Re-use : international working seminar : proceedings, 2nd, March 1-3, 1999

PROCEEDINGS

SECOND INTERNATIONAL WORKING SEMINAR ON RE-USE

Eindhoven, The Netherlands
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Supported by EHTB
(European Professors of Industrial Management)

Host:
Eindhoven University of Technology
Faculty of Technology Management

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Simme Douwe P. Flapper & Ad J. de Ron

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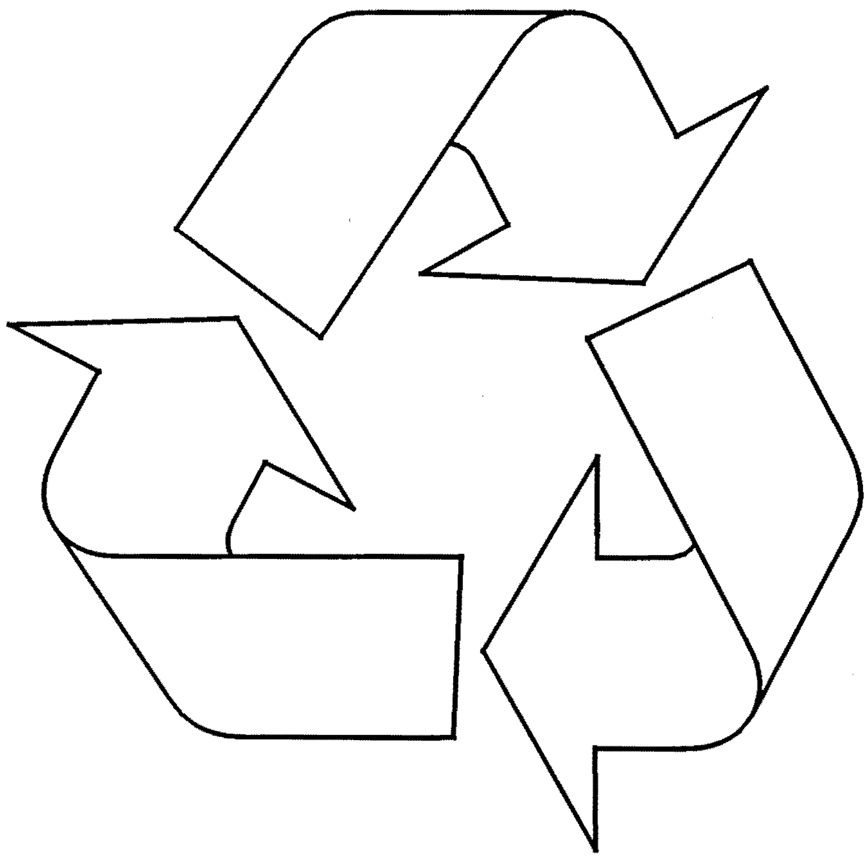

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CONTENTS page

Bi-destination waste collection: impact of vehicle type and operations on transportation costs

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Abstract

Consider two types of waste originating from numerous customers in a given service region. Before the actual collection day, customers call-in for a collection request for either one or both types of waste. Waste 1 needs to be transported to one depot, waste 2 to another one at a given distance from the first. How should the collection be organised: separately with specialised vehicles or combined with dual-compartment vehicles?

This strategic question is analysed using a probabilistic approach. Relationships are derived between spatial parameters and relative effectiveness of the routing policies. Effectiveness is measured in terms of total distance travelled. It appears that the best strategy is determined by a combination of several parameters: the relative size of the average waste 1 quantity to the average waste 2 quantity; the ratio of combined requests to the total requests of waste 1; the ratio of total requests of waste 2 to total requests of waste 1; and the ratio of average waste volume to vehicle or compartment capacity. The framework also offers insight in the role of vehicle type capacity, the metric of the underlying road network, the distance between both depots and the shape and area of the service region.

key words: vehicle routing, multi-flow waste collection, vehicle design, spatial context parameters.

1 Introduction

For the purpose of reuse or recycling, many products flow at their end-of-life from the users back to producers or recovery companies. The logistical management of these take back flows is the field of reverse logistics. Managing reverse logistics involves the application and extension of known models in the context of distribution planning, inventory management and production planning. For an introduction to this field we refer to Fleischmann *et al.* (1997), van der Laan (1997), Flapper and de Ron (Eds.) (1996), Thierry *et al.* (1995) and Kopicki *et al.* (1993).

As a consequence of this evolution, the treatment of solid waste is drastically changing in many countries of Western Europe. First, both households and industrial organisations are encouraged by regulations or economic incentives to separate waste into categories or types. Typical categories are enlisted in Table 1. Second, the collection of waste is being transferred from the public to the private sector, sometimes through public-private partnership mechanisms. Third, waste categories are separately treated in specialised processing facilities.

Table 1: *Waste categories and processing facilities.*

Category or type	*Processing facility*
Rest fraction (solid garbage)	Incinerator or landfill
Wood waste	Green depot or incinerator
Plastic - Tin cans	Recycling or recovery centre
Paper - Corrugated cardboard (uncontaminated)	Paper mill, cardboard mill
Glass (white, green, brown)	Separation and grinding centre
Concrete and asphalt waste, Demolition materials	Road construction facility
Scrap metal	Scrap brokers
Fridges and freezers	Recycling or recovery centre
Computers	Remanufacturing centre
Wet & dry cell batteries, Paint - Oil – Solvents, Tires	Specialised treatment centre

In this context, some waste types need to be kept separate from source to destination. At the source, they are therefore separately stored in containers (or bins, boxes, bundles, bags). Some waste categories can be commingled. In Flanders e.g., plastics as well as tin cans are thrown in the same bag. The separation level should be ultimately dictated by the capability of the processing facility or end-market to accept commingled recyclables or products.

Waste collection and transportation often require specialised vehicles. Different vehicle designs offer different features: hydraulic lifting devices on the side, front, or rear to assist loading waste into the vehicle and thereby to reduce worker fatigue and injury; hydraulic mechanisms to speed up unloading; packing presses to increase total collected weight and cranes to lift bell-shaped containers.

Some recent truck designs have evolved to assist the collection of source-separated recyclables. Different types of multi-compartment trucks emerge on the market, some of them flexible within some limitations in number of compartments, others in the selection of capacity and compaction of the compartments to suit the material mix (see Graham, 1993).

Other truck types focus on multi-mode capabilities. These one-compartment trucks consist of automated cart lifters at the front-left/right sides. The large collection container at the back can be easily transferred to railway carriages or trailers (which can be picked up by so-called LCVs or 'longer combination vehicles', see e.g. MacDonald 1991).

Another consequence of source-separated waste types is the multi-destination aspect. Whilst garbage used to go to the nearest suitable landfill site or incinerator, some waste streams now end up in more specialised treatment centres. In Flanders, e.g. there are several centres for the recycling of plastics and glass, while another centre specialised in the treatment of white and brown goods, called AppaRec, is currently being opened at Tisselt. Other types, such as personal and portable computers can be transported to remanufacturing centres that rebuild products based on a mix of new and reused components.

Since processing costs and disposal fees are exogenous factors, a (private) collector can only make a profit by optimising capital and operating costs. By the specific features of each design, the vehicle type influences not only capital but also operating costs considerably. The problem further addressed in this paper illustrates this. The solution methodology uses results from (asymptotic) probabilistic analysis. It allows identifying, within a framework of a few general assumptions, a set of relevant parameters that influence operating costs. It also leads to analytical expressions for the expected costs in a given scenario. It can provide insight without actually getting involved in the complex underlying combinatorial problem. While some authors adopt the approach to prove asymptotic optimality of certain routing heuristics (e.g. Karp 1977, Haimovich and Rinnooy Kan 1985), it is also suited for the strategic design of transportation systems (see e.g. Stein 1978, Anily 1994).

The paper's structure is as follows. In §2 the problem is described as well as important characteristics of the problem environment. §3 derives results for the case of a single vehicle and illustrates the importance of certain parameters. In §4 the multi-vehicle case is treated similarly. Summary and conclusions can be found in §5.

2 Problem description

Consider two types of waste originating from numerous customers in a given service region (Fig. 1). Before the actual collection day, customers call for a collection request for either one or both types of waste. It implicates that the locations to be visited every collection day will change from one collection day to the other. Waste 1 needs to be transported to depot 1, waste 2 to depot 2.

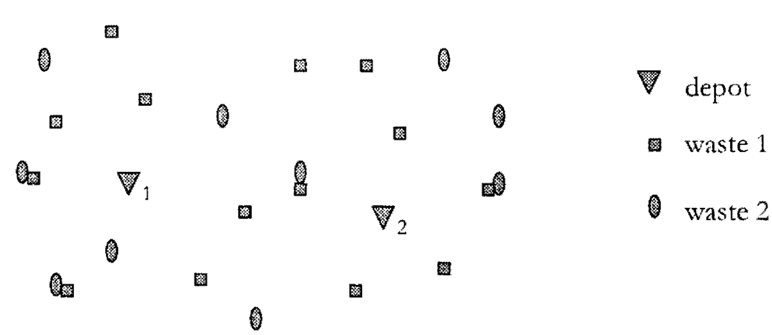

Fig.1: *Dual-flow waste collection. Each flow has its own destination depot.*

How should the collection be organised, e.g. separately with specialised vehicles or combined with dual-compartment vehicles? Four routing policies appear based on two characteristics: single or dual compartments, and single- or multi-purpose compartments (a compartment is dedicated to a waste type or not) (Fig. 2 and Table 2).

Table 2: *Characteristics of each routing policy.*

Routing Policy	*Degree of Flexibility*	***Compartments /vehicle***	***Multi-purpose Compartments***	*Collaboration*

Sepr	Low	1	No.	Not present.
Seprc	Moderate	1	Yes.	High: collection as well as cleaning compartments.
Combr	High	2	No.	Present: collection
Combrc	Highest	2	Yes.	High: collection as well as cleaning compartments.

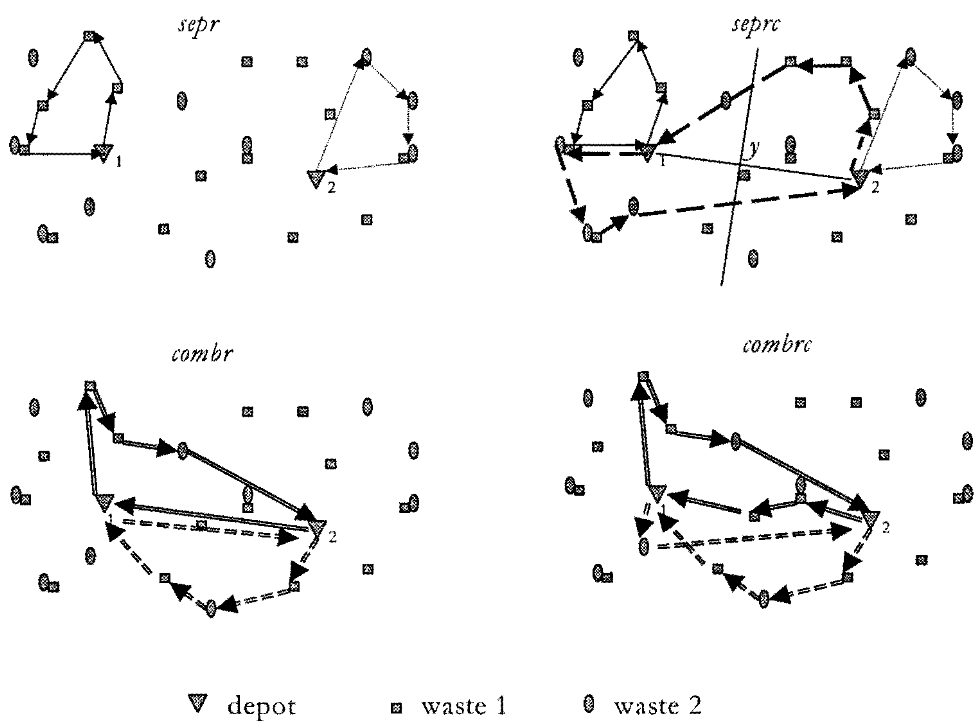

Fig. 2: *Four routing policies.*

- *Separate routing – no collaboration* (*sepr*). A number of single-compartment vehicles based at depot 1 collect waste 1. Single-compartment vehicles located at depot 2 collect waste 2.
- *Separate routing with collaboration* (*seprc*). Each depot serves its own fixed region and has a number of single-compartment vehicles. In each region, vehicles collect waste of a certain type and deliver to the depot which accepts that type of waste. A vehicle which has changed depot either continues with collecting waste of the other type in the other region and delivers to his home depot, or returns empty to his home depot.
- *Combined routing* (*combr*). A number of dual-compartment vehicles located at depot 1 collect wastes 1 and 2, deliver to depot 2, and return to depot 1 to deliver waste 1. Dual-compartment vehicles at depot 2 perform a similar routing.
- *Combined routing with multi-purpose compartments* (*combrc*). A number of dual-compartment vehicles located at depot 1 collect wastes 1 and 2, deliver to depot 2, and either additionally collect

waste 1 and deliver to depot 1 if there is any or return to it empty. Dual-compartment vehicles at depot 2 perform a similar routing.

The degree of flexibility in terms of vehicle design as well as collaboration increases with the policy (Table 2). However, a higher degree of flexibility does not necessarily imply lower operating costs. Cleaning compartments for example can require additional time and resources. Collaboration can imply empty travelling back and forth between depots. But the picture is even more complicated because of the impact of the *spatial context* on operating costs. To keep things as simple as possible, only total distance travelled will be the focus of following sections.

The spatial context can be described with the following parameters. Consider in general the presence of three types of customers: *type 1 customers* with a request to collect waste 1, *type 2 customers* with a request to collect waste 2, and finally *type 12 customers* with both requests. n_1, n_2 and n_{12} represent respectively the number of type 1, type 2 and type 12 customers.

Both customers and depots are located in a service region. Let X denote the distance between depot 1 and depot 2. Let A represent the area of the service region. Whenever the region is split into two (e.g. under *seprc*), one region is indicated by A_1 and has area fA, the other by A_2 with area $(1-f)A$. Customers as well as depots are the nodes of a connected graph.

Define β as the ratio of total (number of) type 2 requests to total type 1 requests. β can be expressed as

$$\beta = \frac{n_2 + n_{12}}{n_1 + n_{12}}. \tag{1}$$

Artificially, count one depot as an exchange customer while defining $n_{120} \equiv n_{12} + 1$, and two depots while $n_{1200} \equiv n_{12} + 2$. Then $\beta_0 \equiv \beta(n_1, n_2, n_{120})$, and $\beta_{00} \equiv \beta(n_1, n_2, n_{1200})$, Let γ be the number of exchange customers to total deliveries, or

$$\gamma = \frac{n_{12}}{n_1 + n_{12}}. \tag{2}$$

Define $\gamma_0 \equiv \gamma(n_1, n_{120})$ and $\gamma_{00} \equiv \gamma(n_1, n_{1200})$. For example: contexts with only type 1 and 12 customers have $\beta = \gamma$ and $0 < \beta \leq 1$; contexts with only type 2 and 12 customers have $\gamma = 1$ and $1 \leq \beta < \infty$; and context with only type 1 and 2 customers have $\gamma = 0$ and $0 < \beta < \infty$. Only situations where the number of waste 1 requests is not smaller than the number of waste 2 requests ($\beta \leq 1$) need our attention. To see why this is true, remark that by changing the role of '1' and '2' in all the formulas which were or will be presented, the case '$\beta \geq 1$' is described with the formulas for $\beta \leq 1$.

Let q_1 (q_2) indicate the average size of a waste 1 request (waste 2 request). Define ε as the ratio

$$\varepsilon = \frac{q_2}{q_1}. \tag{3}$$

C denotes the capacity of a vehicle measured in weight or volume of the relevant waste. Assume C is at least as large as the size of the largest request.

Routing policy names are abbreviated to *sepr*, *seprc*, *combr* and *combrc* in general (see Table 1) and to *sepr,o*, *seprc,o*, *combr,o* and *combrc,o* for the special case of a single vehicle. To compare the policies, it is investigated whether one policy dominates the other (is better in all circumstances). Second, policies for which such a dominance relationship does not exist are compared on the basis of the following measure. Define DR_{XY} as the relative reduction in distance travelled resulting from the adoption of routing policy X instead of Y:

$$DR_{XY} = \frac{D_Y - D_X}{D_Y}, \tag{4}$$

where D_i is the total distance travelled in the optimal solution of policy i. The impact of the spatial context can now be related to the behaviour of DR as a function of the spatial context parameters.

3 Single-vehicle

It was suggested in §2 that the spatial context can have an impact on the relative efficiency of the policies. In this and subsequent sections, the aim is to characterise circumstances.

In the single-vehicle case the one-compartment vehicle has sufficient capacity to collect all waste 1 (2) requests in the region in one single tour starting from depot 1 (2). The two-compartment vehicle can thus collect all requests in at most two tours. For *seprc*, the class of solutions considered are the ones where the region is subdivided by a line orthogonal to the line which connects both depots and crosses this line at a distance y from depot 1 ($0 \leq y \leq X$) (Fig. 2).

Assume the following:

I. the location of numerous customers is drawn independently from the uniform probability distribution over the region,

II. the graph has Euclidean distances.

An important remark is that the statements that will be presented are true in probability. This means that one can always find examples (instances) in which they do not hold. The results only give a good indication of the average behaviour which will result by repeated routing. Thus, the formulas reflect what would be the long term average advantage of one routing policy compared to the other when frequently applied. The deviation between instances and average behaviour will become smaller when the number of customers are increasing.

The underlying methodology stems from the work of Beardwood *et al.* (1959). If $TSP(n)$ is the length of the optimal travelling salesman tour through n points which are independently drawn from the uniform probability distribution over a bounded region of the Euclidean plane with area A, then there exists a constant k' such that with probability one

$$\lim_{n \to \infty} \frac{TSP(n)}{\sqrt{n}} = k' \sqrt{A} . \tag{5}$$

This means that the random variable *TSP(n)* is asymptotically equal to $k'\sqrt{A}\sqrt{n}$ - a nonrandom function of n - with probability 1. k' is believed to be ≈ 0.75. More informally, if d denotes the average distance per point on *TSP*(n), then with high probability

$$d \approx k'\sqrt{A/n}\,, \tag{6}$$

when n is large. As denoted by e.g. Daganzo (1984) it is striking that the right-hand-side of (6) is also a good approximation for the expected distance d in circular and square areas even with *small* n (even for the smallest meaningful number n = 2). Experiments by Stein (1977) confirm these observations.

Proposition 1: In the single-vehicle case, a multi-purpose compartment gives at least as long distances in the optimal routing than a single-purpose compartment.

From (6), it can be deduced that for a finite number of customers:

$$D_{sepr,o} \leq D_{seprc,o} - X \tag{7}$$

$$D_{combr,o} \leq D_{combrc,o} \tag{8}$$

with D_X representing the expected value for the total distance in the optimal solution for policy X. (7) implies that *sepr,o* dominates *seprc,o*, (8) that *combr,o* dominates *combrc,o*, and together they imply that only *sepr,o* and *combr,o* need to be compared for proving proposition 2.

Proposition 2: For a finite number of customers, there is no dominance relationship between single- and dual compartments in the single-vehicle case.

This can be shown by the following bounds on the distance reduction between a dual- and single-compartment vehicle. Based on (6), it can be shown that for a finite number of customers:

$$DR^{LB}_{combr,o\;sepr,o} = \frac{1+\sqrt{\beta_o} - \sqrt{1+\beta_o-\gamma_o} - \dfrac{2X}{k'\sqrt{A}\sqrt{n_1+n_{120}}}}{1+\sqrt{\beta_o}} \tag{9}$$

$$DR^{UB}_{combr,o\;sepr,o} = \frac{1+\sqrt{\beta_{oo}} - \sqrt{1+\beta_{oo}-\gamma_{oo}} - \dfrac{X}{k'\sqrt{A}\sqrt{n_1+n_{1200}}}}{1+\sqrt{\beta_{oo}}} \tag{10}$$

with DR_{XY} defined by (4), and D_X indicating expected values. Superscript *LB* (*UB*) denotes lower bound (upper bound). Fig. 3 expresses the right-hand sides of (9) and (10) as functions of $\beta o(o)$ and with parameters $\gamma o(o)=\beta o(o)$ respectively *0*, A=10000, X=150, $n_1+n_{10(0)}$=100. Positive values of *DR* indicate that *combr,o* is better than *sepr,o*, negative values the opposite.

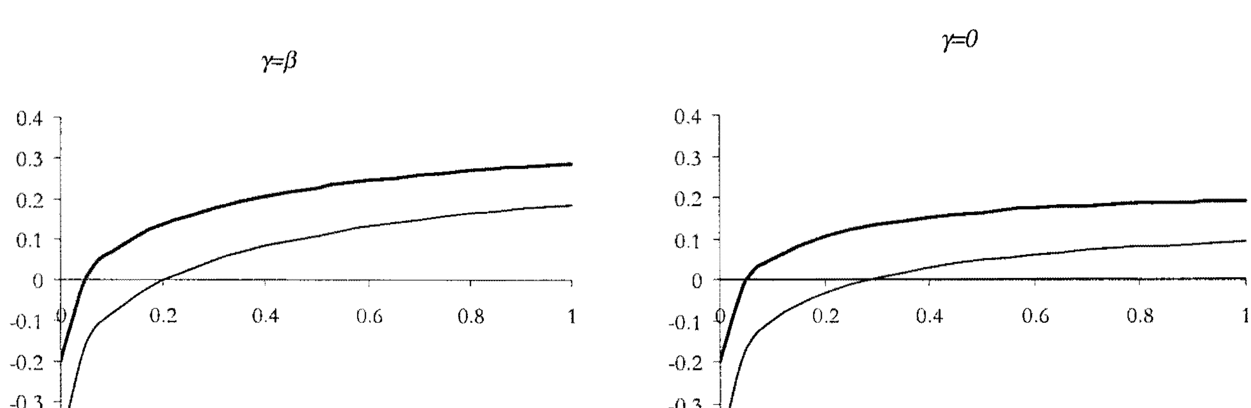

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Fig. 3: *Illustration of formulas (9) and (10).*

4 Multi-vehicle

Vehicles have a limited capacity C and besides I and II it is additionally assumed that all waste 1 (2) requests have an equal size q_1 (q_2). Let $\bar{r}_{di}^{A_j}$ denote the expected distance between depot i and requests located in region A_j.

Proposition 3: In the multi-vehicle single-compartment case, there is no dominance relationship between single- and multi-purpose compartments.
Based on (6), it can be shown that for a finite number of customers the following statement holds:
If

$$(1-f)\left(\bar{r}_{d1}^{A_2} - \bar{r}_{d2}^{A_2}\right) + f\left(\bar{r}_{d2}^{A_1} - \bar{r}_{d1}^{A_1}\right)\beta\varepsilon < \left|1-(1+\beta\varepsilon)f\right| X , \qquad (11)$$

then $D_{sepr} < D_{seprc}$.

