solutions.

The core activity of the reel producer is moulding from granulate, which originates from mixing of a bulk product such as high-impact polystyrene (HIPS) and additives. To meet anti-static requirements, intensive communication with the supplier of additives is indispensable. Mixing can also be outsourced. The customers of the reels, i.e. the SMD-producers, are not the final consumers as they in turn supply the wrapped reels to a score of PCB producers that are localised worldwide. Because the empty reels represent a much lower value than the wrapped reels do at the same volume, cost-effective global transportation of empty reels is far less obvious compared to transportation of the wrapped reels. This imposes a serious restriction on recollection of the emptied reels. Another severe restriction is the complex and highly divergent network of customers and customer's customers.

A technical restriction is, that conventionally produced reels lose their anti-static properties after use. This means that they cannot be reused and their materials cannot be recycled to serve the original purpose. In order to upgrade the products,

additional processes such as coating or spraying are required. On the other hand, lower grade applications are possible for the product as well for the material. This also requires additional, but conventional, processes such as cleaning, sorting and, in case of materials recycling, shredding. Many of these processes can proceed both internally as well as externally. By investigating different extended enterprises, the optimal structure of a product-process chain model can be derived and the desired configuration of the extended enterprise can be established. A simplified version of it is presented in Figure 4.

In this figure, the principal transformation processes and product flows of the reels are represented. The incoming and outgoing flows that are only indirectly relevant to the reel chain are indicated by the arrows on the left. The arrows pointing to the right represent the product flows that are applied in other product-process chains belonging to the technosystem. They are generally used for lower-grade applications (reels for support of wire, granulate for the production of household applications, and so on). Within the reel product-process chain, a subsystem is indicated by the filled rectangle. This includes the activities the reel producer is interested in and can be considered as a virtual enterprise. The corresponding range of processes changes when a particular process is outsourced. From this point of view, a hierarchy of nested systems can be observed: the reel producer, the reel product-process chain, the technosystem, and the surrounding ecosystem, respectively. Virgin materials enter the reel product-process chain, and wastes are discharged from it. Besides that, emissions are produced, particularly in the case of incineration.

Apart from the structure of the model, quantitative data on the different product flows and processes should be acquired. This, however, is in general a cumbersome process. Although even the availability of reliable internal data on costs of individual processes is often inadequate, essential problems arise by the acquisition of external data. Nevertheless, these are crucial to the design of a reuse/recycling system, as the co-operation of many partners is of vital importance here. These partners, however, act as co-makers and as competitors as well. Besides that, one encounters novel technologies (such as: spraying and coating), which have to be included in the model. There still is a lack of experience with the application of these processes. Data on conventional processes, such as transport and bulk plastic production, have been taken from databases such as that of the LCA software package SimaPro. The set of data that is used here thus includes a lot of estimates and, as a matter of fact, uncertainties.

The calculations refer to a base-case, which consists of a set of reasonable assumptions. The data of the base-case on process costs, environmental impact, and energy requirement, are listed in Table I. Table II lists the values that are connected to some flows of useful products that leave a subsystem.

4.3. THE MODEL

The model that has been presented in section 2 has the product life-cycle chain approach as a basic characteristics. Costs are assigned to materials flows that cross the borders of the system, and to processes that act on materials flows. This is a way to combine a physically oriented model to economic criteria. Due to the physical orientation one can use materials balances in the model. We have also distinguished between flows that are expressed in kg, which is usual in the process industries, and flows that are expressed in items, which is usual in the manufacturing industries. If one considers more or less complete materials life cycles, these have both types of processes combined, such as has been depicted in Figure 2. The same is true in the processing of discarded products. In the reel production chain, e.g., all these types of processes are present. In contrast with the model of Figure 3, we go into more detail and distinguish between various relevant processes that are linked by materials flows. This is required if we consider a realistic product and include the possibility to make decisions on the internal structure of the chain. The product-process approach that has been used for costs allocation will also be applied to this model. Consumption is not included in the model. Various flows of materials and products are accounted for. Within the system, subsystems can be defined. Total costs are composed of process costs, which are related to the processes in the (sub-)system, and materials costs that are related to the physical flows that cross the (sub-)system boundary.

Let us define the model of the life cycle of the product that is described in subsection 3.2, see Figure 5.

The basis of the model is given by the definition of a set I of flows and a set J of processes, indicated by index i and j respectively. Flow variables are defined by x_i . These are expressed in kg/yr or comparable units. A quasi-process can represent the environment of the system. The structure matrix S is defined with elements $S_{ijj'} \in \{0, 1\}$. The indices j and j' represent the origin and the destination of the flows, respectively. A subset of processes $K \subset J$ includes those processes that are covered by the reel producer; here these are moulding, mixing, coating, and spraying. Once this subset has been defined, the subsets G and H of I are determined, corresponding to the flows that enter and leave the subsystem.

As only the reels are considered, mass balances can be established for each process. However, some mass flows, e.g. flue gases, are neglected. Therefore, some processes are included where no mass balance holds, e.g. incineration. In this case, the leaving flows are expressed as linear combinations of the entering flows. The amount of resulting slag, for example, is a constant fraction of the mass of reels that is supplied to the incineration process.

If valuable materials or products are entering a (sub-)system, e.g. the reel production system, input costs are combined with these flows. These are determined by quantity and price, which is established according to an externalised market mechanism. If valuable materials are produced, the associated costs are found from the input costs and process costs. *Product revenues* are associated with

the valuable products that are leaving the (sub-)system. These revenues are related to the market price of the product. If materials with a negative value, such as final waste, are leaving a (sub-)system, costs are made that have to be added to the production costs as output costs. Thus *input and output costs* are directly related to the product flows and involve such expenditures as shipping, disposal, or recollection. When the progressive increment of recollection costs with the recycling grade is incorporated in the model, non-linearities are introduced. *Process costs* are connected to transformation processes. These are proportional to the flows *through* the process, which can usually be expressed, because of balance equations, by a linear relation between the flows that are entering and leaving the process.

In the model, the service approach is used for comparison of the results. This means that calculations are carried out with one unit of service as a norm. From the point of view of the reel producer, the unit of service should be defined by the flow of reels that passes from the wrapping to the unwrapping process, as this actually meets the need of the PCB industry for SMD support. It should be stressed that the PCB industry focuses on another norm: the amount of produced PCBs. This has been not adopted in our model, because it would cause unnecessary complications. With all flows divided by the norm, the flow from the wrapping to the unwrapping process equals 1 and all other values of flow variables are related to it.

From the reel product chain of Figure 4 and information that has been gathered from practice, the different relevant processes and product flows have been selected. This resulted in the model's network structure of Figure 5.

From the point of view of the reel producer, the model is optimised with respect to the reel producer's subsystem or extended enterprise, for which the system boundaries have also been indicated in Figure 5. The objective function that should be minimised thus includes the internal costs, i.e. the process costs, which correspond to the processes that are carried out internally, and the input and output costs that are connected to internal flows. The revenues, which are associated with the valuable products that are leaving the system, are included in the objective function with a negative sign. In the case of the costs of the reel production subsystem in Figure 5, the objective function thus includes the process costs that are associated with all internal processes (processes 2, 8, 9, 10, 11, and 12 in Figure 5). Input costs of the entering valuable materials are added. (the flows 1, 6, and 7 in Figure 5). The revenues or the output costs that are associated with the leaving flows (2, 3, 4, 13, 15, 17, and 18) are also accounted for. By doing so, the objective function represents the costs minus the revenues of a (sub-)system, i.e. the profit with negative sign. This should be minimised in order to maximise the profit.

Similar to this example, one can select every subsystem that acts as a functional unit, e.g. the complete chain. Another extension refers to the nature of the costs. Apart from cost analysis, one can optimise according to other quantifiable criteria such as environmental impact, or energy consumption. Evidently, one frequently prefers a solution that is reasonable with respect to various relevant criteria. This can be obtained, e.g. by determining a cluster of near-optimum solutions with

respect to one criterion, and next calculate the score of those solutions on the other criteria and selecting the most reasonable solution. This can result in a solution with near-optimum costs but with an environmental performance that considerably surpasses the optimum one.

It is evident that the optimum configuration that is returned for a subsystem does not necessarily coincide with the optimum of the full product-process chain. This is an essential problem in chain analysis. Every player in the chain tries to optimise its own subsystem, but the economy as a whole has advantage of an optimally functioning complete chain. It is evident that potential conflicts of interests exist here.

4.4. RESULTS

Although costs are expressed in financial units in the model description, they can be generalised to include a variety of undesired effects. In the model, three types of extended costs are introduced: cost in financial units (\$/kg), in energy units (MJ/kg), corresponding to the Gross Energy Requirement (IFIAS 1973), and in environmental costs (EcoPoints/kg) (Ruth 1993). Although the values that are assigned to the parameters originate from no more than a rough estimate, their application nevertheless creates valuable information. It is possible to investigate the consequences of selecting a number of near-optimum solutions from a financial point of view on different system characteristics such as environmental impact. This results in a selection of solutions from those that are slightly unfavourable with respect to the main aspect, but that surpass the optimal solution with respect to other aspects that are not incorporated within the objective function.