Proposition 4: In the multi-vehicle dual-compartment case and for a finite number of customers, there is no dominance relationship between single- and multi-purpose compartments.
Similarly, it can be shown that:
If

$$\left(\bar{r}_{d1}^{A_2} + \bar{r}_{d2}^{A_2}\right)\left(1-\beta\varepsilon-\frac{1}{\beta\varepsilon}\right) + X\left(1+\beta\varepsilon+\frac{1}{\beta\varepsilon}\right) < \frac{k\sqrt{A}\,C}{q_1\sqrt{n_1+n_{12}}}\left(\frac{1+\sqrt{\beta}-\sqrt{1+\beta-\gamma}}{1+\beta\varepsilon}\right), \qquad (12)$$

then $D_{combr} < D_{combrc}$.

A_1 (A_2) in (11) is the region assigned to depot 1 (2) under *seprc*. Fig 4. illustrates the test condition (11) for $\varepsilon = 1, f = 0.5$, $X = 100$, $\bar{r}_{d1}^{A_2} = \bar{r}_{d2}^{A_1} = 100$, and $\bar{r}_{d1}^{A_1} = \bar{r}_{d2}^{A_2} = 100$. As β increases or X decreases, collaboration becomes more and more effective in terms of distance travelled. However Fig. 4 makes clear that for some subsets of the parameter space no collaboration is preferable.

$\mathcal{A}_2$ in test condition (12) is the region in which requests are collected on the returntrip to the home depot under *combrc*, and $\mathcal{A}_1$ is its complement in $\mathcal{A}$. *k* is a constant, 0.57. Fig. 5 illustrates (12) for $\varepsilon = 1$, $\gamma = \beta$, $X = 100$, $\mathcal{A}=21025$, $n_l+n_{l2} = 200$, $\bar{r}_{d1}^{A_2} = \bar{r}_{d2}^{A_2} = 75$ and $C/q_l = 10$. Multi-purpose compartments appear to be often better in terms of distance travelled (especially for higher values of β), but not in all cases.

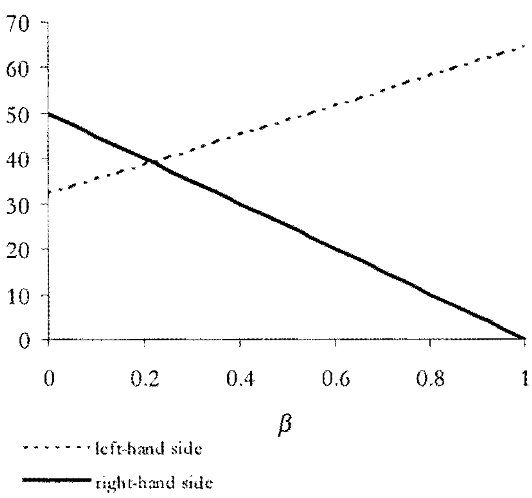

Fig. 4: *Illustration of (11).*

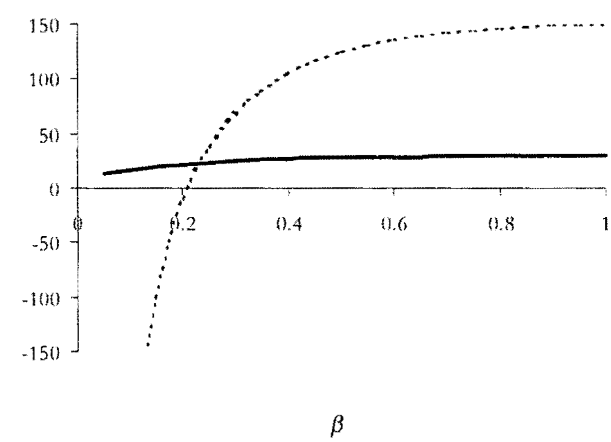

Fig. 5: *Illustration of (12).*

5 Conclusions

These results are preliminary. They demonstrate how spatial arrangement influences the performance of a particular vehicle type (single- versus dual-compartments) and routing policy (collaboration between the depots or no collaboration, single- versus multi-purpose compartments with intermediate cleaning). It became clear that no single policy dominates, instead the relative performance can alter from one spatial context to the other. Further research in this area should deal with a closer comparison of these policies for the multi-vehicle case and the determination of optimal regions under the two policies with multi-purpose compartments.

6 Acknowledgments

This work was supported in part by the European Commission under the RELOOP project (Reverse Logistics Chain Optimisation in a Multi-User Trading Environment), ESPRIT Project No. 255527.

The authors like to thank Prof. L. Van Wassenhove of INSEAD and the members of the REVLOG research group (Reverse Logistics and its Effects on Industry) for the co-operation. The European Commission sponsors REVLOG (ERB 4061 PL97-0650, TMR Programme).

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Supply Chain Management Issues in the Realisation of Circular Economies for Electrical and Electronic Equipment

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The EU and anticipated legislation in the member countries as well as the environmental awareness of the customers forces manufacturers to be responsible for their products at end-of-life (EOL). World-wide, waste from technical products is becoming an issue of attention, causing concern for the manufacturing industry as it is unsure how it will finance such a responsibility. Additionally, it needs to be recognised, that only economical recycling can be the ultimate incentive for companies to support Circular Economies. The design of products with respect to EOL aspects and the establishment and management of economically and ecologically sensible structures for Circular Economies have to consider various Supply Chain Management issues. Forms of related supply chains are described together with the optimisation and management challenges tackled in the three EU-funded research projects TOPROCO, ElectSME and RELOOP. TOPROCO has led to a 1st generation DFR tool. Its shortcomings will be overcome by the ElectSME approach of a 2nd generation tool. RELOOP focuses on the optimisation of take-back activities and reverse channel management.

1 The Importance of the EOL Value Concept

Markets have changed from seller driven to buyer driven business transactions, putting industry under heavy pressure in terms of cost, time-to-market, quality, flexibility and variety. An increase of world population within the next 50 years from 5.5 Billion to 11 Billion is estimated (AltAss94), together with a factor five increase in the overall consumption of energy and raw materials. Even landfill space is becoming a scarce resource, especially in Europe (UmwJah93) (SprDes92). Environmentally conscious behaviour serves industry as a paradigm on its way into the next millennium due to the potentials in satisfying customers' expectations, in attracting new customers and in cutting costs (WecKos94). On an international level ISO 14000ff describes the development and implementation of environmental management systems. In August 1997 more than 1000 European industrial sites had an environmental management system according to the European Eco-Audit scheme in place (ReyBet98). A vital part of holistic approaches for environmentally sensible business behaviour is the production of 'green' goods, together with the realisation of sustainability concepts and Circular Economies, as already dictated by law in Germany (VDI2243/1) (BauPer93) (oVGes94).

Next to customer demand and legislative constraints, where the EU acts a trend-setter (oVFoc97) (EurWor97) (oVEUW98), two major sources of motivation for environmentally sound behaviour can be identified: personal or ethical motives and monetary incentives.

The concept of the End-of-Life Value (EOL Value) is introduced in order to emphasise the fact that only economical recycling can provide the ultimate and long-term incentive for companies to support actively the realisation of Circular Economies. For the EOL Value, the following equation can be developed:

EOL Value = Revenue from material and components for reuse
- cost for collection and transportation of EOL equipment
- cost for processing EOL equipment

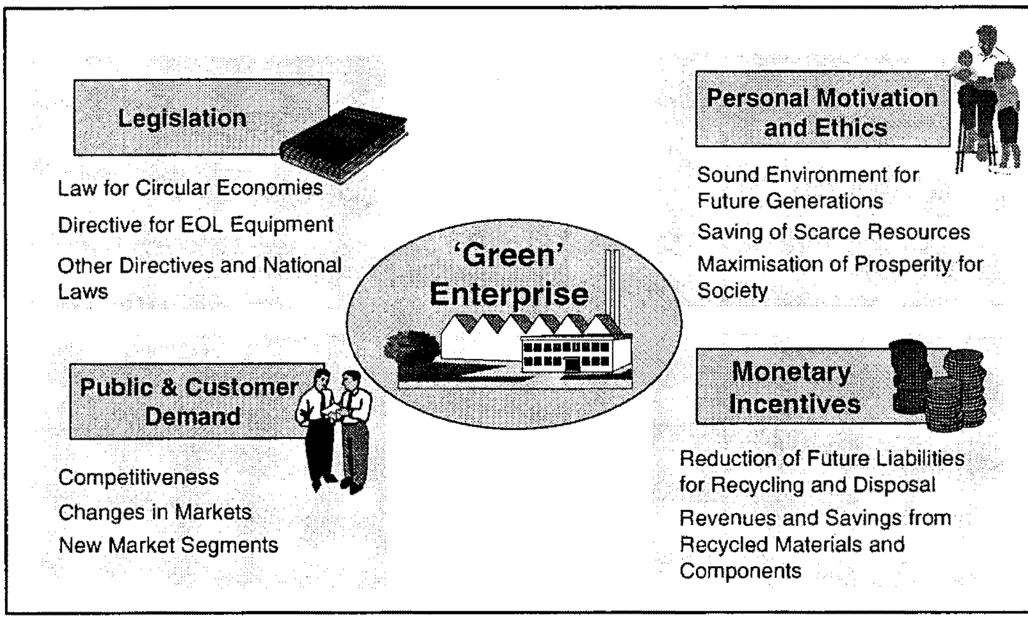

Figure 1: Motivation for environmentally sound behaviour.

Waste from Electrical and Electronic Equipment (WEEE) has been ranked a priority waste stream in Europe by the European Commission. About 1.5 to 2 Million tons of WEEE are to be disposed of yearly in Germany alone (oVLös93), with an increasing tendency due to the high dynamics of innovation within electronics industry. The material content of WEEE reflects almost the entire periodic system with numerous hazardous substances, in many cases of imported equipment even of unknown composition. Cost for the disposal or recycling of WEEE are estimated at two to thirteen ECUs (MalKom95) (oVEUW98) a piece, totalling for the EU to about 1.5 (GruRec95) to 7 Billion ECUs (oVBew94).

2 Product Development and Design for Recycling

Product development is the phase in a product's life cycle, where the highest impact on cost and on product properties, also in terms of environmental soundness can be achieved (EhrMög80) (WarNac97). 90% of German researchers have ranked 'recycling-orientated product design' as a 'topic of utmost importance' (GruDeu93). Similar results are shown in other studies (DeuUmw97) which also state the need for supporting tools and methods (AltLif91) (FabSys92), especially in terms of optimisation of the EOL Value (BulToo97) (HarKen97). Also in the US, electronics industry has decided to 'better act than react' (SieEle96). Even within the product development phase, major emphasise has to be put on the early stages where high impact on product properties can be realised at very low effort. However, a dilemma can be derived from the low availability of data and the high uncertainty in decision making (BocExp95).

A variety of fundamental design and cost calculation literature as well as standards deal with methods and algorithms to determine cost at early stages of product design for manufacturing, assembly and sometimes service, such as (EhrKos85) (GerKos94) (PahKon86) (KolKon85) (RodMet76) (DIN32990/1) (DIN32992) (DIN69910) (VDI2225) (VDI2234) (VDI2235). Design for Excellence (DFX) methodologies have been introduced to consider a variety of requirements, stemming from a products life cycle, already in product design (BulFor97). Tools are readily available to cover the early life phases of products (EitPro96) (FreEin98) (BopKos95) (LebEnt95) (AsiPro98). Fundamental means to improve product design in terms of recycling aspects, such as checklists, examples design catalogues, manuals, value analysis, etc., have been collected and structured in (BriUmw94) (RenNut96) (SuhWis96) and (KahRec96). First approaches in the development of DFR methodologies (MeyRec82) (WeeRec81) (JorPro90) (StePro88) (GehKon86) (VDI2243/1) (SteCos95) (KamPro95) (EveZuk92) (SuhWis96) (SteDFE96) (BeiGün93) (oVSon98) (GriStr96) and what can be called '1st generation' DFR tools have been made (HatDes96) (MiyECO96) (AraCAD93) (AlbKos96) (KahRec96) (ConEco96) (BraAct95) (KriBew95) (NavReS93) (JohPla95) (SpeInd94) (HarKen97) (IshThe93) (FelDes94) (FelLif97b) (EbaDes95) (oVSFB98). The state in industry in terms of support in the DFR area in Germany is depicted in Figure 2, according to (HarKen97). Recycling oriented product design is part of the bundle of integrative measures of environmentally sound business behaviour, and thus is to be preferred over the additive, post-use measures (BopMet98).

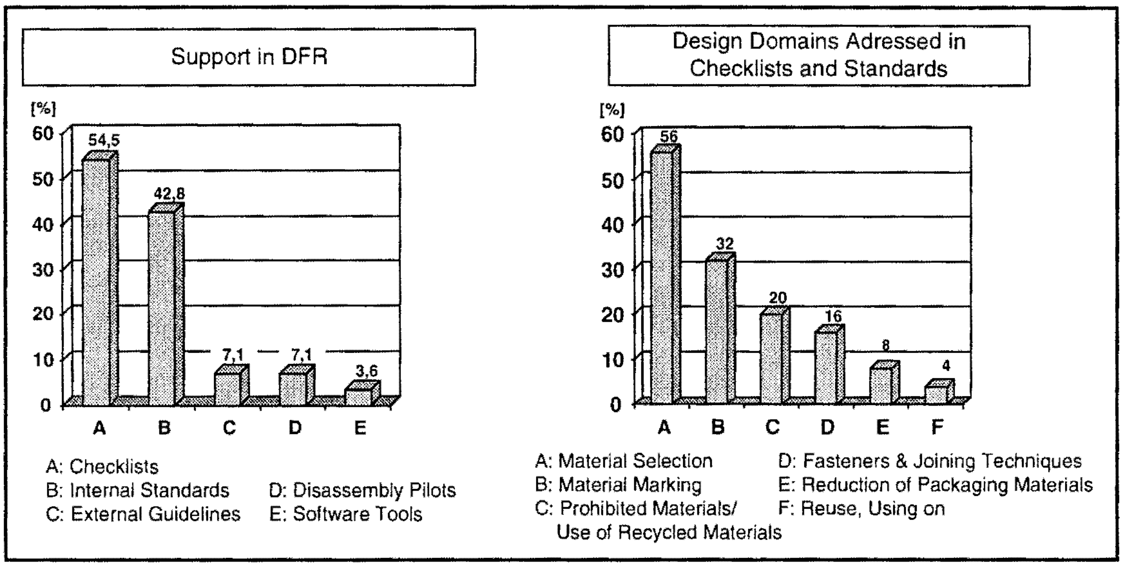

Figure 2: State of DFR support in industry.

A comprehensive overview of the state of the art related to tools and methods for Life Cycle Engineering is given in (AltLif95). A similar picture presents (DeuUmw97). The DFE-situation in the US can be found in (LenThe96). On a very general level (KraPot95) and (SteVer93) describe the requirements for an IT-infrastructure to connect manufacturing and recycling companies. (SteVer93) (oVIDEE97) and (FlaOrg95) describe database systems to support product and recycling data management.

3 Supply Chain Management in DFR and Product Take-Back

In recent years companies have changed from isolated actors to integrated network partners. Looking at industrial manufacturing activities, it becomes obvious that supply chains and networks of co-operation are the foundation for success in global markets. Extended and virtual enterprises are focus of the debate, requiring effective and efficient supply chain management strategies for materials, components, products and even more important, information.

In the product development phase supply chains can be identified in terms of company networks for product development. These networks consist of the OEM's design departments, development service providers such as external design companies, as well as module, system and component suppliers' design departments. It can only be of little benefit if OEMs try to optimise their products in terms of EOL value, not pursuing this goal in a co-operative manner with their suppliers and hence not including their degrees of freedom into their undertakings. A holistic approach based on the sharing of product model data needs to be taken in order to optimise product structure itself, material compositions, selection of fasteners and joining techniques as well as other aspects on all levels of the product structure.

For evaluation of recycling friendliness and EOL value optimisation it is crucial to take into consideration that products are sold in world-wide markets and are also recycled in locations distributed all over the world. Manufacturing companies seem to be setting up co-operative efforts with recycling companies all over Europe and other parts of the world. This leads to the necessity of multidimensional or distributed databases for effective EOL value optimisation, put into use in the supply chains' design departments, covering and providing data from decentralised recycling activities in very different social, technological and legislative environments at very different cost. Furthermore, highly fluctuating flows of WEEE in these different locations need to be taken into consideration as well as varying channel structures and processing stages, depending on the level of recycling pursued for a particular product, such as reuse, using on ('Up- vs. Downcycling') and material recovery. Today quite a variety of take-back systems for electrical and electronic equipment at EOL exist in Europe in forms of supply chains, or reverse logistics channels. But it is not only the interaction of the actors from the recycling network with the manufacturers, but also within the network itself which incorporate a high potential for increased efficiency. Methods and tools are sought for which will provide support in Take-back Logistics (TBL) management, offering strategic, tactical and operational support in order to reduce cost and environmental impact.

4 TOPROCO - A First Generation DFR Tool for EOL Value Optimisation

In order to explain the capabilities and deficiencies in efficient EOL value optimisation of the 1st generation DFR tools, the TOPROCO software (oVTOP98) will be demonstrated in this chapter. TOPROCO was developed in the 30 month European research project 'TOPROCO - Total Product Life-Cycle Cost Optimisation' in a co-operation of various companies from the EEE manufacturing and recycling sectors.

The calculation model and the cost drivers used in TOPROCO for the calculation of the maximum EOL value as the core element of the optimisation process is depicted in Figure 3.

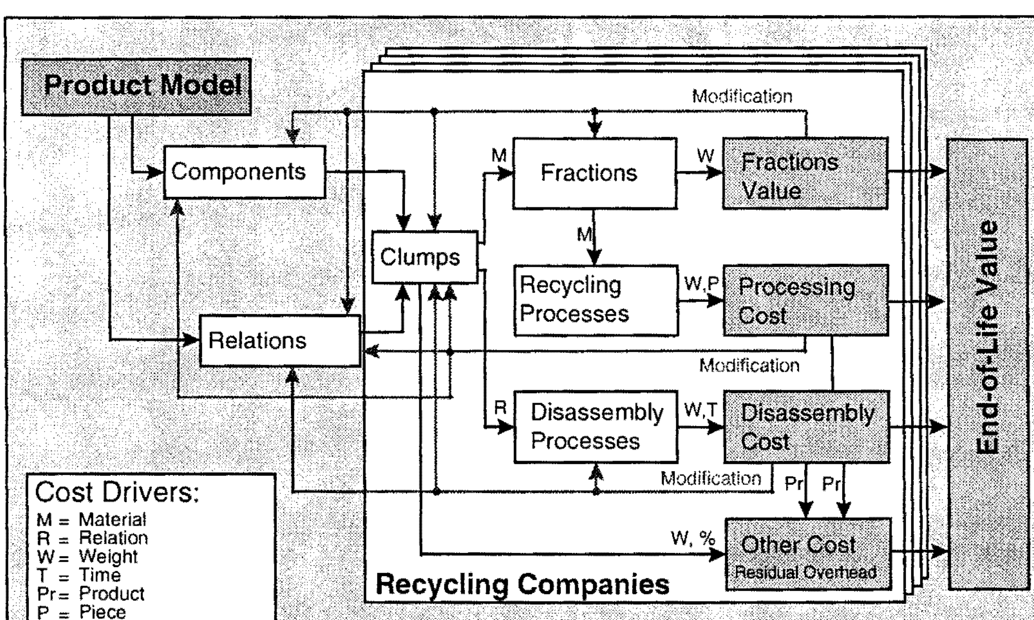

Figure 3: Calculation model of TOPROCO.

In order to overcome the hurdle stemming from the time gap between design of a product and its recycling, the TOPROCO project has developed a scenario modeller on a conceptual basis. A scenario modeller can act as an efficient support in enabling design engineers to consider future constraints for recycling. The need for interfaces to existing engineering tools has been identified. A comprehensive design support system has been included in the TOPROCO software, giving context sensitive design advice based on over 200 rules and examples. The conceptual system architecture is shown in Figure 5.

In the TOPROCO project a computer keyboard was selected as one of the test cases. The objective was to find an economical recycling strategy, in combination with minor redesign measures.

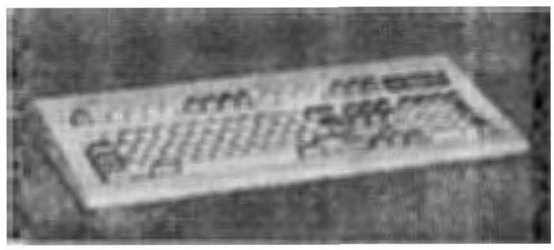

Figure 4: The 'Keyboard' test case from the TOPROCO project.

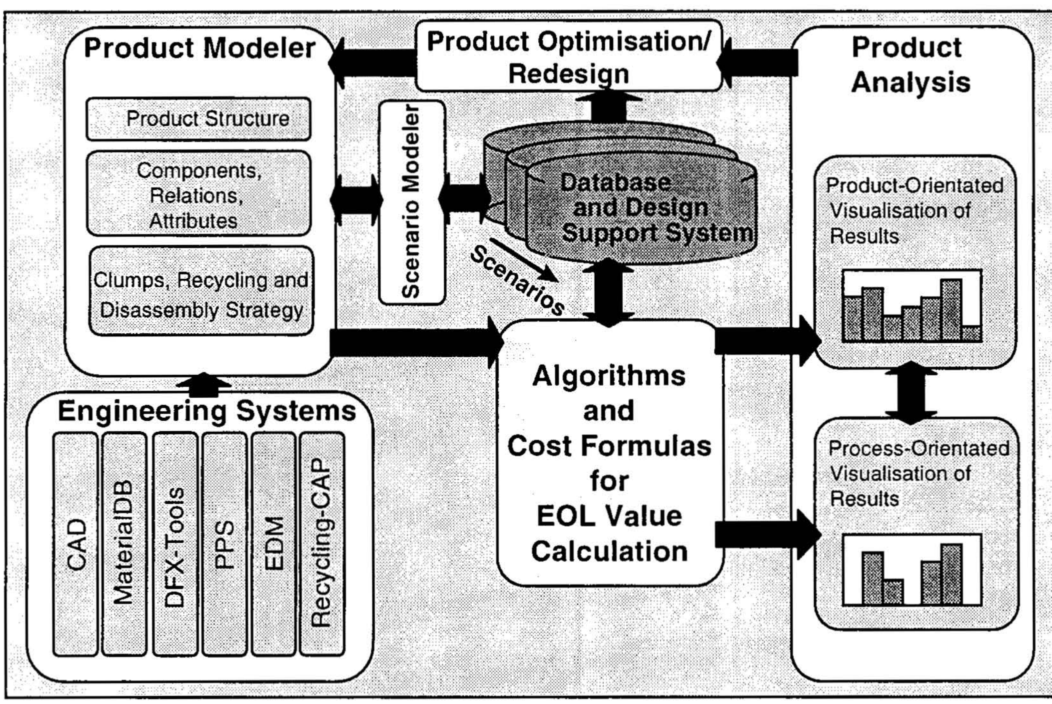

Figure 5: Conceptual architecture of the TOPROCO software.