The model is formulated as follows:

The objective function consists of three terms: one representing process costs, one representing input costs, one representing revenues.

$$\begin{aligned} \text{minimise: } & \sum_i \sum_j \sum_{k \in K} S_{i,j,k} CP_k x_i + \sum_i \sum_{j \notin K} \sum_{k \in K} S_{i,j,k} PV_i x_i - \\ & \sum_i \sum_{j \in K} \sum_{k \notin K} S_{i,j,k} PV_i x_i \end{aligned} \quad (6a)$$

$$\text{subject to: } \sum_i \sum_j S_{i,j,k} x_i = \sum_i \sum_j S_{i,k,j} x_i \quad (6b)$$

Here index i refers to the product flows; the indices j and k refer to the processes. $S_{i,j,k}$ is the structure matrix, see section 3.3. K is the subset of processes that is considered. CP_k refers to the costs per unit of mass throughput of process k (see, e.g., Table I). PV_i refers to the value per unit of mass of materials flow i (see, e.g., Table II). The set of *physical constraints* (6b) reflects mass conservation of

Table III. The flow variables (normalised to flow 5) of the optimal solution of the base case. The flow numbers correspond to those in Figure 5

Flow	1	2	4	5	6	8	9	10	11	12	13	14	18
kg	0.775	0.775	0.225	1	0.3	0.25	0.45	0.125	0.075	0.05	0.03	0.045	0.045

the processes, here process k . The second term in (6a) represents the costs of the flows that are entering the subsystem. The third term refers to the revenues of the flows that are leaving the subsystem. Costs of processes that are beyond the system boundaries are not in the objective function.

Additional constraints are added. In the model that is considered here, a *normalization constraint* is added, which puts a definite flow to 1, e.g. $x_5 = 1$. This defines the unit of service. Apart from this, *technical constraints* might be present. Usually, these put a maximum or minimum on the ratio between two flows, put a maximum on the capacity of a process, etc. An example of such a constraint is: $x_6 + x_7 \leq c_5 \cdot x_5$, with c_5 a parameter that imposes a maximum on the recycling rate.

Transportation costs might be included in the objective function at fixed, averaged, distances. These costs are proportional to the flows. Transportation costs are a substantial part of recollection costs. Accounting for the dependence of recollection costs of recollection rate can be done in most uncomplicated way by subjecting the recollection rate to a maximum value by a technical constraint. Non-linear relations between costs and flows might also be included, thus introducing non-linear terms in the objective function.

The system of Figure 5 was modelled using AIMMS (Bisschop et al. 1993), a user interface for LP, MIP and NLP solvers. The optimum solution of the base case is presented in Table III. There results a profit for the reel producer that equals 0.274 \$/kg, which is maximal. For each kg of wrapped reels (flow 5 in Figure 5), 0.775 kg of raw materials is required. 0.5 kg discarded reels is in landfill, 0.075 kg is incinerated, 0.17 kg is sold as secondary material, and 0.03 kg is sold as reels for lower-grade use. The flows that are belonging to this solution are listed in Table III.

It is assumed here that the system is subjected to the following constraints, which are all active here:

$$x_8 \leq 0.025x_5 \quad (7a)$$

$$x_{11} \leq 0.3x_8 \quad (7b)$$

$$x_{10} \leq 0.5x_8 \quad (7c)$$

$$x_{14} + x_{15} \geq 0.15x_6 \quad (7d)$$

$$x_{13} \geq 0.1x_6 \quad (7e)$$

These constraints result from both legislative and technical considerations. Constraint (7a) is due to legislation, which prescribes a minimum recycling percentage. Disposal cost is considered high with respect to incineration. This is for discouraging landfill, see Table I. However, a restricted incineration capacity is assumed (constraint 7b). The material fraction that is recovered via used reel processing (process 5) is restricted because of technical reasons (constraint 7c). In case of cleaning and sorting (process 10), there is a minimum share of the reels that is suitable for product reuse and that can only be used for materials recycling (constraint 7d). There is assumed a maximum share of reels that can be applied for other purposes than as a carrier of SMDs, e.g., because of market constraints (constraint 7e). Via varying the parameters in these constraints, it is possible to investigate the influence of variables such as changes in policy and technical improvement. It can also be studied to what extent these constraint are active.