Graphical product modelling is conducted through a semantic network of components, physical and logical relations, as well as their attributes, such as material compositions, disassembly directions, weights etc.. In Figure 6 the model for the keyboard is shown, together with the grouping of components into so-called clumps. Clumps are groups of components not to be disassembled any further, hence targeting at a common recycling process.

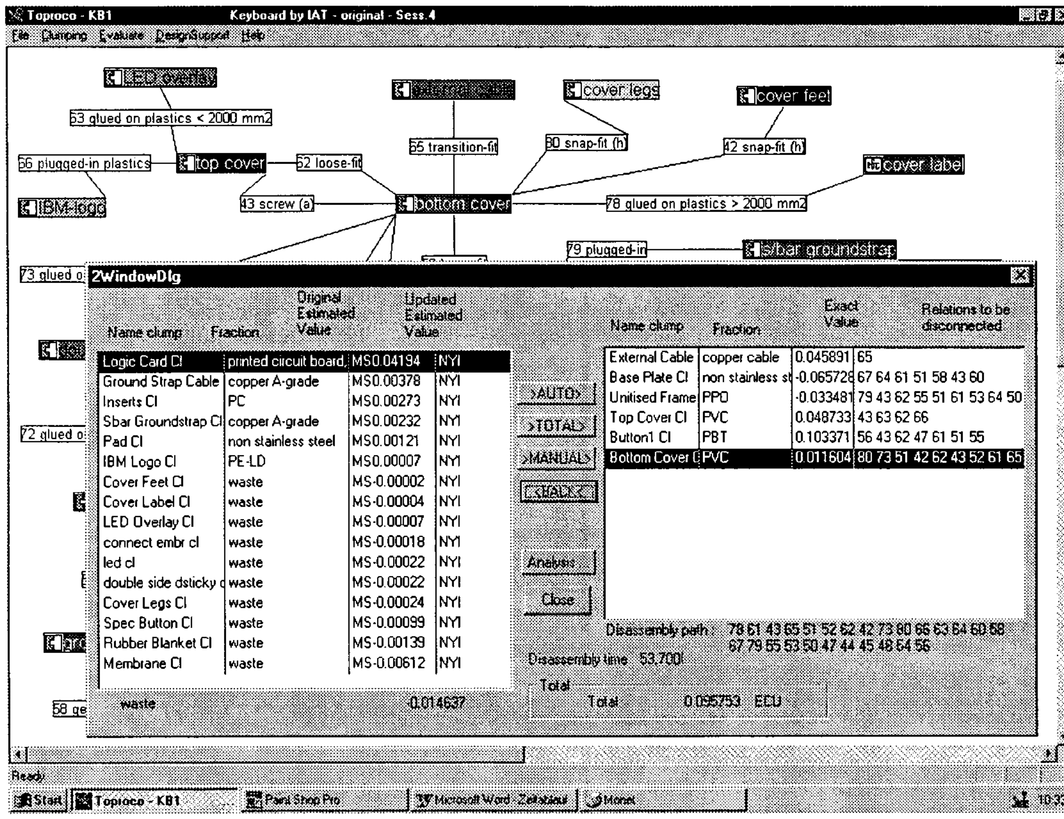

Figure 6: Product model, clumps and optimal recycling strategy of the test case.

Figure 6 also shows the optimal recycling strategy for maximising the EOL value, the clumps in the right hand side window being dismantled from the rest of the product in the left hand side window. Even without redesign measures an EOL value of about 0.1 ECU for one keyboard was realised, as opposed to the cost for disposal, which was in a magnitude of 0.3 ECU.

TOPROCO allows both a product-(or clump-)orientated and a process-orientated output of the contributors to cost and revenue. Simple redesign measures, using the TOPROCO design support system, allowed an increase of the EOL value from 0.1 ECU to almost 0.4 ECU (Figure 7).

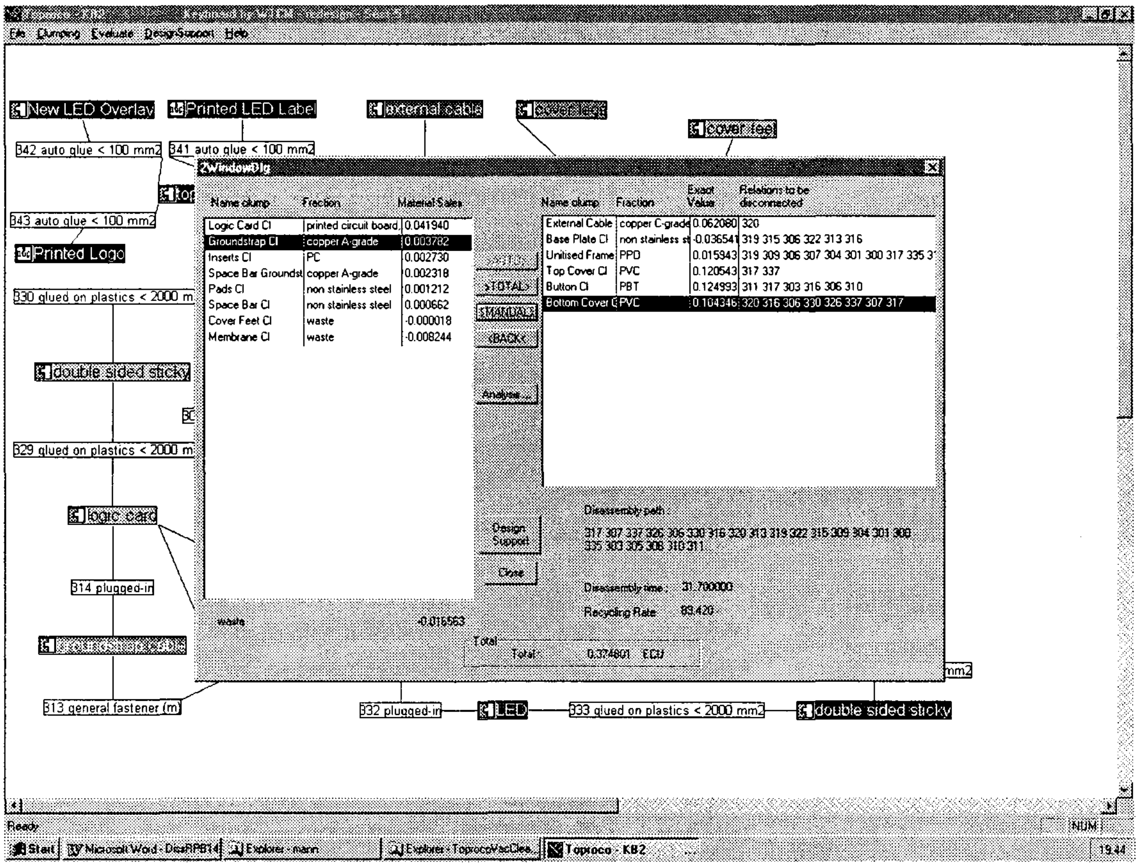

Figure 7: EOL value of the redesigned keyboard.

Other examples from the electronics, appliances and automotive industry show encouraging results in terms of validating the core methodologies used in TOPROCO.

5 Deficiencies of First Generation Design for Recycling Tool

Existing 1st generation DFR tools, such as TOPROCO, exhibit significant limitations with respect to the design phase in which they are used, standardisation and optimisation along entire supply chains as well as with respect to the requirements derived from multi-site recycling at EOL. As a matter of fact, the most important constraints not considered effectively in any of the 1st generation DFR tools are the supply chain management aspects. As a consequence these approaches are not employed in industry.

Up to 80% of the product-life-cycle costs are defined during the design phase which has led to the success of 'Design for X' engineering tools such as Design for Manufacturing. In order to efficiently integrate DFR tools into existing design processes that rely on CAD, as well as to exchange data between manufacturers and suppliers, systems have to use STEP as a basis, which up to now does not include recycling / environmental information.

By using appropriate design disciplines, such as Design for EOL Cost Elimination (DF EOL CE), the product's real value at EOL can be maximised and its waste fractions minimised. However, product design intended to eliminate recycling cost and generate end-of-life value requires a simultaneous and standardised optimisation methodology covering the entire product, including the numerous components and modules from suppliers, which are mainly SMEs. This design methodology should also cover the total design process from the conceptual design phase on, up to the detailed design. Additional constraints for the design engineer derived from the pursuit of the most appropriate design in terms of EOL value over an entire supply chain result in specifications and constraints for the designers which they have to obey during the whole product development process.

Support for this complex task has to be provided not only in forms of relatively crude 'Design for Recycling' guidelines, but context-sensitively by a rule-based expert system giving conceptual support during early design and detailed, specific advice during detailed design.

Optimisation processes in product design requiring the co-operation of several companies within the supply chain are only effective if a standardised model for storage and exchange of product model is put into use. Hitherto, no product data model reflects these requirements, hence the emerging STEP standard needs to be expanded.

Recycling of products sold in world-wide markets often requires decentralised recycling activities in order to minimise cost and environmental impact of take-back logistics. This complies with Europe's common strategy for waste management. Hence, recycling companies, also mainly SMEs, are co-operating with manufacturers and are distributed all over Europe. This in turns makes multi-site databases for the optimisation process a prerequisite, to be provided from all these co-operating recycling companies to allow for a design optimisation targeting at multi-site recycling.

Today's information technology allows distributed engineering and business applications as well as data exchange supported by global networks. Global Engineering Networks (GEN) applications are probably the most rapidly developing platform of co-operative distributed engineering on the Internet and on commercial networks. This approach allows all parties involved to update their portion of data, keeping the database constantly up-to-date. They also may access these data remotely from a customer-tailored client, as well as processing power, if required, and the required algorithms. Information handling has turned out to be critical to the economic success of collection and recycling activities.

From the deficiencies explained the need for a second generation DFR methodology can be derived.

6 ElectSME - An Approach for a Second Generation DFR Tool

In order to overcome the deficiencies of 1st generation DFR tools the ElectSME project has been set up. 'ElectSME - Elimination of End-of-Life Cost Through a Standardised Simultaneous Design Methodology for SME Supply Chains' is a three-year European Commission funded research project which has started in September 1998. The interdisciplinary consortium comprises eight European companies from the electronics industry, from the electronics recycling domain, as well as from research and software development. The project objective is to deliver proof to the entire manufacturing supply chain of the economic benefit of properly designed products for EOL while at the same time bridging the gap between recycling networks and design engineers.

ElectSME will provide innovations on:

1. how to co-operatively and simultaneously eliminate EOL cost over entire supply chains,
2. how to bridge the gap between designers and recycling companies' know-how by providing multiple recycling databases for reliable EOL optimisation,
3. how to include all available recycling technologies from material down-cycling all the way to product or component refurbishment, re-utilisation and reuse,
4. how to reflect future recycling technologies by means of a technology driven database,
5. how to provide context sensitive support in finding the optimal recycling strategy ,
6. how to support early design phases, where the effort to be put into required design changes is still low, and then transfer the optimised product model from this phase into any CAD / PDM environment, using a standardised format.
7. how to cast the methodology into a low-cost software tool, offering multi-user capabilities for design optimisations along the entire supply chain using multiple distributed databases.

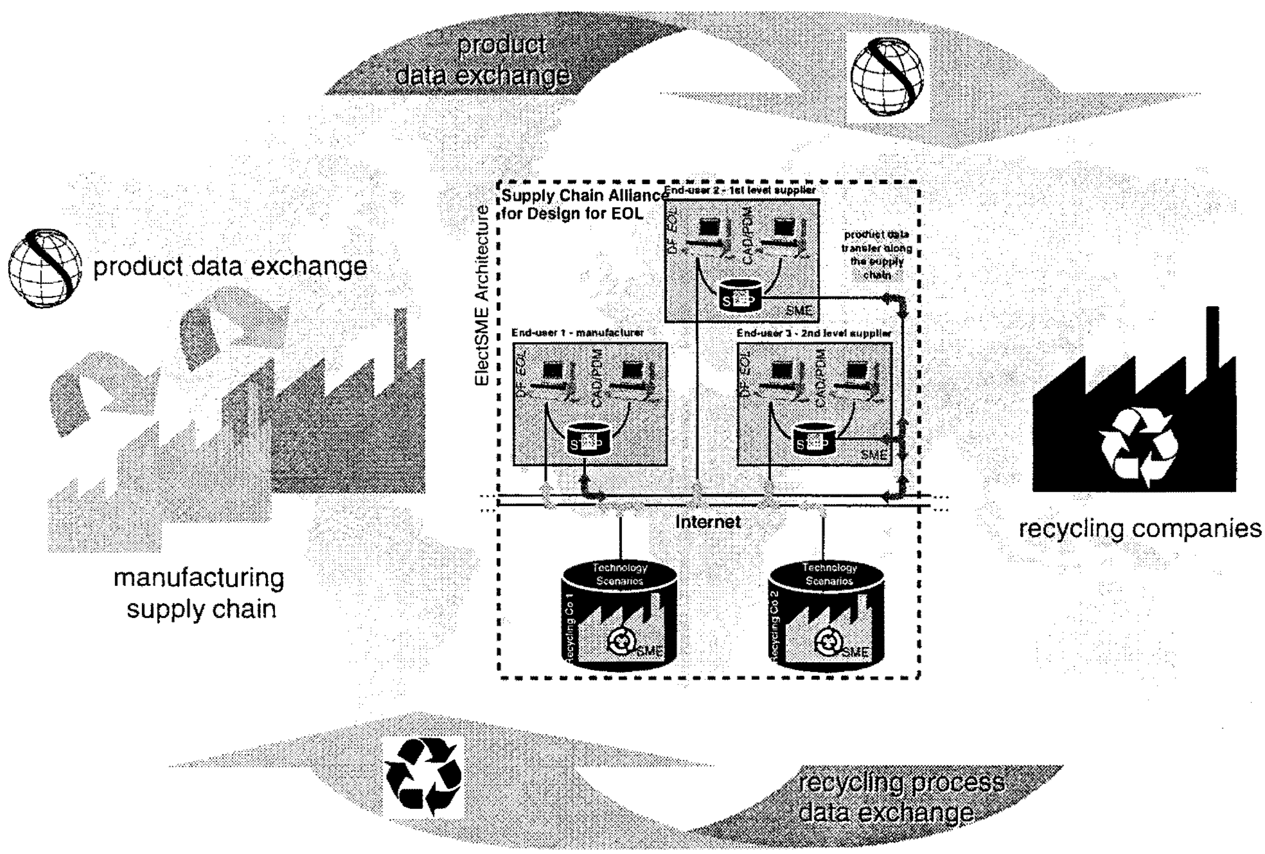

Figure 8: The concept of ElectSME as a 2nd generation DFR tool.

7 RELOOP - The Missing Piece for Holistic EOL Value Optimisation?

Circular economies will result in extensive take-back logistics, generating costs and counter-productive environmental impacts. The evaluation and optimisation of take-back processes for a take-back system to be developed is crucial for the ecological and economical success of Circular Economies (HanKos96). Logistics cost can add up to 50 to 70% of the entire recycling cost (HieMit95). The developing recycling networks or reverse channels create the need for efficient network management. Network management is executed by the OEM itself, or by specific channel controllers, in charge for a particular region and acting as the main point of contact for manufacturers for the fulfilment of their producer responsibility in terms of products at EOL and take-back.

The objective of the EU-Project 'RELOOP - Reverse Logistics Chain Optimisation in a Multi-User Trading Environment' (oVREL98) is to provide a solution for the optimisation of Take-Back Logistics (TBL) on a European scale from an economical and environmental point of view. RELOOP started in January 1998 and will continue until December 2000. The project result will be a WWW- and Geographical Information System (GIS) based engineering tool for distributed TBL optimisation, building upon an extensive database. The development in the RELOOP project focuses on the product type IT-Equipment, even though the commercialised software after project end might be applicable to a wide range of products. Two other related activities are ROUTING (HieVer95) and RELOG (HanKos96).

Ten examples of unique and/or large scale take-back and recycling processes in Europe have been surveyed and analysed within the first year of the RELOOP project. The objective of the study was to investigate issues in reverse logistics "channel management". Emergent structures, actors, and management approaches in the take-back and recycling of electrical and electronic products were identified. The study provides a good overview of the current practice and management of take-back logistics and electronics recycling in Europe.

The study included electronic products that can be labelled as consumable, household, information technology and telecommunication equipment. In order to obtain on one hand a good overview and on the other hand insight in the specific development, management, and organisation of TBL and recycling chains, different company types have been investigated, ranking from IT-Equipment supplier, waste management companies and recycling companies to material producers. It is intended to publish the study results in the near future.

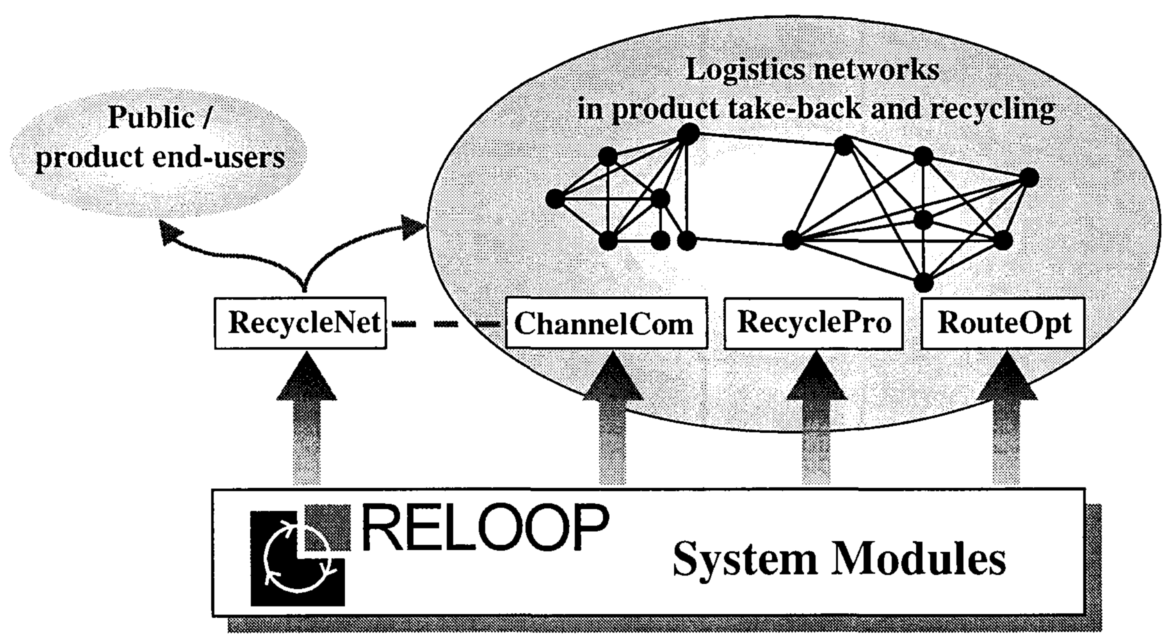

Figure 9: The four main functions of RELOOP

The RELOOP system will consist of various modules which form the base of the RELOOP functions. The main RELOOP functionalities are:

- RecycleNet
- ChannelCom
- RouteOpt
- RecyclePro

The RecycleNet will bridge the gap between collectors and end-users. GIS-based search and selection of information about EOL-product return options will ease the search by the end-users. The visually and algorithmically enhancement of the database query tool supports end-users in a user-friendly, efficient and effective way. For example the search of return options within a radius indicated through a point-click-and-drag of the mouse by the end-user will be possible. Linked to the ChannelCom function, easy access from the RecycleNet to the potential collector will be given.

The RecycleNet function will be commercialised in cooperation with established information and database providers.

The function ChannelCom will allow communication between TBL network partners. In addition, it provides a "order and enquiry" support for parties outside such networks. End-users will be enabled to contact the collection and recycling providers found with assistance of the RecycleNet immediately using a standard set of forms. The standard set of forms will be provided by RELOOP.

Electronical business transactions between TBL network partners will be supported through the provision of forms and procedures, fast and easy transmission and enhanced through GIS. The TBL-specific information need of the users will be considered. Tracking and reporting of data (economical and environmental data) through the take-back and recycling chain will be possible. Information and communication structures for design guidelines regarding TBL and recycling will also part of the ChannelCom. In order to give legislative support RELOOP will provide fast and direct access to the relevant national and European Commission Web sites where legislation and regulation are published.

The RouteOpt will be based on a visually (GIS) and algorithmically enhanced routing core engine. RouteOpt will enable RELOOP users to optimise not only cost, but also considering the environmental impact. It is targeted to take into account the most recent needs concerning the transportation of EOL-products:

- Multi-modal transportation (roads, rail- and waterways in any combination) or combined transportation (the largest part of the route is train or ship)
- Traffic congestion on roads
- Environmental parameters related to the actual driving conditions (road type, vehicle type, traffic jam information,..)
- Vehicle flexibility related to loading / unloading or related to road-compatibility
- Legislation related to EOL-product transportation

A multi-criteria decision support module will allow the user to priorities the selected routes based on multiple criteria.

RecyclePro is a decision support tool which will enable processors of EOL-products to decide the recycling strategy based on multiple criteria. Depending on the recycling strategy, the output of the recycling process will vary, what results in different subsequent processes and markets. The user will be enabled to consider not only his own process but also the subsequent processes and the transportation.

RecyclePro will make use of the GIS-module to provide a clear image of the network varying by use of different recycling scenarios. Databases of company profiles, process specifications, job specifications, commodity prices, etc. will be coupled to allow a calculation of the "optimal" recycling scenario. RecyclePro will not consider only costs but also the environmental impact of the scenarios.

Implementation and commercial exploitation will be done by the software developer PROGIS (AT), based on their geographical information system "WinGIS". WinGIS is a professional geographical information system running under Windows and covering the whole field of geography based information processing.

8 Summary and Conclusions

Supply chain Management issues have been identified in the context of take-back and recycling of WEEE, together with the introduction of the EOL value concept. The necessity for optimisation and management of DFR and recycling channels has been explained. A

1st generation DFR tool, its deficiencies and the innovations a 2nd generation DFR tool for EOL cost elimination were presented in forms of the research project ElectSME. RELOOP is focusing on EOL recycling network management and optimisation as regards cost and environmental impact. Besides the ongoing project work, future activities need to comprise the application of all three tools and the methodologies in industrial environments.