As can be noticed in Figure 5, there are different possible system boundaries, each embracing a different subsystem. Two possible boundaries are depicted. One might study the specific reel production system only, which is usually done by the manufacturer for optimising the design of his subsystem. In this case, the objective function is restricted to the costs that are exclusively made within the subsystem. In this case, external costs and prices are assigned to the flows that cross the boundaries of the subsystem. These are presented in Table II. In case of considering the reel production system only, externally established costs and prices are assigned to flows such as x_6 , x_7 , and x_2 . If, however, a more comprehensive system is considered, such as the reel product chain in Figure 5, these flows are internalised and only the flows that are crossing the boundaries of the larger system are considered. In this case, the products x_{10} , x_{13} , x_{18} , and x_{19} are sold, and an externally established price is assigned to it. The resources and wastes are included in the materials production cost, and the incineration and disposal costs, respectively. A useful feature of this approach is that one is able to optimise both the full chain and arbitrary subsystems, which is useful in analysing the mechanisms that are controlling the chain, but that are, in practice, driven by different interests. In the base case that is reflected in Table III, the complete system has been taken into account.

For the linear problem, a sensitivity analysis has been performed, in which the extended enterprise in Figure 5 acts as the producer. This analysis is based on the costs that have been taken from Tables I and II. The filled dots correspond to transitions in the structure of the optimal solution. This means that processes are switched on or off, which results in discontinuities in the coefficient of direction. Some results of the sensitivity analysis are represented in Figure 6. The dependence of the producer's profit on the change in a number of process costs is depicted here. It is seen that optimal solutions sometimes need a change in configuration.

An example of the results of a non-linear model is presented in Figures 7a, b. The recollection costs are given here by $c_{rec}x_{rec}^2$ with $x_{rec} = x_5 - x_9$, see Figure 5.

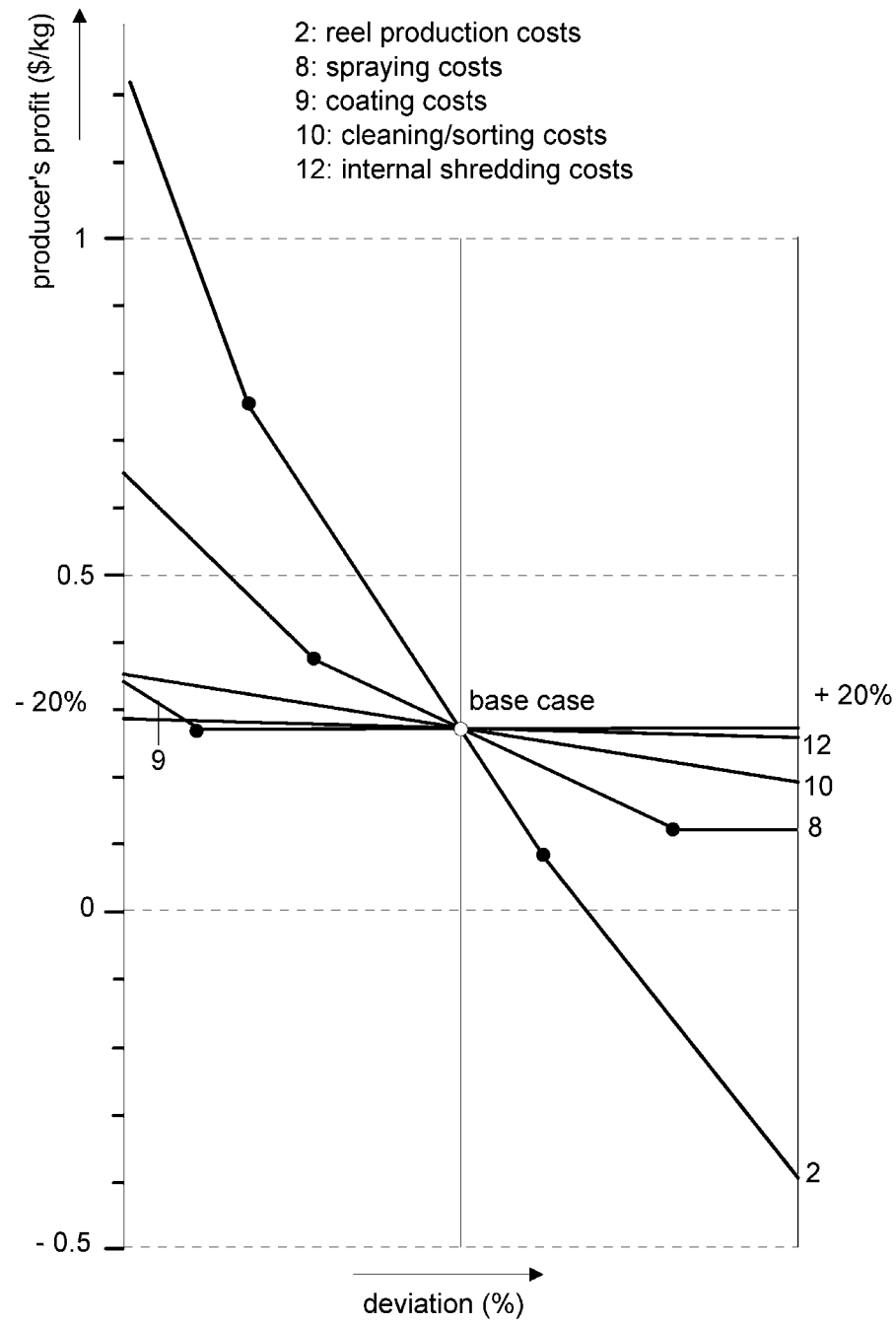


Figure 6. The sensitivity of the producer's profit to variations in some process costs.

This term is added to the objective function. Various values of the constant of proportionality c_{rec} are plotted along the x -axis. The problem is solved with the NLP option (CONOPT) of AIMMS modelling software (Bisschop and Entriiken 1993). In this particular case, the nonlinearity of the model is restricted to one term in the objective functions. There are no non-linear constraints. The objective function reflects here the costs in \$ made by the reel producer's subsystem. In Figure 7a, the magnitude of some flows from Figure 5, normalised to 1, is represented as a function of c_{rec} . Dashed lines indicate transitions between basic solutions. The flow variables in this figure refer to those in Figure 5. Some other results of the calculation are visualised in Figure 7b, viz., the energy use and the environmental load that correspond to the optimal solution for the reel producer at varying c_{rec} . As there is no strong correlation between financial, energetic and environmental merits of the system, a good solution from an economic point of view can be highly unfavourable from any other perspective. Along the y -axis in Figure 7b three different quantities are indicated: \$/kg, MJ/kg, and EcoPoints/kg, all measured with respect to one mass unit of product (reel) that enters the PCB producing process (unwrapping).

Figure 7b shows that the optimal configuration of the system results in a profit for the reel producer, as should be expected. Simultaneously, the profit for the full product-process chain is calculated, which is negative. This result is not surprising, because the reel is only intended for providing a service to the PCB producer (the unwrapping process) and acts as a cost factor there. This producer adds value to its proper product PCBs. Consequently, the chain cost that is returned by this calculation equals the expenditure that has to be paid for the reels to meet the need within the PCB product chain for the service of SMD support, protection and positioning. However, this chain is excluded from the present model that focuses on the reels and is not aimed at the calculation of the profits of the complete SMD chain. It should be noted that PCBs in turn are a part of another chain (electronic devices).

5. Discussion

For a company, the construction of a model according to the above-mentioned method proves to be a valuable tool for gaining insight in the advantages and disadvantages of various recycle chain options. It indicates which recycling processes should be incorporated in the company's activities and which should be outsourced. This can be demonstrated with the results of Table III. The flows x_3 , x_7 , x_{15} , x_{16} , x_{17} , and x_{19} are failing here. This means that the processes 3 (coating), 11 (cleaning aimed at shredding only), and 13 (external shredding) are infeasible from an economic point of view. Shredding is internalised here, so far it concerns the recollected reels. Although the level of detail of the model might need improvement, it is demonstrated that the model can be used for selecting feasible options for a recycling chain. It is evident that such a choice is based on cost estimates, which are often not more than rough guesses. The strength of the model is that it