For both ElectSME and RELOOP a User Interest Group (UIG) was installed as an open forum for interested parties, which may join in at any time. The UIG serves as a platform to exchange know-how and project results, as well as a steering committee for the project.

9 Acknowledgements

The work presented in this paper was made possible by the highly appreciated support through the European Commission in funding the research projects TOPROCO (BriteEuram BRE-CT94-0941), ElectSME (BriteEuram BE97-4630) and RELOOP (ESPRIT 25552). The authors would like to thank the partner companies MANN Organisation, GEP-Daimler-Benz, WTCM, ELCO, Siemens Nixdorf, Atlantic Conceptware, Siemens, Multis, KSW Microtec, Barco, Hewlett Packard, Logic Line Organisation, PROGIS, TME and the University of Leuven (Centre for Industrial Management) and their representatives for their valuable contributions.

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A decision support model for the recovery and reuse of products and components

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Abstract
Recovery and reuse are becoming important issues for manufacturers. On the one hand legislation is introduced now or very soon that obliges manufacturers to be responsible for their products at the end of the life cycle, while on the other hand recovery and reuse may be profitable for the company.
It gives various possibilities to recover discarded or used goods. In view of recovering the added value, product and parts recovery are the most important options. In this paper a model is described that supports management in decisions concerning the recovery and reuse of goods at the end of their life cycle as well as the components or parts of these goods. The developed model has been divided into three submodels, resulting in: initial feasibility, technical feasibility and economical feasibility. This model has been used in practice for recovering parts for service ends. It is concluded that the model has shown to be useful in practice. However, further research has to be carried out in order to investigate the validity and reliability of the model.

Keywords: recovery; reuse; remanufacturing; management tool; feasibility; mathematical model.

1. Introduction

Because of society's increasing concern for the environment and resulting governmental legislation, companies are involved more and more with environmental aspects. Examples of such legislation are the Dutch rules with respect to product responsibility of manufacturers for their products at the end of the life cycle. This implies that a manufacturer is responsible for the environmental friendly processing of their discarded goods, while they have to fulfil some prescribed values for the mass fraction of the recovered materials and parts that will be reused. The Dutch are frontrunners in the world with respect to this legislation, but it will be introduced in more countries soon. The European Commission, for instance, is preparing such legislation now and it is expected that product responsibility will be introduced in all EU countries within a few years (European Commission, 1997).

Although companies may consider product responsibility to be a threat, it can be seen as an opportunity too. For instance, companies like IBM, Xerox and Oce have been engaged

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in recovery activities for several years and it has been shown that these are profitable activities. Not only purchasing costs are reduced because of remanufacturing of used components; such components and parts are also used for after sales services. Besides that, used goods are also reconditioned so that they fulfil 'as new' specifications. These products are put in the market again, although in some cases this might be a different market than for new products.

In this paper a model is described that supports management in decisions concerning the recovery and reuse of goods at the end of their life cycle as well as the components of these goods. Material reuse (recycling) is not considered as, on the one hand, the recovered added value is relatively low, while, on the other hand, this activity is not connected directly to the business processes of the manufacturer (e.g. manufacturing, services). With the developed model the economic feasibility of the recovery of used goods and components is estimated based upon data regarding the goods (e.g. design, information), the market and logistics.

As literature concerning reuse of products, components or materials is not consistent with respect to the nomenclature for the different recovery activities, in this paper the following definitions are used (Melissen and De Ron, 1998):
Recovery or asset recovery is used as a general expression for bringing back used or discarded goods and/or parts and materials from these goods in the economic process. This means that the added value of the good is recovered fully or partly. Returning a used (or discarded) good to a state which fulfils 'as new' specifications will be called reconditioning. If the good is renewed to a state that fulfils required specifications, not as rigorous as those for the same new product, the process is called refurbishing, while the process that returns a good to working order is called repair. The process that results in a part or component that fulfils 'as new' specifications is called remanufacturing, while a process resulting in parts or components with specifications lower than 'as new'; this is called revision. Cannibalization is the process that results in parts or components specified as working order. All these processes can be divided into subprocesses, including disassembly, cleaning, inspection, testing, repair, and reassembly.

1. Analysis of recovery influencing aspects

From an overview of the current state of the art with respect to recovery based upon literature (Flapper and De Ron, 1996, 1998) and interviews with several companies, the most important aspects that influence recovery activities can be summarized as follows, see figure 1.

Supply

The supply of used or discarded goods forms the input of the recovery chain. Information, which is needed with regard to the discarded goods, is the location of the goods supplied, the quantity and quality of the goods and the scale of goods supplied (world, European Union, country). The goods supplied can come from an internal or external market. The external market can be divided in consumer goods and business-to-business goods. Generally producers have more data about business-to-business products than consumer products with regard to the locations and quantities of the installed base.

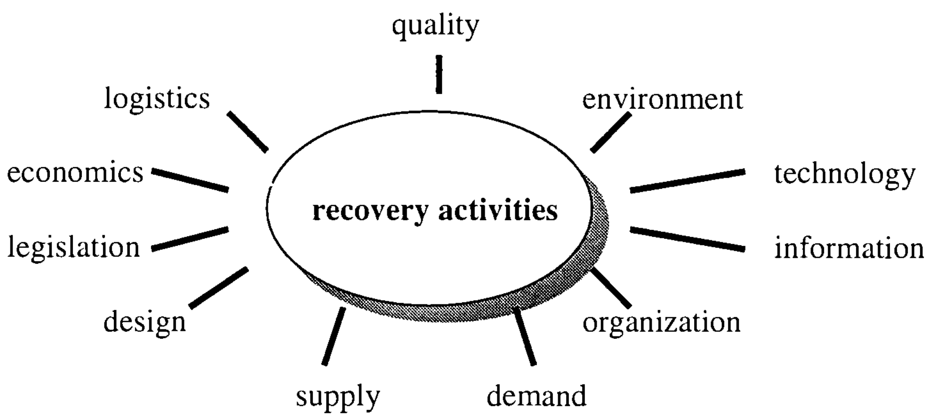

Fig.1: The most important aspects that influence recovery activities.

Demand
The demand for recovered products or parts is of essential importance. When there is no demand, it is no use to investigate the possibilities for recovery and reuse. The location of the demand, the required quantity and the expected quality need to be mapped. It is possible that sales organisations are interested in reconditioned or refurbished products for a special kind of reason. The demand for remanufactured parts can come from a production plant or a service organisation. Beside the possibilities within the organisation itself, an external market might be interested in reprocessed products or parts too.
Environment
The impact of recovery activities on the environment may be positive as savings are made when comparing to the current manufacturing process. When products or parts are recovered, the negative environmental impacts of the production of new products and parts are reduced. Examples are the savings of energy, materials, waste, land, and water and air pollution. There also are negative impacts like the transportation, energy used and waste created by the recovery process, and the land, water and air pollution as a result of the recovery processes. All this means, that the calculation of the exact impacts of recovery activities on the environment is very complicated.
Legislation
As has been described in the introduction, legislation is an important driver for companies to consider recovery. As producers will be responsible for their end-of-life products, they have to find a way to take back their products for free and make arrangements for the collection and environmental friendly processing of these goods. With regard to the recovery process, producers are obligated to recover a certain percentage of the total mass collected and to process hazardous parts and materials.
Logistics
The most important part of the aspect logistics is the transport of goods and parts for recovery ends. The total distance that needs to be covered in a recovery process can be divided in two main sections:

- the removal of discarded goods from the location where it is offered to the recovery process,

- the removal of reprocessed products or parts from the recovery process to the demand market.

To fulfil the demand, a collection strategy for the supply of discarded goods needs to be developed. An example of a collection strategy is offering fees to users for their used goods. The locations of the supply, the demand and the recovery process influence the total distance that needs to be covered. Depending on the characteristics of the product and the specification of transport (scale, speed, etc), a choice can be made between transport by plane, by ship, by train or by truck.

Quality/Reliability

Quality and reliability are important issues to inspect before recovering. To predict the quality and reliability of a good or part, information about for example failure rates, mean time between failures and circumstances, is needed. Statistics can be used and the prediction of quality and reliability can be based on a sample of the goods or parts (Kecedioglu, 1993).

Technology

Technology deals with the methods, the machines and tools needed for the recovery process. This process can be broken down into subprocesses, like: identification, inspection, disassembly, cleaning, assembly, testing, repairing, internal transport. For the reprocessing of products and parts, all or a combination of these subprocesses is needed (Penev, 1996; Melissen and De Ron, 1998).

Design

In the design process of a product, the end-of-life phase should be taken into account. The decisions about the issues influencing the recoverability of a product, are made during the design phase. Examples of these issues are the way parts are connected and whether the product is built up of modules. These issues lead to a product, which is easy to recover, resulting in short disassembly times and thereby less disassembly costs.

Information

Information about the products and parts to be processed is needed for the recovery process. This information should be registered very carefully. Furthermore, information is needed about the location of the products, from where they have to be collected and how many products are available at one location. Before deciding whether to recover products and parts or not, it is important to have information about the quality and reliability of the goods. When the quality and reliability of the goods do not meet the required standards, reuse of products and parts might not be possible.

Organisation

The aspect organisation deals with all subjects within the recovery chain. Examples are the management of the chain, but also arrangements about warranty periods for recovered products or parts. Another subject is the marketing of reconditioned items. With certain marketing tools awareness can be created by the customers leading to stimulation for buying these items. A possible consequence is a better company image regarding to the environment, a so-called ‘green image’.

Economics

It will be clear that all aspects mentioned above have a relationship with economy. The supply of goods will have an effect on the revenues. It also leads to costs for the collection and transportation. The demand of products and parts determine the revenues.

The law has its influence on the reverse logistics. As producers are obliged to take back the goods that are discarded, this will result in extra costs.
The economic feasibility of recovery and reuse is based on the financial result of the above mentioned revenues and costs.

3. The design of the model

Before the model was designed, first the goals, the function, the requirements and the characteristics of the model have been defined (Cross, 1994). Based on these results a model has been developed. The outcome of the model is a prediction of the economic feasibility of the recovery of products or parts in order to be reused. The total model can be divided in three submodels, see figure 2.

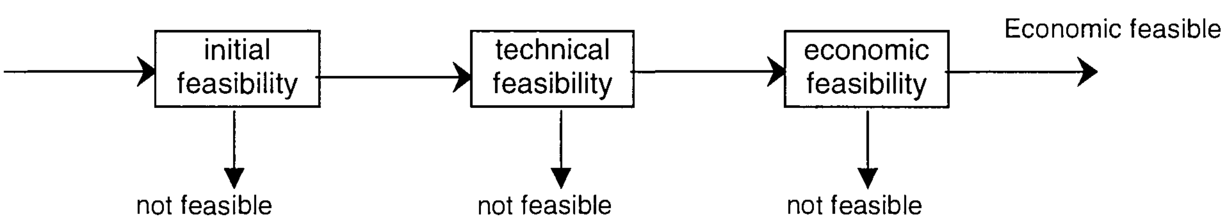

Fig.2: The three submodels

The initial feasibility is based upon the demand for recovered products or parts and components and the supply of discarded goods. If the demand can not be fulfilled for a specific part because of a lack of supply, it makes no sense to continue the feasibility study. Therefore, recovery is initial feasible, if:

$$TSG \geq \{\gamma_p.TDP + \max_{c}(\gamma_{co,c}.TDC_c / n_c)\} \qquad (1)$$

As equation (1) indicates, recovery is initially possible only if the supply of goods can cover a certain percentage of the total demand for recovered products and parts. The value of the fraction (γ_p and $\gamma_{co,c}$) is determined by the client and the supplier. It is supposed that the demand for recovered products has to be fulfilled over the demand for recovered parts.

The technical feasibility deals with the quality and reliability of the goods (and their parts) supplied and the required quality and reliability of product and parts or components demanded.
Recovery is technically feasible if:

$$\left.\begin{aligned} & q_p.TSG \geq TSP \geq \gamma_p.TDP \\ & q_c.(TSG - TSP).n_c \geq TSC_c \geq \gamma_{co,c}.TDC_c \text{, for } \forall c \end{aligned}\right\} \qquad (2)$$

If eq. (2) is not fulfilled, the recovery may not be feasible for product recovery (the first equation), but might be feasible for component recovery (the second equation). In that case TDP=0 and q_p=0 in the first part of eq.(2) and all the following equations.

To determine the economic feasibility, the revenues and costs resulting from the recovery processes, need to be calculated. Recovery is economic feasible if the financial result fulfils the financial requirements made by the company or the chain actors. The different revenues and costs can be expressed as follows:

- financial result:

$$FR = TR - TC \tag{3}$$

- total revenues:

$$TR = R_p.TSP + \sum_c (R_{co,c}.TSC_c) \tag{4}$$

- total costs:

$$TC = C_{col} + C_{pro} + C_{dis} + C_{\log} \tag{5}$$

-
- collection costs:

$$C_{col} = P_g.TSG \tag{6}$$

- processing costs:

$$C_{pro} = TSP.C_{pr} + (\min\{q_p.TSG, TSD\} - TSP).C_{insp} + \sum_c (TSC_c.C_{cr,c}) \tag{7}$$

- disposal costs:

$$C_{dis} = \{(TSG - TSP).W_g - \sum_c (W_{co,c}.TSC_c)\}.C_{lf} \tag{8}$$

- logistic costs:

$$\begin{aligned} C_{\log} = {} & TSG.W_g.D_{sp}.(\delta_a.C_a + \delta_r.C_r + \delta_s C_s + \delta_t.C_t) + \\ & + TSP.W_g.D_{pc}.(\delta_a.C_a + \delta_r.C_r + \delta_s.C_s + \delta_t.C_t) + \\ & + \sum_c (TSC_c.W_{co,c}.D_{pc,c}).(\delta_a.C_a + \delta_r.C_r + \delta_s.C_s + \delta_t.C_t) \end{aligned} \tag{9}$$

The decision to recover goods and parts or components is made by the company. This decision can depend on the economic feasibility, but it is also possible that a company does not decide to execute recovery activities although the financial result is positive or because of some other reason.

4. Application of the model

To test the designed model, a pilot project has been executed at a company that had supply problems with parts for service ends. Some of the suppliers of parts do not deliver anymore the parts needed for service although the company is obliged to deliver service for their systems until at least the year 2001. One of the possibilities to solve this problem is reusing the parts of the systems in the field. To investigate the possibility of recovery and reuse of parts, this pilot project has been started.

4.1 Analysis of the demand

The starting point of mapping the demand, is a total parts list of the particular system. Based on this list, two categories of demanded parts are created: critical parts and interesting parts. The first category contains parts, which can not be delivered anymore in the nearby future. The problem earlier described refers to these parts. These parts should always be recovered (remanufacturing). The second category consists of parts, which are interesting to recover from an economic point of view. When a system will be processed to recover the critical parts, it is worthwhile to investigate if perhaps other parts are also interesting to recover. Making a Pareto analysis has created this category first. Although 20% of the total parts list is representing 80% of the total costs for a system, it would not be wise to spend time and money to a number of these parts because the yearly consumption is very low.
To solve the service problem, the quantity of systems that should be collected, has to be calculated. The critical part with the largest year consumption, determines the initial required quantity of systems ($Q_{i,r}$) to be collected. Because some service parts are repairable, an extra flow of service parts is created. These parts are sent back to the company when they are replaced by an operating part. The parts are repaired and can be used again as service parts. But not all the parts can be repaired. So when a critical part is repairable, still a fraction f of the total demand should be collected by recovering them from systems. The minimum quantity of systems to be collected is ($f.Q_{i,r}$) systems.
The location of the demand is important for the logistics process. As in the current situation the service department is demanding the parts, there are two possibilities for the location: the current warehouse for service parts or a new warehouse elsewhere, based on the optimization of the financial result.

4.2 Analysis of the supply

To map the possible current supply, it is important to know the quantity and the locations of the systems in the field. On a regular base the company gets information from the field about the installed base. From this information Table 1 has been created, where the quantities of the different countries are combined to continents.

	Percentage of the total
Europe	43,5%
North-America	43,1%
Asia	7,4%
South-America	4,2%
Africa	1,7%
Total	100,0%

Table 1: The distribution of systems over the world.

Note that the company will be responsible within a few years for almost half of the total systems after they have been discarded as a result of future EU legislation.

4.3 Determination of the collection strategy

A strategy has to be determined to get at least ($f.Q_{i,r}$) systems back from the field. The systems need to be collected to fulfil the demand for service parts. Several strategies are possible to be applied, e.g.:

- start a special action to stimulate the return of systems. To discuss the best way to start an action, contact with the field is necessary.
- exchange systems by 'old' for 'new'. Let sales people of new systems know that there is an interest in the particular systems.

To get the best result, a combination of the above mentioned strategies is possible. Actually it is possible to choose for an active or passive way for collection. For the systems it is possible to collect actively in Europe. When systems are collected passively, no extra actions are done and the systems will be offered randomly all over the world.

4.4 Determination of the technical feasibility

To determine the technical feasibility, more information about the parts is necessary. This information should contain data about the possibility to disassemble systems in order to obtain parts and data about the quality of the parts. After checking both types of parts, the critical and the interesting parts, all parts seemed to be technical feasible to be recovered for reuse ends.

4.5 Design of the recovery process

The total recovery process can be divided in several subprocesses, e.g.:

- Identification and inspection of the systems
- Disassembling the total system for the demanded parts
- Testing of the parts based on quality norms
- Packaging and labelling of the demanded parts

When the total recovery process is known, the costs for this process can be calculated. Afterwards one should consider the revenues and the costs for recovery, to make a definite list of parts to be disassembled when reusing parts is implemented in practice. The costs for the total recovery process is determined by multiplying the time needed for the execution of the subprocess by the hourly rate of labour.
After calculating the costs for the total recovery process per part, the revenues gained by saving purchase costs per part were higher than the costs made for the several subprocesses. An extra investment needs to be made for a test system to check the functionality of the parts.
The costs for the recovery process will increase per year as more parts will become critical each year and so the demand for parts will increase. This results in more time needed for the execution of the processes which increases the costs. On the other hand, the revenues will increase too.

4.6 Design of the logistics process

To map the logistic process, the location of the supply, the demand and the recovery process are essential. The total transport can be divided, in a supply and a delivery channel, as shown in figure 3.

Supply **Supply channel** → *Recovery Process* **Delivery channel** → *Demand*

Fig. 3: The logistics process

In the supply channel collected discarded systems are transported to the location of the recovery process. Depending on the chosen collection strategy, it is possible to calculate the costs for transport.
From an organisational point of view the company would like to have the recovery process close to the demand location. This means that the transport costs to the demand location can be neglected in this study.
It is possible to use several kinds of transport, for example by air, by rail, by sea or by road. From a cost minimisation point of view, in this project a choice has been made for transport by sea for systems returning from out of Europe and transport by road within Europe. In Table 2 the transport rates per system are shown.

supply location	Transport costs
North-America	950,-
Europe	475,- (average)
Germany	300,-
Italy	650,-
France	490,-
Benelux	220,-
United Kingdom	450,-
Spain	750,-
Asia	850,-
South-America	1150,-
Africa	1150,-

Table 2: Transport rates per system (guilders).

Based on these figures the total costs for transport can be calculated. The variant of active collection (by paying a fee) will be concentrated on Europe. The passive way of collection means that the current installed base is taken back after discarding by the user. The costs for transport are much higher for a passive collection because systems are coming from all over the world.

4.7 Calculation of the economic feasibility

The revenues that can be made are based on the savings of purchase costs. The total demand for a particular part is multiplied by the factory-selling price. Because the total number of parts disassembled, is varying within the considered years, the revenues are varying too, see Table 3 (For reasons of confidentiality, no real data are given).

	f.Qi,r systems/ year
Year 1	366.500
Year 2	436.400
Year 3	476.600
Year 4	486.900
Year 5	492.500

Table 3: Revenues from reprocessed parts (guilders).

The total costs are divided into costs for collection, recovery, disposal and logistics.
The costs for collection need to be determined by a market research, as there is no experience with such collection strategies.
The costs for disposal can be neglected as the waste has a certain value, which means that no costs are paid to an external specialised waste company for waste collection and disposal.
The costs for the recovery process and the costs for logistics have been calculated for five years, see Table 4 and 5.

Year 1	18.560
Year 2	19.650
Year 3	20.860
Year 4	21.310
Year 5	21.630

Table 4: Costs for the recovery process (guilders).

Variant 1: active collection	6.650
Variant 2: passive collection	10.550

Table 5: Costs for logistics (guilders).

The total financial result, being the difference between the revenues and the total costs, is shown in Table 6.

year	Active	Passive
1	341.300	337.400
2	410.100	416.200
3	449.000	445.100
4	458.900	455.000
5	464.200	460.300

Table 6: Financial result (guilders).

From Table 6 it can be concluded that recovering and reusing parts is economic feasible, because the financial result is positive.

From this project, the following conclusions can be drawn:

- The current service problems can be solved by recovering and reusing parts from discarded systems,
- The total recovery and reuse process will be a lucrative business when implemented in practice,
- The difference in the financial result between active and passive collection has turned out to be minimal. Active collection is recommended because this situation can be controlled better.
- The collection strategy may have an important influence as the calculated results are based on the actual returning of the systems.

5. Conclusions

After investigating the state of the art it became clear that the main reason for companies to be interested in recovery and reuse is that they can make money with it. Reuse could also have a positive impact on the environment, but for companies this is not the main reason.
After analysing the aspects that are important when starting with recovery and reuse, the conclusion can be drawn that not all the aspects have the same importance. (Re) design, information, organisation, environmental impacts are issues that can be investigated after the company has decided to set up recovery and reuse activities. Redesign can result in an easier recovery process, but is not an issue that influences considerably the prediction of the economic feasibility. The same can be concluded for the registration of information and the needed information system. The organisation of the recovery and reuse activities is extremely important but effectuated after the company has decided to recover and reuse. Most companies will start with recovery and reuse, when a business process needs it and the costs are reasonable; environmental impact does not play an important role on forehand.

The model has shown to be usable in practice. The project has shown that the model indeed supports decisions concerning recovery and reuse. However, this model is just a first step. The different parts of the model will be studied further so that a more accurate prediction can be made and extended with not foreseen aspects.

No conclusions can be made about the validity and reliability of the model. The model is not used in more cases and it also is not used more than once in the same case. Therefore, this will be a subject for further research too.