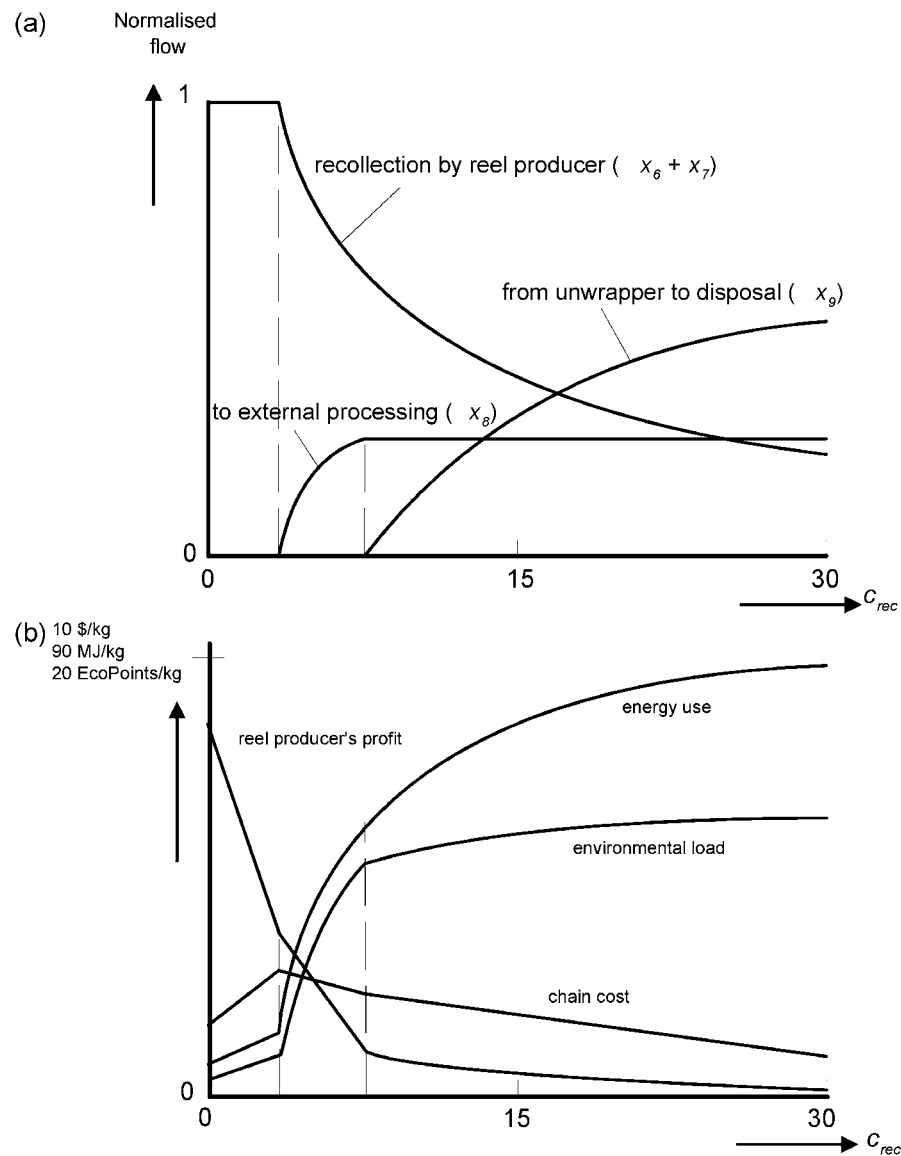


Figure 7. Some results of the calculation.

combines many data to a network structure, and it can conveniently assess changes in parameter values, which might reflect in a structure change. Sensitivity analysis is another useful tool that can be applied for dealing with uncertainty in these estimates, via investigating the robustness of solutions to possible changes in, e.g., price, policy, or customer behaviour.

As it decides between different options, it puts to zero those flows that counteract the objective. As a matter of fact, the corresponding processes (with zero

throughput) are also excluded than. On the other hand, one might include some processes in the subset that contributes to the objective function and investigate to what extent the profit has changed. By doing so, definite flows are internalised too, which means that their values no longer appear in the input costs. It should be stressed that the model is a decision *tool* only. However, part of the arguments whether or not a definite decision should be made is not quantifiable and these aspects are not incorporated in the model.

The model can easily be adapted to changing technological options, and sensitivity analysis with respect to parameter values can be carried out straightforwardly. In this case, realistic solutions are generated. In practice, however, a problem arises that is intrinsic to product chains. The enterprises within this chain often act with each other on a basis of negotiation, which hampers the necessary exchange of information. Although this problem can be overcome to some extent, via sensitivity analyses with respect to those parameters that are highly uncertain for example, the difficulty can not be completely eliminated. In the chain that is described here, communication with the end users is even more difficult, because there is no direct relationship between them and the reel producer, as there is an additional company between the reel producer and end user. Nevertheless, an exercise such as has been carried out here, appears to be useful for various enterprises, as they are forced to gather information that often is not even present on a company level, and to acquire a basic idea of what a possible recycling system will look like.

The pros and cons of the different possible options reflect themselves, apart from the process costs, the environmental impact, and the energy use, which are quantified in Table I, in features that touch the product specifications. Coating, e.g., affects the dimension of the reel, but results in better anti-static properties than spraying does. The clients frequently use stickers that have to be removed in reuse of the reels. There are crucial logistic problems, because the wrapped reels represent a high value (because of the SMDs), which makes worldwide transportation profitable. This is in contrast with the emptied reels. If one applies the recollected reels for lower-grade applications, the value of these reels considerably decreases. In case of materials recycling, the additives that have been applied for establishing the properties of the reels, are now turned into impurities. This might affect the range of secondary applications. Reuse as reels touches the problem of property. Many reels might be damaged because the client's client does not feel responsible for the discarded product yet. The considerable amount of product types further reduces the possibility of product reuse. From the producer's point of view, a streamlining of the product range can be beneficial in this case. The case that has been presented in detail shows a cascading. Part of the recollected reels is reused after spraying, part is reused for lower-grade applications, part is externally used as a material.

For the enterprise that has been investigated here, a recycling system including partial recollection, regeneration by coating, and product reuse turns out to be a preferable solution, from the viewpoint of both costs, environment, and energy

use. On the other hand, the preferable recollection ratio strongly depends on the exact relationship of the costs and the recollection ratio. Generally, the precision of the determination of the curve can not exceed that of an educated guess.

6. Conclusions

In this paper, a systematic network approach to product-process chain modelling and optimisation is described. The method was applied to a case of industrial products characterised by sophisticated material requirement but with a relatively simple structure. The structure of the corresponding product-process chain is divergent and complicated with respect to data collection. For the bulk materials, information is available by suppliers and in databases for LCA software. Information on product values is often available, but if one arrives at processes that are deeply downstream in the chain, such as at the customer's customers, only crude estimates and guesses are possible. Actually, the producer does not know which enterprises the customer's customers really are and what exactly happens with the discarded reels. The internal processes are much better documented, but problems arise by the introduction of new technologies that should be more established before unambiguous information on costs and technical performance comes available. Nevertheless, the described approach returns realistic results that are a basis for more detailed studies. For the involved company, this survey is no more than a first phase in the way to a well-established reuse/recycle system. Much depends on future developments on the market, in legislation and in the activities of other companies in the chain, as well as of technical innovation.

From a theoretical point of view, the product-process approach offers a method for defining different subsystems within the system that is described, and for optimising according to the requirements of a selected subsystem. Such a subsystem can correspond to a real or an extended enterprise. This meets the requirements of a concrete company or an industrial branch. Comparison with a full chain optimisation is easily carried through. The method also addresses the problem whether or not outsourcing should be taken into account. The observed flexibility of choosing the systems boundaries is a useful decision tool for various stakeholders, including chain directors and authorities, to study the reaction of the chain's companies to different measures.

Apart from the application of the method to other and more extended product chains, some extensions of the model are of interest for further research, namely: the modelling of a system that includes a hierarchy of nested subsystems, and the inclusion of a measure for complexity, which can act as an additional constraint. This can be realised by the incorporation of integer variables and the application of Mixed Integer Programming (MIP).

Acknowledgements

The authors wish to express their gratitude towards Mrs. J.E.H. Collet from DPI for providing valuable advice and information, and for her further support of this project.