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List of Symbols

c	type of part or component
C_a	transport rate by air (money value/tonkilometer)
C_{col}	collection costs (money value)
C_{cr}	recovery costs of part or component type c (money value/kilogram)
C_{dis}	disposal costs (money value)
C_{insp}	inspection costs (money value/good)
C_{log}	logistic costs (money value)
C_{pr}	recovery costs of a good (money value/good)
C_r	transport rate by rail (money value/tonkilometer)
C_s	transport rate by sea (money value/tonkilometer)
C_t	transport rate by road (money value/tonkilometer)
D_{pc}	distance between the location of the recovery process and the client for reprocessed products (kilometer)
$D_{pc,c}$	distance between the location of the recovery process and the client for remanufactured parts or components of type c (kilometer)
D_{sp}	distance between the location of the supplied goods and the recovery process (kilometer)
f	fraction of broken parts that can not be repaired
FR	financial result (money value)
n_c	number of parts or components of type c in a good

P_g	price of a discarded good (money value)
q_c	fraction of parts or components from a good that fulfil the quality standards
q_p	fraction of goods that fulfil the quality standards
$Q_{i,r}$	number of goods to be supplied that fulfil initially the required demand for reprocessed products and remanufactured parts or components
$R_{co,c}$	revenues from a part or component of the type c (money value)
R_p	revenues from a reprocessed product (money value)
TDC_c	total demand for parts or components of type c (#/time period)
TDP	total demand for reprocessed products (#/time period)
TR	total revenues (money value)
TSC_c	total number of parts or components of type c that has been supplied to the client (#/time period)
TSG	total supplied goods (#/time period)
TSP	total number of products that has been supplied to the client (#/time period)
$W_{co,c}$	weight of a part or component of type c (kilogram)
W_g	weight of a good (kilogram)
$\gamma_{co,c}$	covering factor for the total demand for parts or components of type c
γ_p	covering factor for the total demand for reprocessed products
δ_a	decision factor air transport (0,1)
δ_r	decision factor rail transport (0,1)
δ_s	decision factor sea transport (0,1)
δ_t	decision factor road transport (0,1)

Reusable Distribution Items with a Technically Preset Maximum Number of Usage

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Abstract

Up to now hardly any attention has been paid to the fact that, from a technical point of view, reusable distribution items (DI's) like bottles or pallets can only be reused a preset limited number of times. In this article the consequences of this limitation for decisions concerning the use of reusable DI's are examined. The average cost for one trip is determined exactly and compared with an approximation based on the trippage factor.

1 Introduction

For many producers DI's make up a considerable part of the economic cost for distributing their products. For this reason, as well as due to a growing environmental concern among others resulting in the forced take back of DI's combined with rising cost for their disposal, many companies are reconsidering the DI's they use for distributing their products. There is a considerable amount of literature available on the decision between one-way and reusable DI's, see e.g. Flapper [3]. Upto now no explicit attention has been paid to the fact that from a technical point of view copies of DI's can be reused only a preset limited number of times. Numbers found in literature include 5 times for card board boxes and 25-30 times for slip sheets, see EVO [2], 50-100 times for polyethylene pallets, see Anonymous [1], 250 times for injection molded containers and more than 1000 times for compression molded fiberglass containers, see Trunk [8].

The purpose of this paper is twofold:

1. To show how the above preset technical limitations can be taken into account in cost calculations for deciding which DI to use for which product-customer combination

2. To discuss the use of an approximate expression for the cost based on the so called trippage factor. This factor denotes the expected number of times a given copy of a DI is used. The reason for paying attention to this approximate cost is the widespread use of the trippage factor in practice for the decision which DI to use, see e.g. Flies Sr and Flies Jr, [4], Goh and Varaprasad [5] and Stehfest et al [7].

The structure of the rest of this paper is as follows. In Section 2 we first give a description of the model that is used. In Section 3 the exact expression for the economic cost per trip is derived for the situations described by the model. The expression for the trippage factor is determined in Section 4, where also an approximate expression for the economic costs per trip based on the expression for the trippage factor is given. In Section 5 the cost is calculated for a special situation often occurring in practice, using both the exact expression for the cost and the approximate expression based on the trippage factor, and the obtained results are compared and discussed. The paper ends with some overall conclusions and suggestions for further research in Section 6.

2 The Model

Figure 1 shows the flow of a copy of a DI. After a copy of a DI has been bought or rented by a company, it is loaded or filled with products and distributed to the customers of the products. Once the copy of the DI is unloaded or emptied by the customer, the copy should be transported to a location where the copy is tested in order to find out whether or not it can be reused. Based on the result of the test, the copy may be either disposed or reconditioned (cleaned, repaired) and sent to the company for a reload or refill.

During each of the above stages the copy may get lost. The reason for losses during the different stages may be quite different: the copy may no longer be technically reusable, it may be used as a collectors item or as a container for something else or simply have been thrown away by the customers. The sizes of the different loss streams are usually not the same. For example, in a German study on refillable milk bottles by Stehfest et al. [7] it was found that 20% of these bottles were not returned at all, whereas 1% got lost during cleaning.

In general there are two main loss streams, indicated in figure 1: one at the customer, the other at the location where used copies of the DI are tested before they are reconditioned. In the rest of this paper we assume that these are the only two loss streams but the presented calculations can easily be extended to take into account other loss streams as well. It is assumed that the probability p that a copy of a DI is returned by a customer does not depend on how often this copy has been used. (There are situations where more new than worn out looking copies of a DI are lost at a customer, as for instance holds for beer bottles for collections. Usually this loss stream is relatively small. It is no problem to extend the model and the calculations presented hereafter to take this type of situations into account as well.) In order to keep things simple but still realistic, it is also assumed that testing, reconditioning and reloading, refilling all take place at one location.

In this paper we consider situations where there is always demand for the returned, reusable copies of a DI. This applies e.g. for the beer bottles used by Heineken for their regular beers, the PET bottles used by Coca Cola for distributing Coke and wooden pallets used for distributing bricks, during the grow and saturation phases of the business economic life cycles of these products. (In separate papers attention will be paid to situations where the demand for a DI is decreasing more rapidly than the amounts of the DI becoming available for reuse and to the many situations where the business economic life-cycle of the products that are distributed by means of the DI is the most important

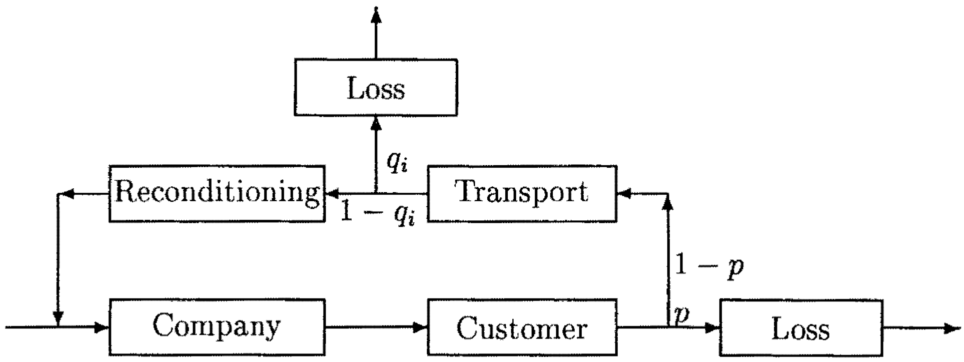

Figure 1: The flow of a DI

limiting factor on the number of times a given copy of a DI can be used.) In that case the probability that a returned copy of a DI will be reused mainly depends on its quality and therefore it is reasonable to use the probabilities that a copy of a DI can be reused ($1-q_i, i = 1, 2, \dots, N$) as a measure for the quality of the copy. Because of the technically preset number of uses N, the probability q_N that an item is not reused after having been used N times is 1. In general the following relations holds:

$$0 \leq q_1 \leq q_2 \leq \dots \leq q_{N-1} \leq q_N = 1 \tag{1}$$

3 Economic Cost Function

For the comparison of different DI's economic aspects are decisive. We use $E[K]$, the average cost per one use (trip) for one copy of a DI, for deciding which DI to use for which product-customer combination

$$\begin{aligned} E[K] &= \sum_{n=1}^{N} \frac{1}{n}\Big(E[K_n \mid X_n = 0]P(X_n = 0) + E[K_n \mid X_n = 1]P(X_n = 1) \\ &\quad + E[K_n \mid X_n = 2]P(X_n = 2)\Big) \end{aligned} \tag{2}$$

where K_n denotes the total cost for using a copy of a DI if this copy is used exactly n times, and

$$X_n = \begin{cases} 0 & : \text{ loss by the consumer after the } n\text{-th use} \\ 1 & : \text{ loss by the company after the } n\text{-th use} \\ 2 & : \text{ no loss after the } n\text{-th use} \end{cases} \tag{3}$$

For the distribution of X_n we get for $n = 1, 2, \dots, N$

$$P(X_n = j) = \begin{cases} p(1-p)^{n-1} \prod_{i=1}^{n-1} (1-q_i) & \text{for } j = 0 \\ q_n(1-p)^n \prod_{i=1}^{n-1} (1-q_i) & \text{for } j = 1 \\ (1-q_n)(1-p)^n \prod_{i=1}^{n-1} (1-q_i) & \text{for } j = 2 \end{cases} \tag{4}$$

where we define $\prod_{i=1}^{0} := 1$ whereas for all other values of n the probability $P(X_n = j) = 0$.

Obviously $E[K_n \mid X_n = 2] = 0$ and therefore we get

$$\boxed{E[K] = \sum_{n=1}^{N} \frac{1}{n}\Big(E[K_n \mid X_n = 0]P(X_n = 0) + E[K_n \mid X_n = 1]P(X_n = 1)\Big)} \tag{5}$$

In general the following cost are important in calculating the average cost per trip for a copy of a DI:

$c_P(N)$	:	the cost for procuring one copy with maximal preset number of usage N
c_T	:	the cost for transporting one copy of a DI one time from the customer to the location where the testing, reconditioning and reuse take place
$c_R(n)$	:	the cost for one time reconditioning a copy of a DI which has been used exactly n times
c_D	:	the cost for disposing one copy of a DI by the company

For a more detailed overview of the different cost that play a role in this context see Flapper [3] and the references mentioned there.

In the following it is assumed that whether or not a collected copy of a DI can be technically reused, can be estimated before a cleaning or other reconditioning operation is started. So only technically reusable copies are reconditioned, where it further is assumed that the reconditioning is always successful which holds for most situations in practice.

We assume that the procurement cost is a linear function in the preset number N:

$$c_P(N) = a_0 N + a_1 \quad a_0, a_1 \in IR \tag{6}$$

Further we assume that the quality of a reconditioned copy of a DI is just enough to allow reuse again. Hereafter two often occurring types of reconditioning cost are considered.

3.1 Constant Reconditioning Cost

The reconditioning cost c_R does not depend on the number of times a copy of a DI has been used. This holds among others for the cleaning of PET and glass bottles. Clearly $c_R < c_P(N)$ because otherwise reconditioning would be more expensive than buying a new.

The cost for using a copy of a DI up to the moment that this copy gets lost for reuse, depends on where the copy gets lost. If a copy is not returned, which means it is lost at the consumer, we get

$$E[K_n \mid X_n = 0] = a_0 N + a_1 + (n-1)(c_T + c_R) \tag{7}$$

If a copy is returned, we get

$$E[K_n \mid X_n = 1] = a_0 N + a_1 + c_D + n c_T + (n-1) c_R \tag{8}$$

The exact average cost per trip for one copy of a DI is then given by:

$$E[K] = \sum_{n=1}^{N} \frac{1}{n}\Big\{ \Big(a_0N + a_1 + (n-1)(c_T + c_R)\Big)p(1-p)^{n-1}\prod_{i=1}^{n-1}(1-q_i)$$
$$+ \Big(a_0N + a_1 + c_D + nc_T + (n-1)c_R\Big)q_n(1-p)^n\prod_{i=1}^{n-1}(1-q_i)\Big\} \quad (9)$$

3.2 Linear Reconditioning Cost

In general the quality of a copy of a DI decreases each time it is used. Because of this the cost for reconditioning a used copy upto a reusable level may increase in the course of time, as for instance holds for the repair of wooden pallets. Hereafter we assume that $c_R(n)$, denoting the cost for reconditioning a copy of a DI which has been used n times, is given by:

$$c_R(n) = b_0n + b_1 \qquad b_0, b_1 \in IR \quad (10)$$

The following relation shows how many times a copy of a DI should be used at most when the above cost function holds:

$$n < \frac{a_0N + a_1 - b_1}{b_0} \quad (11)$$

If a copy has been used more, then the copy should not be reconditioned but replaced by a new copy.

Under the above assumptions we have

$$E[K_n \mid X_n = 0] = a_0N + a_1 + (n-1)(c_T + b_1) + b_0\frac{n(n-1)}{2} \quad (12)$$

$$E[K_n \mid X_n = 1] = a_0N + a_1 + c_D + nc_T + (n-1)b_1 + b_0\frac{n(n-1)}{2} \quad (13)$$

and hence

$$E[K] = \sum_{n=1}^{N} \frac{1}{n}\Big\{ \Big(a_0N + a_1 + (n-1)(c_T + b_1) + b_0\frac{n(n-1)}{2}\Big)p(1-p)^{n-1}\prod_{i=1}^{n-1}(1-q_i))$$
$$+ \Big(a_0N + a_1 + c_D + nc_T + (n-1)b_1 + b_0\frac{n(n-1)}{2}\Big)q_n(1-p)^n\prod_{i=1}^{n-1}(1-q_i)\Big\} \quad (14)$$

4 An Approximate Economic Cost Function

In practice usually the exact average cost for one trip are not considered but a very rough approximation which uses the trippage factor which denotes the expected number of times a given copy of a DI is used, where it is (implicit) assumed that there is a demand for each reusable copy of a DI. This assumption is valid for the situations considered in this paper.

If U denotes the number of times a copy of a DI is exactly used then in the case of a preset maximum number of uses N, the random variable U can only have one of the following values: $1, 2, \ldots, N$ and has the following distribution:

$$P(U = n) = \begin{cases} (p + (1-p)q_n)(1-p)^{n-1} \prod_{i=1}^{n-1} (1 - q_i) & \text{for} \quad n = 1, 2, \ldots, N \\ 0 & \text{for} \quad n > N \end{cases} \tag{15}$$

Then the trippage factor is given by

$$\boxed{E[U] = \sum_{n=1}^{N} \left\{ n(p + (1-p)q_n)(1-p)^{n-1} \prod_{i=1}^{n-1} (1 - q_i) \right\}} \tag{16}$$

This expectation can be used to define an approximate expression for the average cost for one trip. Again we consider the two different cases with constant and linear reconditioning cost. In the first case we will use the following approximate expression for the cost using the trippage factor $E[U]$

$$\boxed{\Pi_c := c_T + c_R + \frac{a_0 N + a_1 + c_D}{E[U]}} \tag{17}$$

In the case of the linear reconditioning cost we use the following approximation.

$$\boxed{\Pi_l := \frac{a_0 N + a_1 + c_D}{E[U]} + c_T + b_1 + b_0 \cdot \frac{E[U] - 1}{2}} \tag{18}$$

5 Comparison of the Exact and Approximate Cost

In this section we compare the exact and the approximate expected cost for one use for situations where

$$q_i = (\frac{i}{N})^2 \quad i = 1, 2, \ldots, N \tag{19}$$

which among others holds for wooden pallets, see Josiassen [6].

5.1 Constant Reconditioning Cost

The exact average cost per trippage in this case are obtained via

$$P(X_n = j) \begin{cases} p(1-p)^{n-1} \prod_{i=1}^{n-1} (1 - (\frac{i}{N})^2) & \text{for} \quad j = 0 \\ (1-p)^n (\frac{n}{N})^2 \prod_{i=1}^{n-1} (1 - (\frac{i}{N})^2) & \text{for} \quad j = 1 \end{cases} \tag{20}$$

for $n = 1, 2, \ldots, N$, resulting in:

$$E[K] = \sum_{n=1}^{N} \frac{1}{n} \Big\{ \Big(a_0 N + a_1 + (n-1)(c_T + c_R) \Big) p(1-p)^{n-1} \prod_{i=1}^{n-1} (1 - (\frac{i}{N})^2)$$
$$+ \Big(a_0 N + a_1 + c_D + n c_T + (n-1) c_R \Big) (1-p)^n (\frac{n}{N})^2 \prod_{i=1}^{n-1} (1 - (\frac{i}{N})^2) \Big\} \tag{21}$$

The approximate trippage costs follow from (17) and:

$$P(U = n) = \Big(p + \frac{n^2}{N^2}(1-p) \Big) (1-p)^{n-1} \prod_{i=1}^{n-1} (1 - \frac{i^2}{N^2}) \tag{22}$$

resulting in

$$E[U] = \sum_{n=1}^{N} \Big\{ n \Big(p + \frac{n^2}{N^2}(1-p) \Big) (1-p)^{n-1} \prod_{i=1}^{n-1} (1 - \frac{i^2}{N^2}) \Big\} \tag{23}$$

To compare the cost expressions we have, quite arbitrarily, chosen the following values for the different parameters: $a_0 = 2$, $a_1 = 30$, $c_D = 0.5$, $c_R = 1$ and $c_T = 0.1$ In figure 2 we show $E[K]$ and Π_c as a function of N for different values of p.

It can be seen that the difference between the results obtained with the two expressions for the cost increases with N. Moreover, apart from some small values for N, $E[K]$ is always higher than Π_c.

Table 1 shows the optimal DI for different values of p using the exact and approximate cost expressions.

5.2 Linear Reconditioning Cost

In this case the exact expression for the average cost per trip is given by the following sum:

$$E[K] = \sum_{n=1}^{N} \frac{1}{n} \Big\{ \Big(a_0 N + a_1 + (n-1)(c_T + b_1) + b_0 \frac{n(n-1)}{2} \Big) p(1-p)^{n-1} \prod_{i=1}^{n-1} (1 - (\frac{i}{N})^2)$$
$$+ \Big(a_0 N + a_1 + c_D + n c_T + (n-1) b_1 + b_0 \frac{n(n-1)}{2} \Big) (1-p)^n (\frac{n}{N})^2 \prod_{i=1}^{n-1} (1 - (\frac{i}{N})^2) \Big\} \tag{24}$$

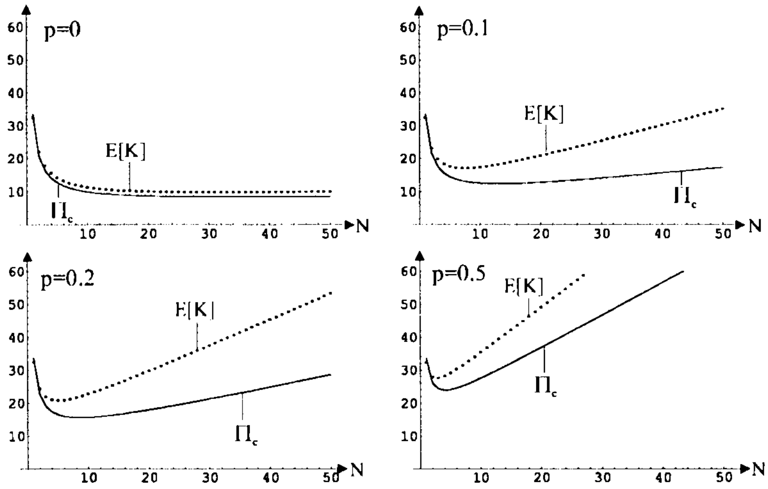

Figure 2: Exact and approximated average cost per trip for one copy of a DI for situations with constant reconditioning cost

	Optimal Preset Number N		Minimal Average Cost for One Trip	
p	Exact	Approximation	$E[K]$	Π_c
0	33	31	9.9251	9.9197
0.1	13	7	18.2823	17.1375
0.2	9	5	22.1824	20.8178
0.5	4	3	28.2014	27.6016

Table 1: Optimal DI for situations with constant reconditioning cost

while the approximate cost can be computed by (18) and (23).

We have chosen the following values for the cost parameters: $a_0 = 2$, $a_1 = 30$, $c_D = 0.5$, $c_T = 0.1$, $b_0 = 0.5$ and $b_1 = 0.5$ in order to compare the exact and the approximate objective function.

Figure 3 shows $E[K]$ and Π_l as a function of N for different values of p, whereas Table 2 shows the optimal DI according to the two cost expressions for different values of p.

Again the results are very different and correspond with the results obtained for the constant recondition cost. Therefore we think, that the approximations based on the trippage factor (17) and (18) are not recommendable especially because of the extra effort for getting the exact value of the cost.

6 Summary and Conclusions

In this paper we have shown how preset technical limits on the number of times a copy of a DI can be reused can be taken into account when deciding on which DI to use for which product-customer combination. It has been shown that the results obtained using the

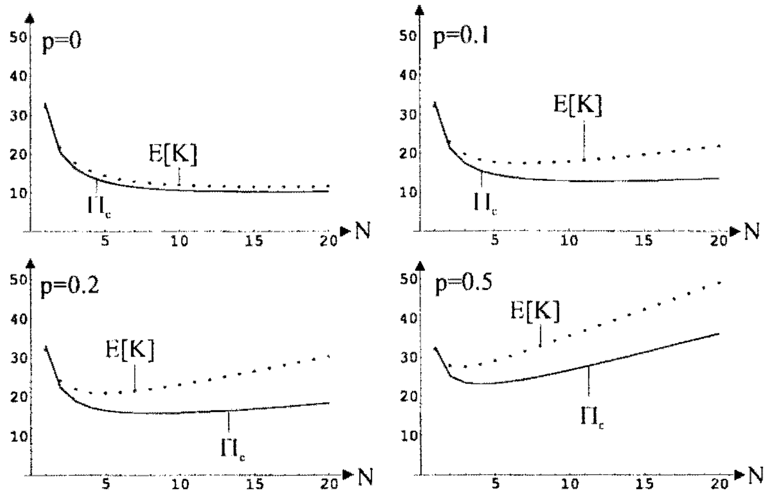

Figure 3: Exact and approximated average cost per trip for one copy of a DI for situations with linear reconditioning cost

	Optimal Preset Number N		Minimal Average Cost for One Trip	
p	Exact	Approximation	$E[K]$	Π_l
0	16	16	11.5926	11.5926
0.1	11	7	18.1923	17.3949
0.2	8	5	21.8927	20.8876
0.5	4	3	28.1978	27.5595

Table 2: Optimal DI for situations with linear reconditioning cost

exact expression for the cost do, sometimes considerably, differ from the results obtained via the expression for the costs based on the often used trippage factor suggesting not to use the latter.

Apart from some special situations, the approach discussed in this paper can only be used for a first rough comparison between different DI's. It indicates which DI results in the lowest cost per trip. The here presented approach does not give the absolute cost for using a certain DI however. Reason for this is that time is not taken into account in the approach. Due to the time that copies of a DI stay at the customers, and the times required for transport, testing and reconditioning, much more copies of a reusable DI may be required to fulfil demand, making the usage of reusable DI's less attractive. In order to deal with the above time aspects other, more detailed models, including stocks of DI's, are necessary to come to a definite decision.

In this paper attention has been focussed on the economic cost for using a certain DI to distribute a certain product to a certain customer. Another important decision criterium for deciding which DI to use, are the environmentally effects of using a DI because the latter contributes to the "green image "of the company. By replacing the economic cost by emissions and waste flows, the model presented in this paper can also be used for getting insight into the operational environmental aspects of using different DI's.

7 Acknowledgement

The research presented in this paper makes up part of the research on re-use in the context of the TMR project REVersed LOGistics financially supported by the European Union (ERB 4061 PL 97-650) in which, apart from Eindhoven University of Technology, take part the Aristoteles University of Thessaloniki (GR), the Erasmus University Rotterdam (NL), INSEAD (F), the Otto-von-Guericke-Universitaet Magdeburg (D) and the University of Piraeus (GR).

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" Work in Progress "

The need for Cooperation and Coordination in a Reverse Distribution Channel - an initial model

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Bergen, October 1998

ABSTRACT:

A growing concern regarding protection of the environment is forcing businesses to focus on environmental issues. Waste handling dominates today's work to protect the environment. In this respect, reverse logistics and distribution is an important topic to address to be able to achieve cost efficient solutions. As such solutions need to be both environmentally and economically sound, certain limitations exist. The argument of this paper, is that reverse distribution channels should be conceived as inter organizational relations (IOR's). The question concerning reverse channels is then what kind of governance structure is better (i.e. most efficient). A model is developed based on the transaction cost framework, and implications for cost and governance mechanisms are presented. To address the issue of reverse channel is a task forced upon businesses by the Norwegian Government. The work that is being conducted as reported in this paper, is trying to develop a decision making framework for managers for how to organize their waste collection effort.

1. Introduction

There is a growing concern regarding the protection of the environment, which is forcing businesses to focus on environmental issues. These kind of issues however, demand careful consideration of different solutions. Waste handling solutions need to be both environmentally *and* economically sound.

Even though source reduction ideally is the best strategy towards waste[1] management, waste handling dominates today's work to protect the environment. In this respect, logistics is an important topic to address to be able to achieve cost efficient solutions. Traditionally, logistics has been defined as the planning, developing, organizing, coordinating and control of the material flow from the supplier to the end user (Eriksson and Persson 1981). In green logistics, one also takes responsibility for the products after consumption, through reuse, recycling to final disposal, by coordinating the processes necessary to exploit products and materials throughout their life cycle (Jahre 1995).

Reverse logistics describes the part of green logistics which concerns the reverse *flows* of goods and information from the point of consumption to the point of origin (Jahre 1995). One can argue that a reverse logistics consist of three main areas, illustrated below:

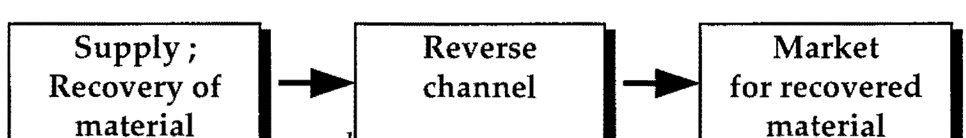

Figure 1: Main areas in the reverse distribution channel.

Each of these areas are of equal importance, but the main focus in a logistics perspective is the reverse channel (RC). RC represent the process of moving the goods from point of consumption to the point of treatment. The supply side will mainly be a marketing issue; one need to inform the consumers of the return possibilities. Obtaining a market for recovered products may in many respects prove to be difficult, due to the complex issues of technology, economics and legal challenges. The supply and market issue are

[1] "Waste" is used as the term representing all kinds of used products in the process of being returned.

certainly of major importance, but it is beyond the scope of this paper. The focus here will be that of reverse channels.

1.1 The research question

The establishment of a RC should focus on getting the job[2] done with a minimum of *new* resources. This is also emphasized in the national strategic goal for handling of waste and recycling, introduced by the Norwegian government (St. meld. nr. 58, 1996-97):

> The waste problems are to be solved in such a way that it creates a minimum of damage for humans and the natural environment, *and at the same time use a minimum of the resources in the society.*

To achieve this goal, businesses have to cooperate and coordinate their effort in recovering used products. Reverse channels could then be categorized as a certain kind of inter organizational relationship. An advantage about IOR's, or social action systems, is their ability to act as a unit (Van de Ven 1976). In relation to Oliver's (1990) determinants of inter organizational relationships (IOR), the need for efficiency and stability drives forth such an organizational arrangement. *Efficiency* refers to input/output ratio, which for waste collection purposes could be defined as collecting the largest amount of waste with the least amount of new resources. *Stability* refers to coping with uncertainty, which is central to waste collection. In Norway we have recently experienced a debate between researchers and professionals as to whether recycling is a viable path to protection of the environment. To a great extent it is due to lack of knowledge about the area.

According to Haugland (1996), two main questions need to be asked when establishing cooperative relations between businesses. First it is a question of which actor is to do what activity (which to a great extent is a question of logistics management). A next step is to determine how to organize and govern the cooperation (which is a question of inter

[2] This refers to the relocation of products from the point of supply to the market for recovered products.

organizational theory and strategic logistics management). However, these questions are interwoven. Regarding reverse channels, the latter question concerning organization and governance have only briefly been studied (Jahre and Flygansvær 1996). It will therefore be the focus of this work.

To both be able to relocate used products and at the same time use a minimum of "new" resources in accomplishing the task, constrains the reverse channel. One way to solve this challenge is to use *existing* channel capacity for moving the goods. Without the systems being both economic *and* environmental viable, the need for such systems disappears. One can argue that the effort to collect waste is not value adding to anything "but" the environment. The reason for companies to engage in such effort is because the public opinion and the government demands it. In this line of argument the reverse logistics issue is a cost minimization issue only. Such a limitation forces cooperation between several companies. Tweede (1992) reports that cooperation between channel members has been a device to overcome resistance towards environmental sound solutions. As Rosenau et. al. (1996) also report, the cost and savings do not accrue to the same party in the reverse channel, which highlights the need for effective gainsharing among partners.

The transaction cost economics (TCE) perspective has offered three generic governance structure alternatives which differ in their relative efficiency (Dyer 1996). The framework determines whether transactions will be carried out within organizations, in intermediate structures (IOR's), or in the market (Oliver 1990). The key to efficiency is the ability to effectively match governance structures with transactions (Williamson 1991).

It is the argument of this paper, as indicated above, that reverse channels are determined to be organized as IOR's. Therefore the question concerning reverse channels, is what kind of hybrid governance structure should be implemented to minimize the transaction costs. The research question to explore in this study is then;

What kind of governance structure is appropriate for a reverse channel for collection of waste (used products)?

1.2 Characteristics of reverse channels for waste collection

The ability to look into the research question posed above, demands a brief discussion of the characteristics of reverse channels for waste collection. Previous studies document the existence of certain types of RC, and the difference between closed and open systems prove a fundamental one (Jahre and Flygansvær 1996, Jahre 1995, CLM 1993). In *closed systems*, producers collect their own products and use them again for the same purpose. In *open systems* products are collected by different actors than the producers, and used for different purposes. Rank Xerox typically collects their own copiers, and use them to produce new copiers, while the municipalities collect waste like paper, plastic and household refuse, and the use of this waste is not necessarily connected to its original use. Three main characteristics of these two kinds of systems are listed in the table below (based on a study conducted by Jahre and Flygansvær, 1996).

Closed system:	**Open system:**
The producer is most often the channel captain.	There is no obvious channel captain.
Actors are "integrated" in a company.	Actors exist on an independent basis.
The whole spectrum of waste handling available; reuse, recycling and disposal.	Limited waste handling possibilities; recycling and disposal.

Table 1: Reverse channels characteristics

Even though there are different kinds of reverse channels, an important common denominator is the need for cooperation and coordination between companies. The decision of who is to do what is to a great extent given for the closed systems, while this is more uncertain for an open system. When Rank Xerox is collecting their own copiers they need to cooperate with their customers, dealers and third party logistics providers, but there is never any doubt that Rank Xerox is in charge; i.e. is the channel captain.

Collecting waste in an open system however, involves users (which might be both persons and companies), municipalities, logistics providers, and end markets for waste. In this system there is not an obvious channel captain. Still, no matter which system turns out to be the better, the need for a channel captain will exist.

The choice of actors is a question of whether a company is going to do it by themselves, let the public service do the job, use a professional third party, or leave it to the consumer (Jahre 1995). For a closed system, the actors involved are most often the same as those bringing products to the consumers in the first place. The choice of actors will then most often fall naturally. This is not the case for an open system, and the decision of which actors to include will be a more comprehensive task. These choices will then influence the division of activities between the actors. However, each solution will consist of independent actors who are integrated in a common system for handling of waste.

An important characteristics is also the existence of different kinds of waste; from waste like household refuse, paper, plastics to waste from electronics and cars. The kind of waste to be handled influence the design of the reverse channel (Jahre and Flygansvær 1996). In this respect several decisions have to be made (Jahre 1995). These concern how to handle waste (i.e. reuse, recycling or disposal), and which actors to include. Choices like these, will influence the performance of the RC. The demand for control in reusing products makes reuse an option only for the closed system. Few, if any, customers are willing to buy products without some kind of guaranties, and companies are reluctant in letting other actors sell their products. Flee markets are not included in this line of argument, even though these kinds of markets do have a function regarding reusing of products. On a general basis, waste handling alternatives are dependent on the degree of control in the system. A closed system provide a strong channel captain and a high level of control, and will therefore provide the possibility of reusing products. An open system however, provides a lower level of control and makes the possibility of reuse difficult.

2. From vertical integration to vertical control by vertical relationships

The channels literature report developments towards cooperative relationships rather than integrated hierarchical or pure market governance (Dyer 1996, D'Aveni and Ravenscraft 1994, Christopher 1992). A major reason for this is the ability to achieve the advantages of hierarchy without pulling along the disadvantages. An important aspect however, is that governance do matter in cooperative relations as reported by Dyer (1996). It is a question of effectively aligning governance structures with transactions to obtain efficiency advantages in the relationships. This prove promising for cooperative reverse inter organizational channels.

2.1 The governance problem for reverse channels

The transaction to be looked into in this paper is the *collection of waste*. As discussed above, reverse channels is predetermined to be organized as a hybrid governance structure mainly due to the need for efficiency and stability. As demonstrated by Rosenau et. al. (1996), it is arguable that such channels are dependent upon an effective channel captain to be in control to avoid suboptimizing.

The governance problem for a reverse channel is then to structure a cooperative relation where one actor has the overall responsibility. Rephrased; one actor need to obtain *vertical control* in the reverse channel relationship. The reverse inter organizational relationship need therefore be an overall contractual relationship with a high degree of vertical control.

Who are then the contractual partners where the goal is protection of the environment? It can be argued that the government represent the interests of the environment and is the principal of such an arrangement. The consumers and companies are then the agents who are to achieve the goal of greater sustainable development. It has been argued above that such a goal is best achieved if the agents work in cooperation and coordinate their effort. In Norway a relation has been established for the electric and electronics (EE) industry, and the industry has as a joint effort established a channel captain to handle the contractual obligations. The governance structure needed is vertical control, and is therefore the dependent variable in the suggested model.

What are then the independent variables? The key ones are according to Rindfleisch and Heide (1997) asset specificity, environmental uncertainty and behavioral uncertainty. Given that collection of waste is to be performed using excess capacity, it may be argued that there is no need for new investments, therefore asset specificity would not be of importance in this respect. However, establishing a channel captain could be interpreted as an investment in specific human capital and categorized as specific asset in the relation. The need for such an arrangement comes forward because there is a non-existent market for these services. The construct of uncertainty also prove interesting in this respect. As Rindfleisch and Heide (1997) write, "the most popular operationalization of environmental uncertainty focuses on the unpredictability of the environment". This is one of the challenges for waste management today. Lack of knowledge about possibilities and consequences, keeps the uncertainty level high. Combined with the non-existent market, it highlights the need for a visible hand as represented by the channel captain. The construct of behavioral uncertainty refers to difficulties associated with monitoring the contractual performance of exchange partners (Rindfleisch and Heide 1997). It is basically an ex post problem. This is also relevant with respect to waste management, but it is beyond the scope of this paper. The following proposition may then be formulated:

P1: Due to a high level of uncertainty created by a non existent market a reverse channel needs to be coordinated by a channel captain to keep the transaction cost at a minimum level.

The regulations made by the government to ensure protection of the environment, are very much open ended. That is, how the companies solve the task of protecting the environment is in their own hands, as long as they reach the specified goals within set time frames. As an example, the government in Norway has decided that 80% of electronic waste is to be collected by the year 2004, which is agreed upon with the industry through the contract mentioned above. How this goal is to be achieved however, is a problem for the industry to solve. This could be categorized as an adaptation problem according to the TCE framework (Rindfleisch and Heide 1997). An adaptation problem is created when a firm, whose decision makers are limited by bounded rationality, has difficulties modifying contractual agreements to changes in the external environment. Open ended regulations have incorporated this aspect, and allows for modifications in the work as it is being done. Being aware of the need for such adaptation, gives the industries the possibility to create sound solutions for the environment. It also opens the possibility of using existing capacity in the coordination effort. The need for the industry as a whole to fulfill a government demand, and in addition having to use excess capacity to keep the system cost down drives forth cooperative effort. The following proposition may then be formulated:

P2: *Due to a need to fulfill governmental demands on an industry basis, and at the same time having to use excess capacity to limit the use of resources, companies involved in a reverse channel for waste collection need to cooperate.*

Thus, the antecedents of the adaptation problem, which in this context is vertical control, are the need of cooperation between the companies in the industry, and coordination by way of a channel captain. The use of existing capacity and fulfillment of government goals provides the incentive to cooperation, while the non-existent market demands establishing a channel captain. The discussion may be summed up in the suggested model illustrated below.

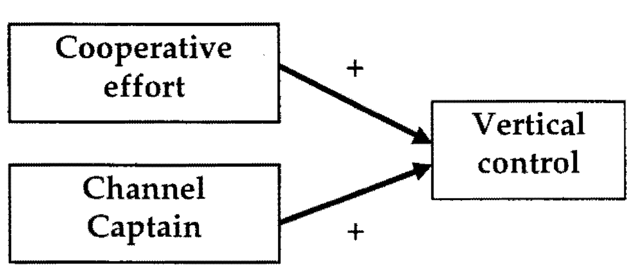

Figure 2: An initial model

Next there is a need to discuss what kind of cost are imposed in such a situation, and which kind(s) of governance mechanisms are appropriate. That is, which governance mechanisms provide vertical control in such a way that the cost of running an reverse inter organizational relationship is minimized. These issues are however only briefly mentioned, and further insight will be provided in the prolonged work of this paper.

2.2 Cost issues in a reverse inter organizational relation

The cost issue with respect to logistics management, is to minimize the total cost for a given service level. The cost issue with respect to IOR's, is to minimize the cost of running a system which allows for vertical control as a governance structure. These types of cost are more fundamental than those of logistics management. To illustrate the difference; the cost of IOR's are the cost of running the system, while the logistics cost are the cost that keeps the system running. The latter will not be part of this study.

The governance structure is to provide an efficient solution; that is achieving the proposed goals at the lowest cost. There are different costs involved. The major groupings are transaction cost, information cost and production cost. Theory show that there is a trade off between these cost; that is if transaction cost is low, production cost tend to rise (D'Aveni and Ravenscraft 1994), and information cost will vary with the availability of performance measures.

D'Aveni and Ravenscraft (1994) show that vertical integration tends to reduce transaction related and overhead costs, but production cost has a tendency to rise due to bureaucracy. The study find a net advantage in favor of vertical integration. That is, reduction in transaction related and overhead costs weakly exceed the increase in production costs. The authors use this to explain the trend towards disintegration in the 80- and 90-ies. Companies are forced to focus on the methods that stimulates the advantages of vertical integration, but exclude disadvantages. This implies that if one replaces vertical integration as a form of organizing with vertical relationships, in such a way that the level of transaction and overhead cost doesn't rise, one would also be able to gain the advantage of keeping the level of production cost at a minimum. This is the cost advantages companies wants to gain by using the strategy of outsourcing. However, such a situation actually incorporate more companies into the decision making process. This calls for a greater level of coordination than the prior form of organizing. That is the level of information cost will then most likely rise, especially when there is need for a high degree of coordination like in the reverse channels network as posed above.

2.3 Governance mechanism in vertical relationships

Supply Chain Management (SCM) thinking address vertical relationships. Christopher (1992) points out that supply chain management is not the same as "vertical integration". Vertical integration implies ownership, but businesses are now increasingly focusing on their core competencies and everything else is outsourced (Christopher 1992). As Christopher (1992) writes; there is a crucial requirement to extend the logic of integration outside the boundaries of the firm to include suppliers and customers. This is the concept of supply chain management. A definition is provided by the International Center for Competitive Excellence in 1994: "Supply chain management is the integration of business processes from end user through original suppliers that provides products, services and information that add value for customers" (Cooper, Lambert and Pagh 1997). Dyer (1996) studied the Japanese auto industry and found that they compete with their entire value chains. Companies are co-specialized, and work activities is decentralized without sacrificing economies of scale or co-specializing of assets. Still there is need for governance. Governance influences the performance of a value chain because it affects: (1) transaction cost, (2) the level of relation-specific investment, and (3) the strategic use of information (Dyer 1996). The literature supports the need for vertical relationships, as D'Aveni and Ravenscraft (1994) argue that true competence may be gained by replacing vertical integration with vertical relationships. Even though the literature provide some general ideas of how to achieve this level of cooperation, there is much work left, both general and in the context of reuse. Introduction of vertical control may prove promising.

Which combination of governance mechanism are the best to ensure vertical control in a reverse cooperative relationship? The actors in the relationship need to be able to act independently, but also coordinate their effort in protection of the environment. The governance structure need to allow for this duality. Developments towards more flexible governance mechanisms prove promising in this respect. It is to a greater extent possible to build governance structures with elements *across* the generic alternatives of market, hybrid and hierarchy.

3. Concluding remarks

A new phenomena is addressed using an existing theoretical framework. The next step in the process will be to establish a proper research design. The problem is rather structured, but address a new phenomena. This calls for a flexible design to begin with, and then a more structured procedure when the existing theoretical framework is related to the new phenomena in a sufficient manner. As protection of the environment has not been studied in this manner earlier, it demands some exploration at the outset. This calls for careful discussion of the problem and its concepts. The case study method may prove promising for the exploratory part of the study.

Waste are divided into fractions or types by the Norwegian government. The industries are given more responsibility to solve the waste problems their products cause. To ensure this, the Norwegian government establish contracts with the industries. Today, such contracts exist for packaging, batteries, tires and electronics. These cases will provide valuable information to the research suggested in this paper.

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Predicting the Return of Scrapped Products through Simulation – a Case Study

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Abstract

In this paper the development of a simulation model for the prediction of the return of scrapped products is presented. The model is based on life cycle data (sales figures and failures) and influence factors (e.g. life time, wear and tear, usage) on the return of scrapped products. Therefore, an empirical study on life cycle data of photocopiers is applied. The simulation model consists of sub-models concerning sales, failures, usage and returns of photocopiers. It can be applied to predict returning amounts of photocopiers with reference to planning periods.

1 Motivation

Today, companies are forced to predict their return of scrapped products at the end of the product life cycle (PLC) by voluntary or legal liabilities. On the one hand, these prognoses are needed for the planning of recycling and waste disposal. On the other hand, they are needed in material requirements planning for the calculation of the return of secondary materials from recycling processes into production., The return of products to be recycled from consumers to producers varies depending on consumers' behaviour and product life cycle. Up to now, neither production planning, scheduling, and control systems (PPC-systems) nor recycling or disassembly planning systems are containing methods for the prognosis of the return of scrapped products to be recycled.

Subject of this paper is to approach a model for such prognosis based on life cycle analysis of photocopiers. Therefore a simulation model is developed which consists of sub-models for the analyses of sales, failures, usage, and return of photocopiers. The model is investigated to find out, in which periods which amounts of scrapped photocopiers return to the producer.

2 Submodels

2.1 Sales model

2.1.1 Product Life Cycle

The PLC can be understood as a general model describing the development of turnover over all life periods of a product [12]. The PLC is divided into four stages [2]:

- *Introduction stage*: In this stage, a new product is rolled out into the market. The turnover is growing slowly and profits cannot be gained because of high costs for launching the product.
- *Growth stage*: During this stage, the new product is increasingly accepted by the market and profits are growing
- *Maturity stage*: This stage is characterised by decreasing growth of turnover and stagnant profits, because the product is widely accepted and it becomes harder to find new customers.
- *Decrease stage*: The traditional PLC model ends with the decease stage, in which turnover and profits are decreasing and the products will finally be removed from the market or substituted by another.

2.1.2 Empirically Investigated Model

The investigation is based on the sales figures of three photocopiers over a long period of time. By data protection reasons, the name of the company who handed over the data to us is not mentioned. Through the analysis of the data presented in figure 1 to 3 three stages could be identified:

- Stage 1 with a relatively sharp growth of sales
- Stage 2 with stagnation on a high level
- Stage 3 with decreasing sales over a longer period.

In all figures illustrating PLCs of different photocopiers, a on the left side steep rising and on the right side slightly dropping curve could be identified.
The attempt to describe the sales curves with a Gaussian distribution failed. It was impossible to construct a reasonable adjustment line in a probability net for a Gaussian distribution. In practise, the steeply rising beginning of sales which would be typical in a Gaussian distribution could not be proved for photocopiers. This is caused by customers' behaviour: In a branch with high innovation rate it is typical that customers demand on the latest products. Therefore, the Weibullian distribution [1, 8] is more appropriate to describe the sales curves over the whole PLC, because two parameters are employed to describe the appearance of the curve on the left and right side.