References

- Alexander, J.H. (1993), *In Defence of Garbage*. Westport, Connecticut: Praeger.
- Allen, J. and S. Anderson (1998), 'Implications of the Packaging Waste Regulations', *Logistics focus* **6**(5), 24–27.
- Ayres, R.A. and L.W. Ayres (1996), *Industrial Ecology: Towards Closing the Materials Cycle*. Cheltenham: Edward Elgar.
- Azapagic, A. and R. Clift (1995), 'Life Cycle Assessment and Linear Programming – Environmental Optimisation of Product System', *Computers and Chemical Engineering* **19**, S229–S234.
- Bailey, I.G. (1999), 'Competition, Sustainability and Packaging Policy in the UK', *Journal of Environmental Planning & Management* **42**(1), 83–102.
- Bisschop, J. and R. Entriken (1993), *AIMMS: The Modelling System*. Haarlem, The Netherlands: Paragon Decision Technology.
- Bloemhof-Ruwaard, J.M., M. Salomon and L.N. van Wassenhove (1994), 'On the Coordination of Product and By-product Flows in Two-level Distribution Networks: Model Formulations and Solution Procedures', *European Journal of Operational Research* **79**(2), 325–339.
- Bloemhof-Ruwaard, J.M., L.N. van Wassenhove, H.L. Gabel and P.M. Weaver (1996), 'An Environmental Life Cycle Optimization Model for the European Pulp and Paper Industry', *Omega* **24**(6), 615–629.
- Carter, C.R. and L.M. Ellram (1998), 'Reverse Logistics: A Review of the Literature and Framework for Future Investigation', *Journal of Business Logistics* **19**(1), 85–102.
- Fleischmann, M., J.M. Bloemhof-Ruwaard, R. Dekker, E. van der Laan, J.A.E.E. van Nunen and L.N. van Wassenhove (1997), 'Quantitative Models for Reverse Logistics: A Review', *European Journal of Operational Research* **103**(1), 1–17.
- Fleischmann, M., H.R. Krikke, R. Dekker and S.D.P. Flapper (2000), 'A Characterisation of Logistics Networks for Product Recovery', *Omega* **28**(6), 653–666.
- Frenz, W. (1996), *Verordnungen zum Kreislaufwirtschafts- und Abfallgesetz: Textausgabe und Kommentar*. Cologne: Heymanns.
- Goedkoop, M. and R. Spriensma (2000), *The Eco-indicator 99: A Damage Oriented Method for Life Cycle Impact Assessment*. Report. The Hague, The Netherlands: Ministry of Housing, Spatial Planning, and the Environment (<http://www.pre.nl>).
- Graedel, T.E. and B.R. Allenby (1995), *Industrial Ecology*. Englewood Cliffs, New Jersey: Prentice Hall.
- Guinée, J.B., H.A. Udo de Haes and G. Huppes (1993a), 'Quantitative Life Cycle Assessment of Products, Part 1: Goal Definition and Inventory', *Journal of Cleaner Production* **1**(1), 3–13.
- Guinée, J.B., R. Heijungs, H.A. Udo de Haes and G. Huppes (1993b), 'Quantitative Life Cycle Assessment of Products, Part 2: Classification, Validation and Improvement Analysis', *Journal of Cleaner Production* **1**(2), 81–91.
- Hart, S.L. (1997), 'Beyond Greening: Strategies for a Sustainable World', *Harvard Business review* **75**(1), 66–76.
- Hoshino, T., K. Yura and K. Hitomi (1995), 'Optimisation Analysis for Recycle-oriented Manufacturing Systems', *International Journal of Production Research* **33**(8), 2069–2078.
- IFIAS (1973), Report of the International Federation of Institutes for Advanced Study Workshop no. 6 on Energy Analysis, Guldsmeshyttan, Sweden: IFIAS.

- Kandelaars, P.P.A.A.H. and J.C.J.M. Van den Bergh (1997), 'Dynamic Analysis of Materials-product Chains: An Application to Window Frames', *Ecological Economics* **22**(1), 41–61.
- Krikke, H.R. (1998), *Recovery Strategies and Reverse Logistic Network Design*, Ph.D. Thesis. Enschede, The Netherlands: Twente University.
- Krikke, H.R., A. Van Harten and P.C. Schuur (1998), 'On a Medium Term Product Recovery and Disposal Strategy for Durable Assembly Products', *International Journal of Production Research* **36**(1), 111–139.
- Lambert, A.J.D. (1999), 'Linear Programming in Disassembly/clustering Sequence Generation', *Computers and Industrial Engineering* **36**(4), 723–738.
- Ruth, M. (1993), *Integrating Economics, Ecology and Thermodynamics*. Dordrecht, The Netherlands: Kluwer Academic Publishers.
- Smith, B. (1999), 'Packaging Regulations Review', *Logistics Focus* **7**(3), 25.
- Stahel, W.R. (1994), 'The Utilisation-focused Service Economy: Resource Efficiency and Product-life Extension', in B.R. Allenby and D.J. Richards, eds., *The Greening of Industrial Ecosystems*. Washington DC: National Academic Press, pp. 178–190.
- Starreveld, P.F. and E.C. van Ierland (1994), 'Recycling of Plastics: A Materials Balance Optimisation Model', *Environmental and Resource Economics* **4**, 251–264.
- Thierry, M., M. Salomon, J. van Nunen and L. van Wassenhove (1995), 'Strategic Issues in Product Recovery Management', *Californian Management Rev.* **37**(2), 114–135.
- Tillman, A.-M., T. Ekvall, H. Baumann and T. Rydberg (1994), 'Choice of System Boundaries in Life Cycle Assessment', *Journal of Cleaner Production* **2**(1), 21–29.
- Veroutis, A.D. and J.A. Fava (1997), 'Elements of Effective DFA Program Management and Product Stewardship', *Environmental Quality Management* **7**(1), 61–70.
- Wilck, J. (1997), 'Responsible Care Makes Global Moves', *Chemical Market Reporter* **252**(2), SR 16–17.