The reliability function R(t) of a Weibullian distribution with two parameters is the following [3, 4, 5]:

$$R(t) = \exp\left[-\left(\frac{t}{T}\right)^{b}\right]$$

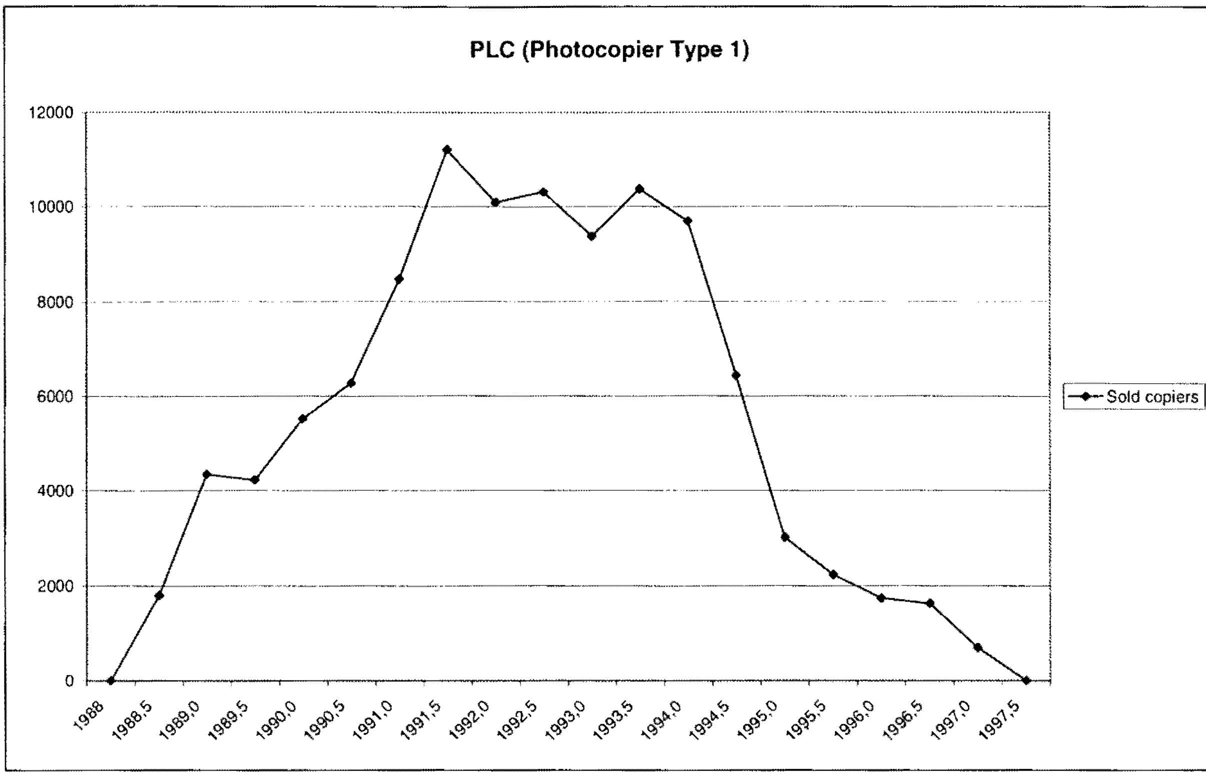

Fig. 1 PLC of photocopier 1

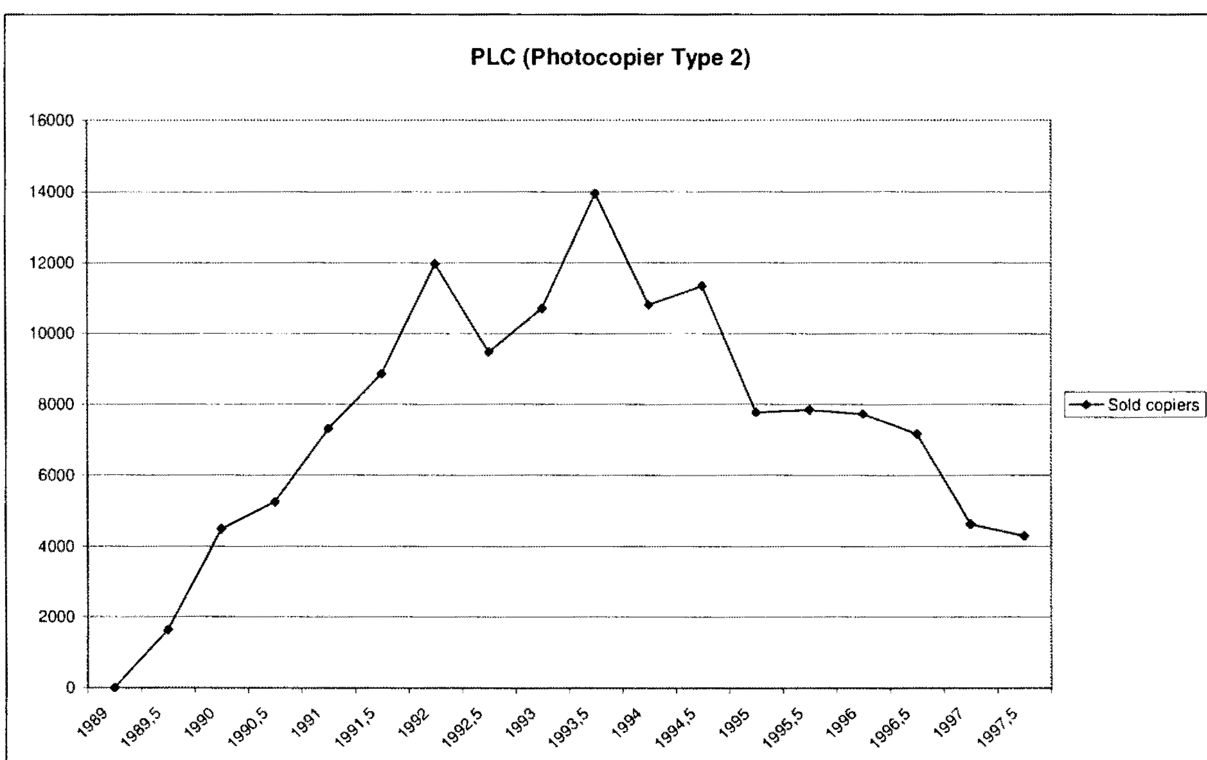

Fig. 2 PLC of photocopier 2

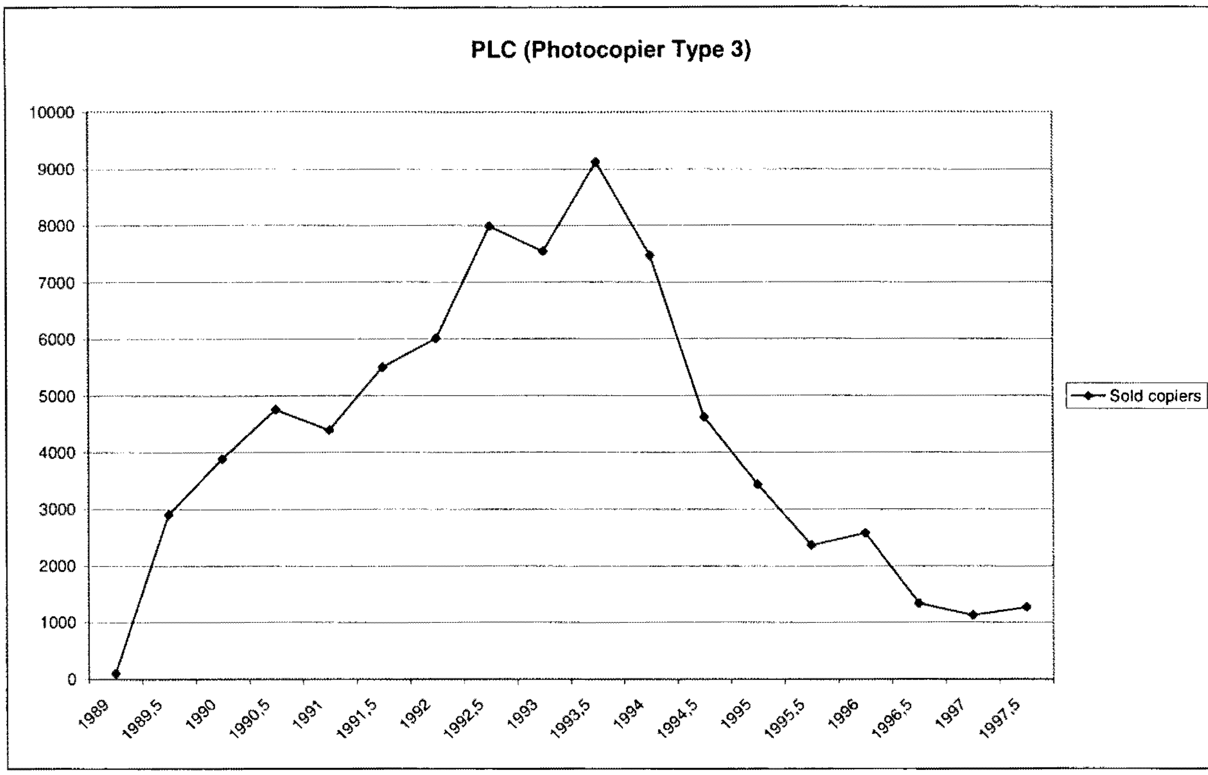

Fig. 3 PLC of photocopier 3

The Weibullian distribution with two parameters for the sales model is described by the following parameters:

T: T is the scale parameter. In our model, T determines the beginning of the stage where the curve becomes slightly dropping. This stage is reached when 63.2% of all sales are carried out.

b=2: b is defined as the form parameter.

The grade of this adjustment can be shown applying a life cycle network [10], if a reasonable adjustment line can be constructed. In figure 4, the sales figures of photocopier 3 are sketched in a life cycle network. Now it is obvious that the Weibullian distribution can be applied for the sales model. The life cycle networks for the photocopiers 1 and 2 are nearly identical with figure 4.

2.2 Failure Model

The evaluation of failure data has shown that the Gaussian distribution cannot be reasonably applied for the description of the behaviour of failures over time [6]. A logarithmic transformation does not put things right in most cases, too. Again, applying the Weibullian distribution is useful for the failure model in a PLC [7, 9], but with three parameters in this case. A lot of failures are caused by damages appearing with a (long) delay between cause and effect. Therefore, a long term summation of "microscopic" damages is necessary until a macroscopic failure becomes visible. The period in which only microscopic damages appear causes a delay between the rollout of a new product and the first failures. This delay is called "failure free period" (t_0), which is the third parameter of the Weibullian distribution underlying the failure model.

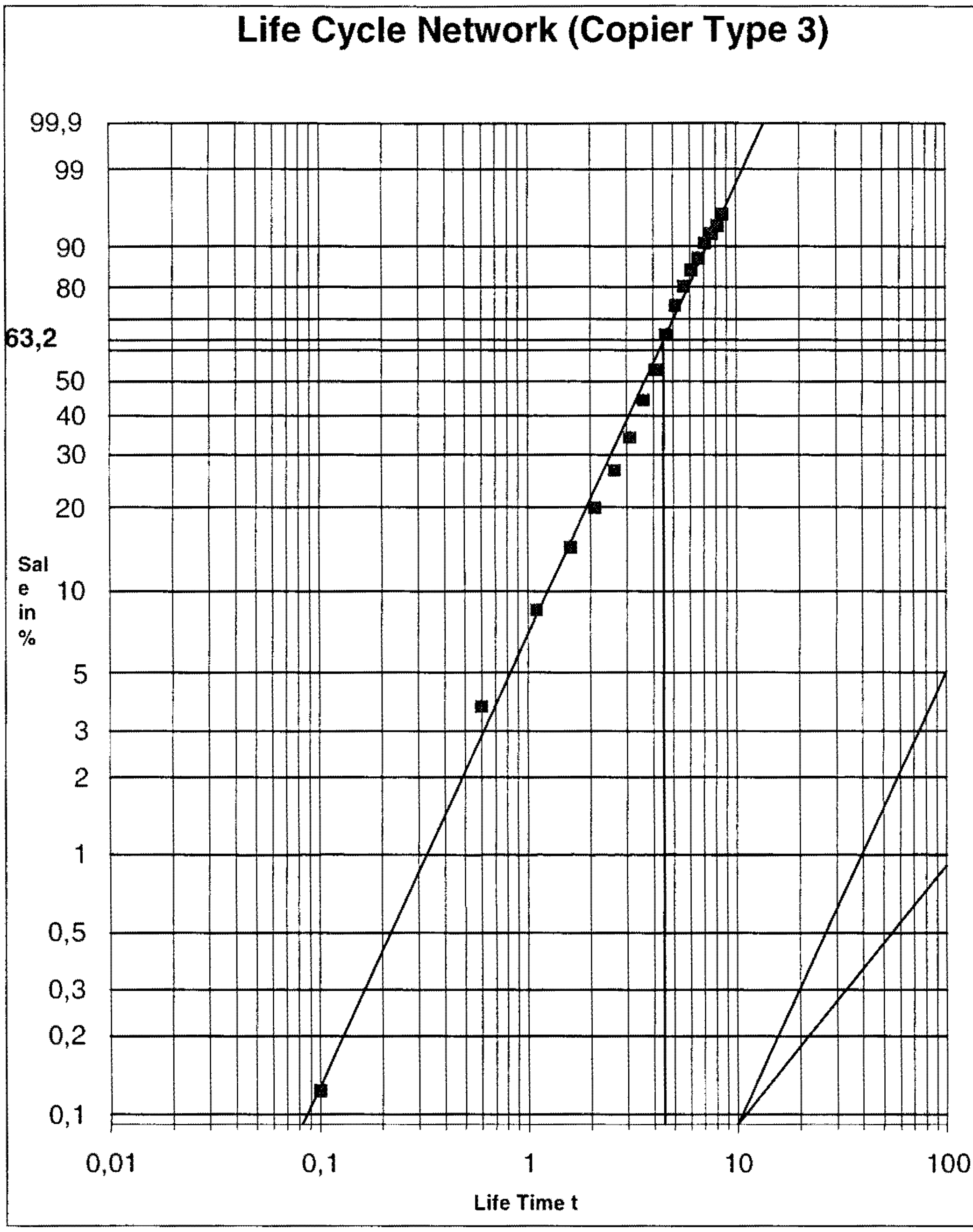

Fig. 4 Life cycle network of photocopier 3

Furthermore, a main advantage of the Weibullian distribution is the variety in which it can be applied for the description of different types of failures, e.g. if they are very early or caused by accident or wear and tear. This feature is caused by the form parameter b which makes the Weibullian distribution to generalisation of the Gaussian distribution. The reliability function R(t) of the Weibullian distribution with three parameters is given below:

$$R(t) = \exp\left[-\left(\frac{t - t_0}{T - t_0}\right)^b\right]$$

As in the sales model, characteristic parameters for the Weibullian distribution with three parameters can be given for the failure model, too:

T: as given in chapter 2.1.2

b: Form parameter which in this case is a measure for the characteristic type of failure. The following assignments of b to types of failures are reasonable:

- $b<1$: Early failures
- $b=1$: Failures by accident
- $b>1$: Failures by wear and tear

t_0: Failure free period

All types of failures are relevant for technical products. Failures by accident are characterised by the fact that time has no influence on the appearance of the failure. Therefore, the failure rate is assumed as constant. Failures by wear and tear are appearing if products become increasingly unreliable over time. In this case, the failure rate depends on time. Early failures appear particularly in the introduction stage of the PLC. Here, the failure rate depends on time, too, but the effect of time is positive, i.e., the rate is decreasing over time. Summarising all types of failures, a so-called "bathtub curve" results as shown in figure 5.

In this model, it is assumed that early failures are sorted out by the producers or suppliers and the following failures by accident can be neglected until the end of t_0 is reached. After that, failures by accident and by tear and wear have to be taken into account increasingly. This overall behaviour of failures is typical for technical products with high quality.

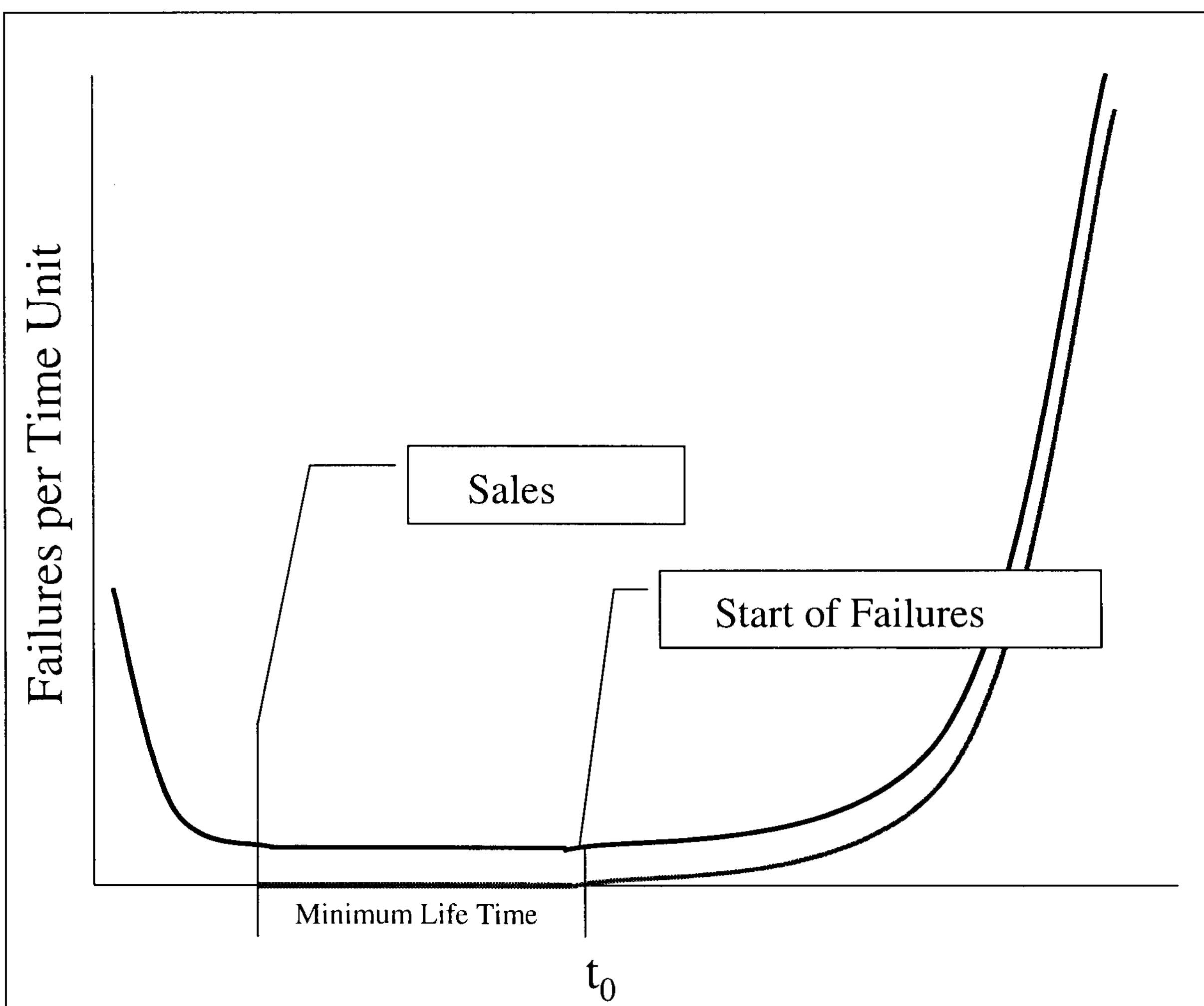

Fig. 5 Bathtub curve of failure model

2.3 Usage model

The usage model is based on the assumption that many users make few copies per day or few users make many copies per day. Obviously, this can be modelled with a logarithmic normal distribution. Therefore, the lower bound is 0, because less than 0 copies per day are not possible. Furthermore, a logarithmic normal distribution is remarked in the automotive industry regarding run km per year and car, too. Within the scope of this study the behavioural patterns concerning different types of photocopiers have been analysed. Therefore, a sampling was taken with 35 types of photocopiers over five years. The graphical interpretation shows a good adjustment to of the adjustment line in the logarithmic probability network (figure 7). Furthermore, a geometric mean of 5,550 pages per month and a measure of dispersion $\in$ = 1.4 was evaluated. It is remarkable that most of the photocopiers are made for a throughput of 3,000 pages per month only. This means that nearly 90% of all users use photocopiers more extensive than planned by the producer. The histogram in figure 6 depicting the probability density function of a logarithmic normal distribution shows a good correspondence between empirical and theoretical frequency distribution.

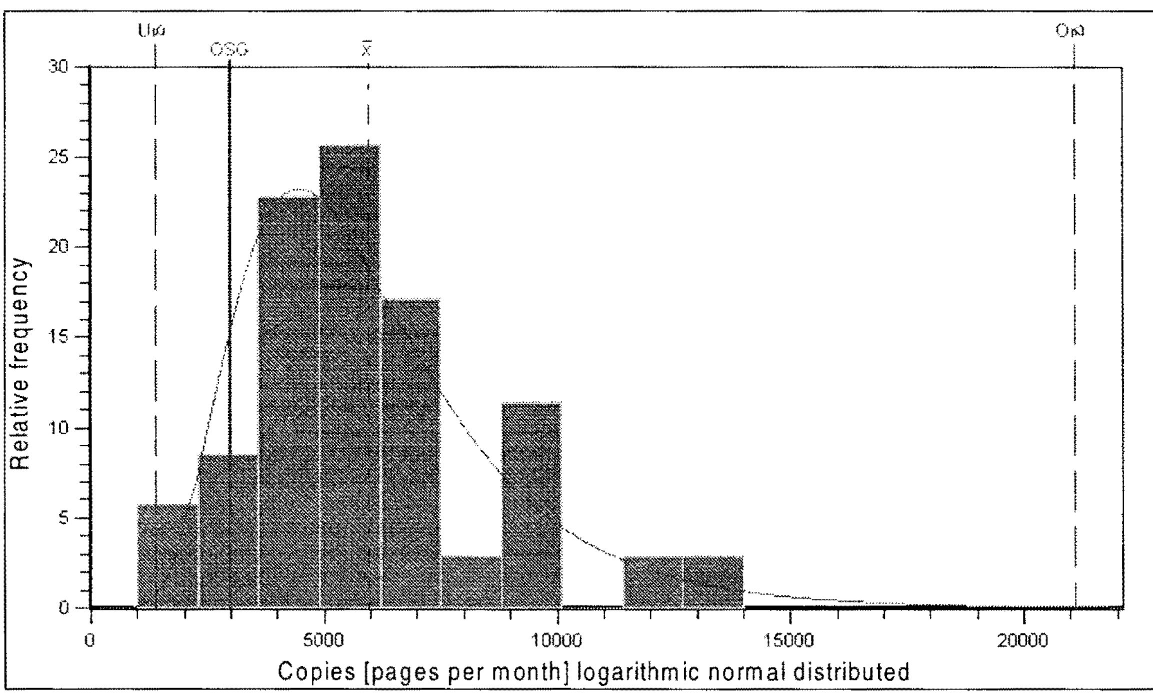

Fig. 6 Histogram

2.4 Return Model

Despite existing incentive systems, it cannot be assumed that all sold products return to the producer at the end of the life cycle. For example, this can be caused by ignorance, damage, export and convenience.

Therefore, the return quota is less than 100%. Depending on incentives or sanctions (often prescribed by law), different return rates are possible. The return quota (probability of returns over time) is assumed as uniformly distributed.

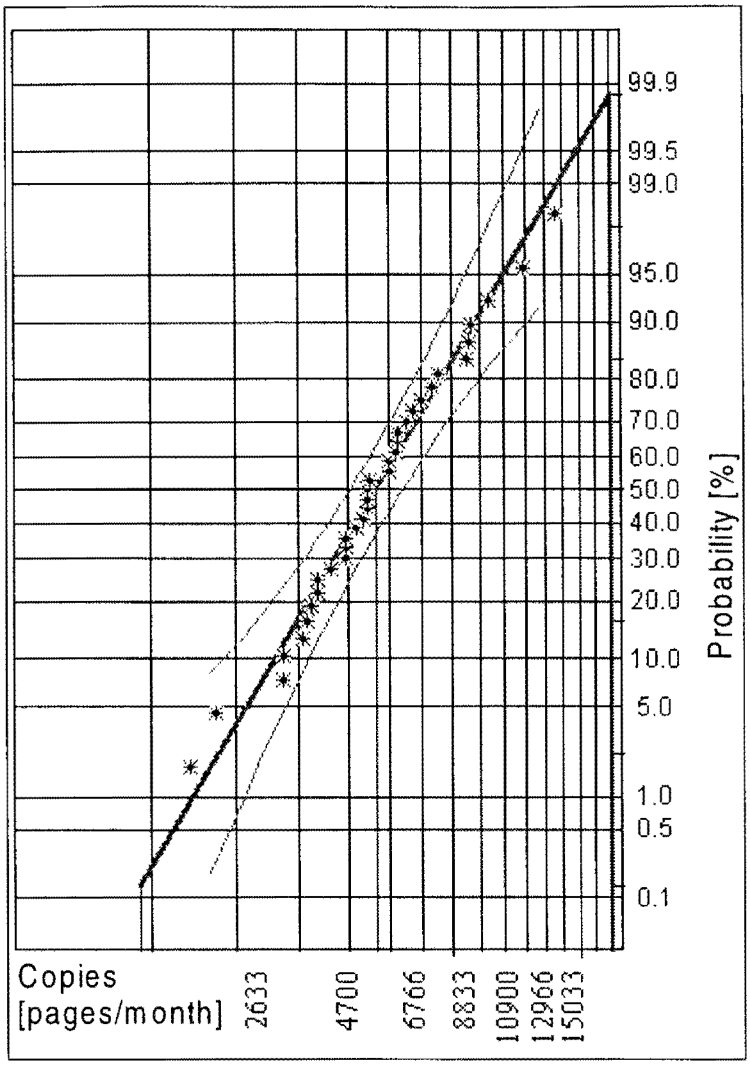

Fig. 7 Logarithmic probability network

3 Simulation

The simulation model was developed and executed with the conventional spreadsheet program Microsoft Excel. The simulation of sales over time, life time and usage characteristics is based on the submodels described in chapter 2. The assumption underlying the simulation model are the following:

- The decrease stage of a photocopier begins three years after its rollout (T = 36 months).
- The form parameter for sales is 2 with respect to results of chapter 2.1.2 (b = 2).
- The minimum life time of a photocopier is determined to 200,000 pages (t_0).
- The characteristic life time of a photocopier is determined to 400,000 pages (T).
- The measure for the failure is set to 3 (b = 3).
- The average amount of copies is 5,000 pages per month.
- The measure for asymmetry of the normal distribution is assumed as 1.5 ($\in$ = 1,5).

The simulation is related to a production series of a photocopier of which 1,000 pieces were produced and sold. A series of experiments has shown that increasing the amount of sold photocopiers has no influence on the information capability of the model. Therefore, the amount of 1,000 pieces is sufficient. In the first run of the simulation model it was assumed that the return quota is 60% for each photocopier at the end of its life cycle, i.e., the incentives or sanctions are not very successfully implemented. In the second run the return quota is assumed with 80% (well working incentives or sanctions). The results of these runs are presented graphically in figure 8 and 9.

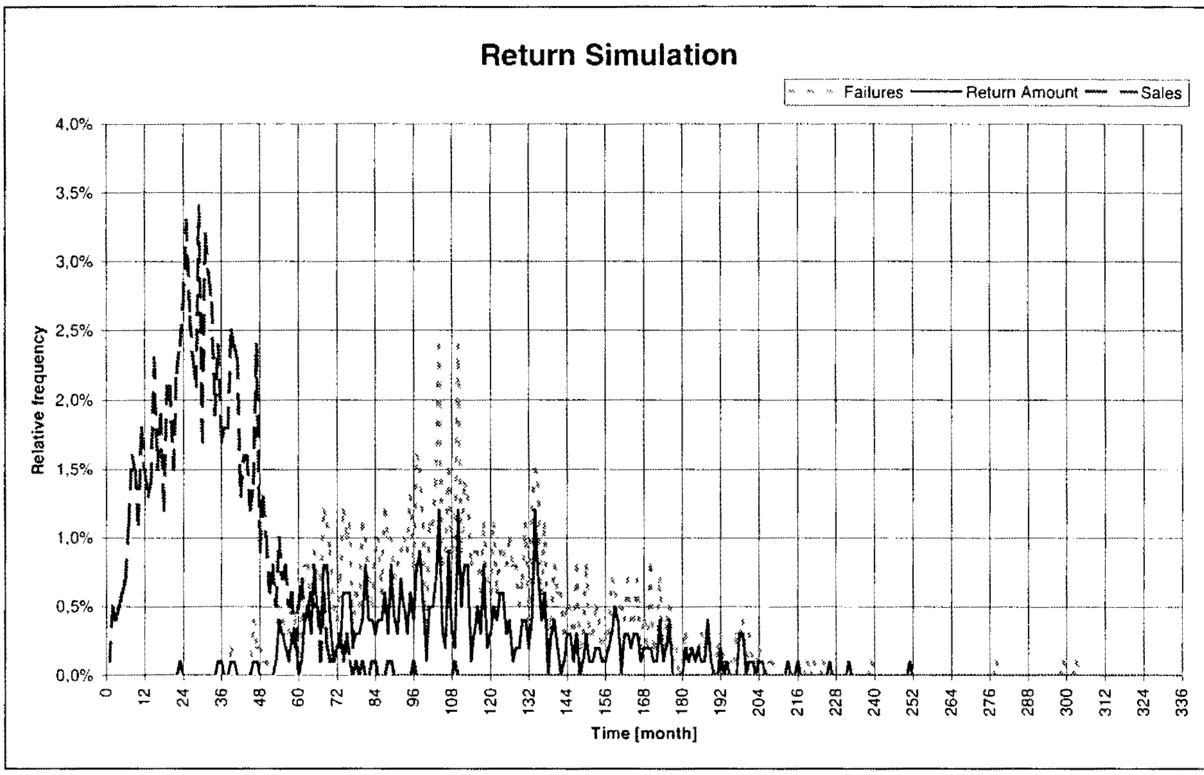

Fig. 8 Simulation results with return quota 60%

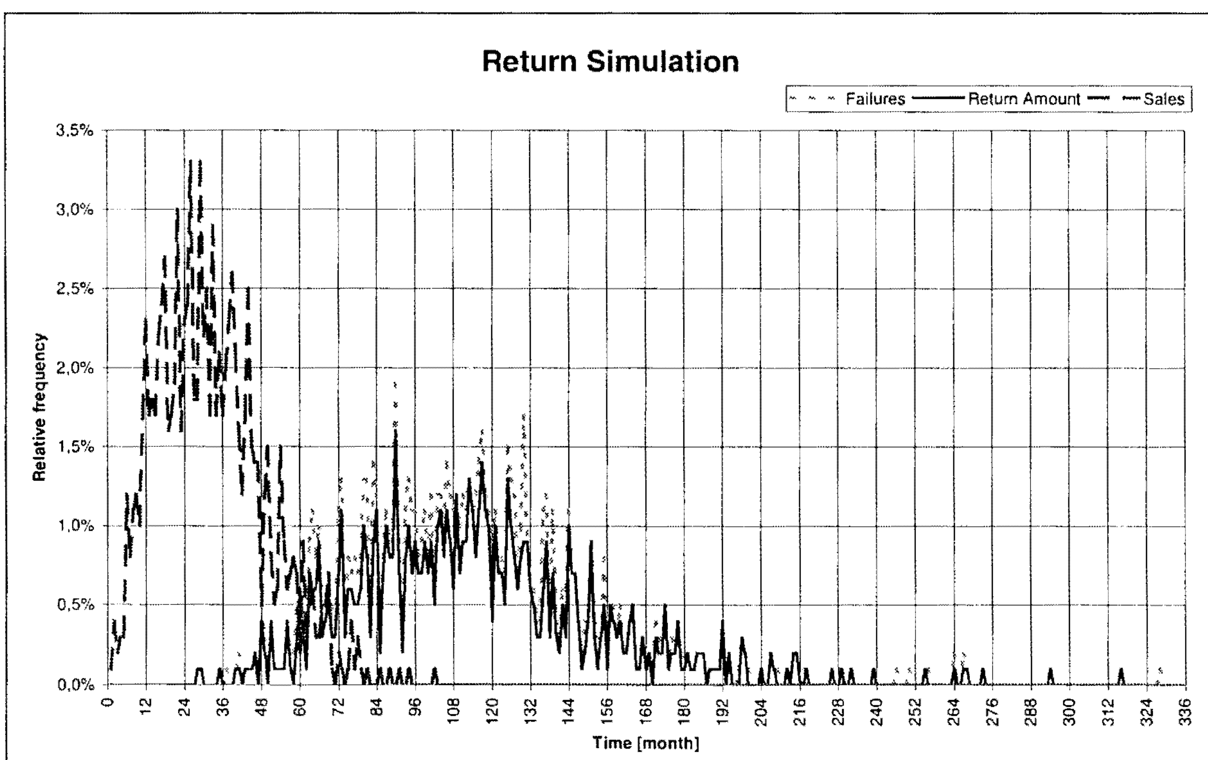

Fig. 9 Simulation results with return quota 80%

4 Interpretation of Simulation Results

Only after two to three years the first photocopiers are returning, i.e., recycling starts during the decrease stage. When the PLC is finished, only 15% of all returns are back. In other words, about 85% of all recycling has to be done after the PLC is finished. One key result of this study is the so-called "triplicate rule":

- After three years the peak value of sales is exceeded.
- After nine years the PLC is finished.
- After approximately 25 years the return of scrapped products is finished.

This results were discussed with representatives of several recycling firms and they acknowledged that this would correspond to their experiences. The results can be confirmed with life cycle data and data regarding cars taken off the road published by German "Straßenverkehrsamt" [11], too.

The peaks concerning sales and returns show a brad range of variations, which can be described with the chance variation of binomial distribution. Therefore, decreasing sales figures do not smooth finish out the curves.

5 Summary

The simulation model of results presented here only considers the influencing factors PLC (represented by a Weibullian distribution of sales figures), product life time, and intensity and frequency of usage (modelled with a logarithmic normal distribution). This influencing factors on the return of scrapped products are base data for the simulation model. Because of the simulated frequency distribution, the demand for recycling of scrapped products can be predicted. Applying upper and lower bounds for random variables, recycling resources can be made available conservatively. These upper and lower bounds can be computed empirically through repeated simulation.

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ASPECTS OF INDUSTRIAL RECYCLING OF ELECTR(ON)IC APPLIANCES

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Abstract: Facing an increasing amount of electr(on)ic appliances to be recycled each year as well as the overstocking of the disposal sites in Germany in near future, the Federal Ministry of Education, Science, Research and Technology's project "Industrial Disassembly of Electronic Products for Recycling (IREAK)" has been brought into life in August 1996. The aim is the development of new strategies for recycling and reuse and the realisation of a flexible industrial disassembly and recycling system for all kind of used electric and electronic products. This paper discusses methods of the design of products due to recycling and disassembly, the development of alternative disassembly systems, the realisation of an industrial recycling enterprise and the development of an intranet-based information system for manufacturers and recycling enterprises.

Keywords: Data base, Disassembly, Ecology, Electrical Appliances, Information Systems, Recycling.

The project that this paper is based on was promoted by the Federal Ministry of Education, Science, Research and Technology (Förderkennzeichen 01 RK 9737). The responsibility for the content of this publication lies with the authors.

1 IREAK - AN INDUSTRIAL RESEARCH PROJECT FOR RECYCLING OF ELECTR(ON)IC APPLIANCES

1.1 New demands on recycling of electr(on)ic appliances due to changing boundary conditions

In Germany, there are about 1.5 million tons of electric and electronic waste to dispose annually. As 75% of the disposal sites in Germany will be overstocked in 2000 (see Umweltbundesamt 1994), a significant increase of the recycling quota is necessary for ecological and economical reasons. To ensure furthermore international competitiveness and to preserve our natural environment, new strategies for recycling of materials and the reuse (see Schlögl 1995) of electr(on)ic appliances or their components have to be developed.

As one consequence of the limited capacity of disposal sites in Germany a new legal obligation, i. e. the "Kreislaufwirtschafts- und Abfallgesetz", dated from October 7th, 1996, was imposed on any manufacturer. It demands to develop concepts for recycling and to prepare balance-sheets about the recycling quotas of their products.

The flow of material in recycling systems as well as the flow of information have to be modified and adapted to new requirements. Fig. 1 and Fig. 2 show the original and the intended flow of information and material in recycling systems. There is a main flow of material from the manufacturer towards the customer and from the customer via the recycling companies towards the disposal site. The suggested recycling is hardly pronounced and reuse nearly does not exist. An exchange of information exists only between construction and manufacturer concerning the design of the production system. Still, the aimed situation designates a rich exchange of information between manufacturers, construction and recycling companies regarding the design of the production system as well as the disassembly system. The main flow of material will be organised in form of a circle linking the recycling companies with the manufacturers. This link will be realised not only by supplying raw materials like copper, iron and plastic material again to the production cycle, but also by reusing components and single parts entirely. The material flow from the recycling companies towards disposal sites or incineration should be minimised.

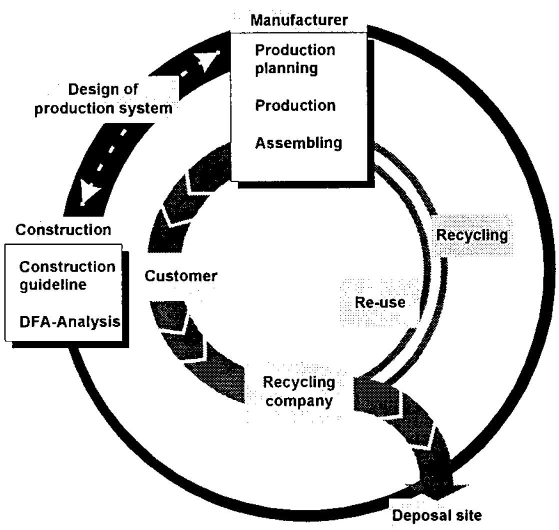

Fig. 1 Present flow of information and material in recycling systems

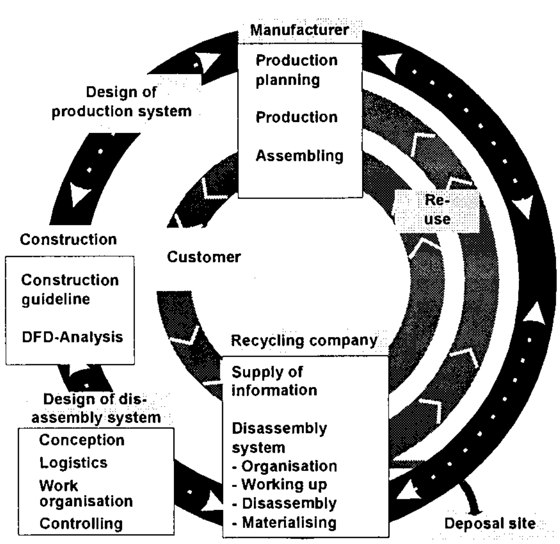

Fig. 2 Intended flow of information and material in recycling systems

Taking into account these facts, the IREAK-Project started in August 1996.

1.2 What does IREAK stand for? – Motivation and objectives of the project

Within the framework of the Federal Ministry of Education, Science, Research and Technology's project "Industrial Disassembly of Electronic Products for Recycling (IREAK)" the aim is to develop and realise a flexible industrial disassembly and recycling system for all kind of used electric and electronic products.

Crucial points of the project aim at the development and realisation of a flexible, economical disassembly system, new organisational concepts for recycling enterprises and the development of adequate information systems for the support of the processes in the factories concerned. Moreover, a guideline for the design of electr(on)ic products, appropriated for recycling, will be developed. Aspects of disassembly, reuse and recycling are taken into consideration by means of methodical gathering of recycling relevant data as well as the analysis of actual products.

In order to ensure the supply of the acquired knowledge and the developed tools for ecological and recycling appropriated design as well as to facilitate the communication between manufacturers and recycling enterprises, an information system based on internet technologies allowing world wide access for authorised users will be developed.

Regarding the envisaged new industrial recycling enterprise there are also some important social and work science aspects to be dealt with. New concepts for the organisation of modern recycling companies as well as training and qualification programmes have to be developed within the framework of IREAK. In addition, an ecological controlling will accompany the conception, development and realisation of the industrial recycling factory (see Deutsche Gesellschaft für Luft- und Raumfahrt 1998).

1.3 Structure of the project and tasks of the different partners

The partners in the research project constitute a powerful industrial consortium, covering every aspect of the life cycle of electronic products. Telefunken Microelektronik and Grundig act as producer of high-tech electronic parts, Hetzel Elektronik-Recycling (HER) is a specialist for disassembly and recycling of electronic appliances. Information technology support is given by Delta Industrie Informatik whereas R&D support is given by the Institute for Human Factors and Technology Management (IAT), University of Stuttgart, and the Brandenburgische Technische Universität Cottbus (BTU). A&O-research contributes to the project by providing expertise in work science and developing appropriate training and education programmes for recycling staff. GW Sohlberg is involved as a manufacurer of work systems applicable for assembly as well as for disassembly. The Gesellschaft für Entwicklungsberatung und Produktrecycling (GEP) is involved as the project coordinator and expert for "design for environment" engineering.

In order to realise the above-mentioned aims, the project is divided into eight scopes of duties which can be summarised as follows:

- ❑ Planning and realisation of an industrial disassembly and recycling factory
- ❑ Development of design guidelines for electr(on)ic products taking into account environmental impacts and recycling
- ❑ Development of information technology support for industrial recycling factories and product design
- ❑ Development of new concepts of education, staff and organisation for recycling companies. Development of an ecological controlling.

Based on the above-mentioned topics, four subjects will be described more particularised in the following chapters.

2 METHODS FOR DESIGN FOR ENVIRONMENT (GEP)

2.1 Design methodology

A main issue of the IREAK project is the development of an appropriate Methodology of Design for Environment (DFE) with the aim to improve the reuse and recycling capabilities of future electr(on)ic products. This methodology should be generally applicable and universally useable and capable of being integrated in different design processes. Therefore, the widely accepted Guideline VDI 2221 "Systematic approach to the development and design of technical systems and products" (see VDI 2221) has been used as the basic methodology. The environmental tasks have been added to the different design steps defined in this guideline. This methodology supports DFE in the entire design process (Fig. 3). Though DFE is a methodology focused on the entire life-cycle, the end-of-life phase with reuse and recycling is especially emphasised in this project.

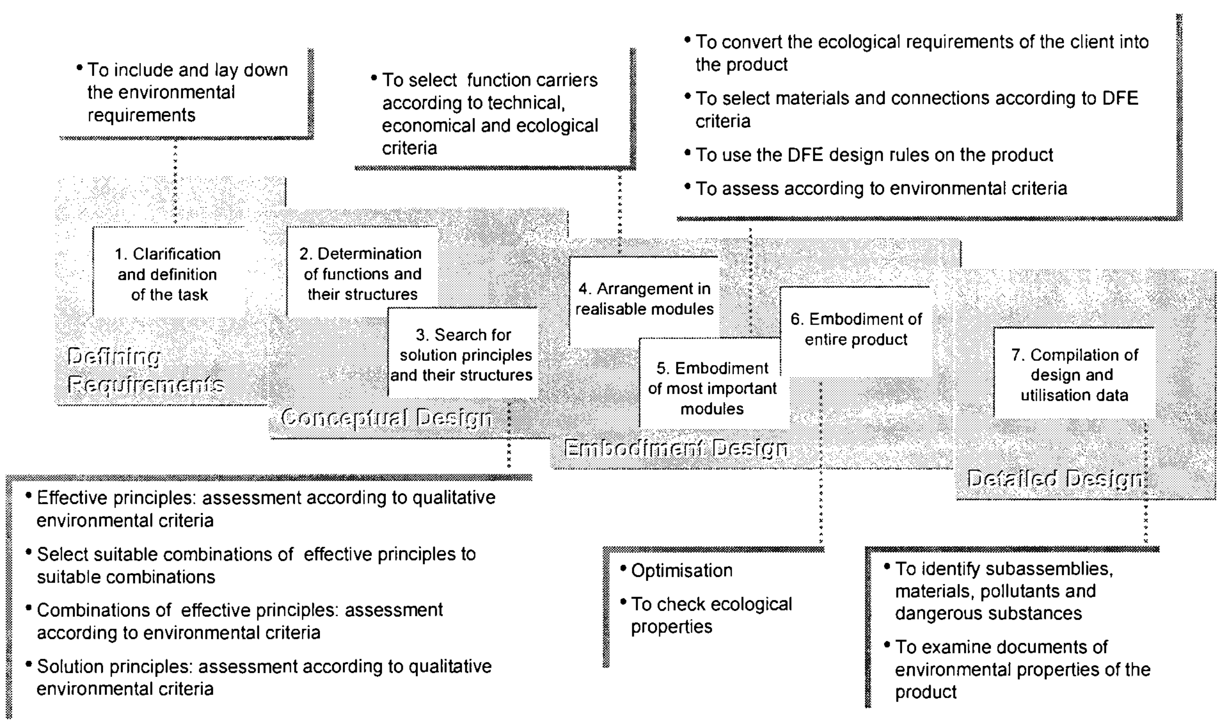

Fig. 3 Methodology of Design for Environment (DFE)

2.2 Knowledge base and Data base

To practise DFE, following the DFE-Methodology based on VDI 2221, an enlargement of the designer's knowledge regarding the whole life cycle, especially on the end-of-life phase, is necessary. To integrate the environmental aspects into the product design steps, different knowledge have been identified for which respective data bases are needed (Fig. 4). The basic knowledge as well as the specialised knowledge has been provided which are necessary to apply the methods and the tools during the design process. In addition, a couple of data bases – fundamental data as well as specific design data – are provided, too.

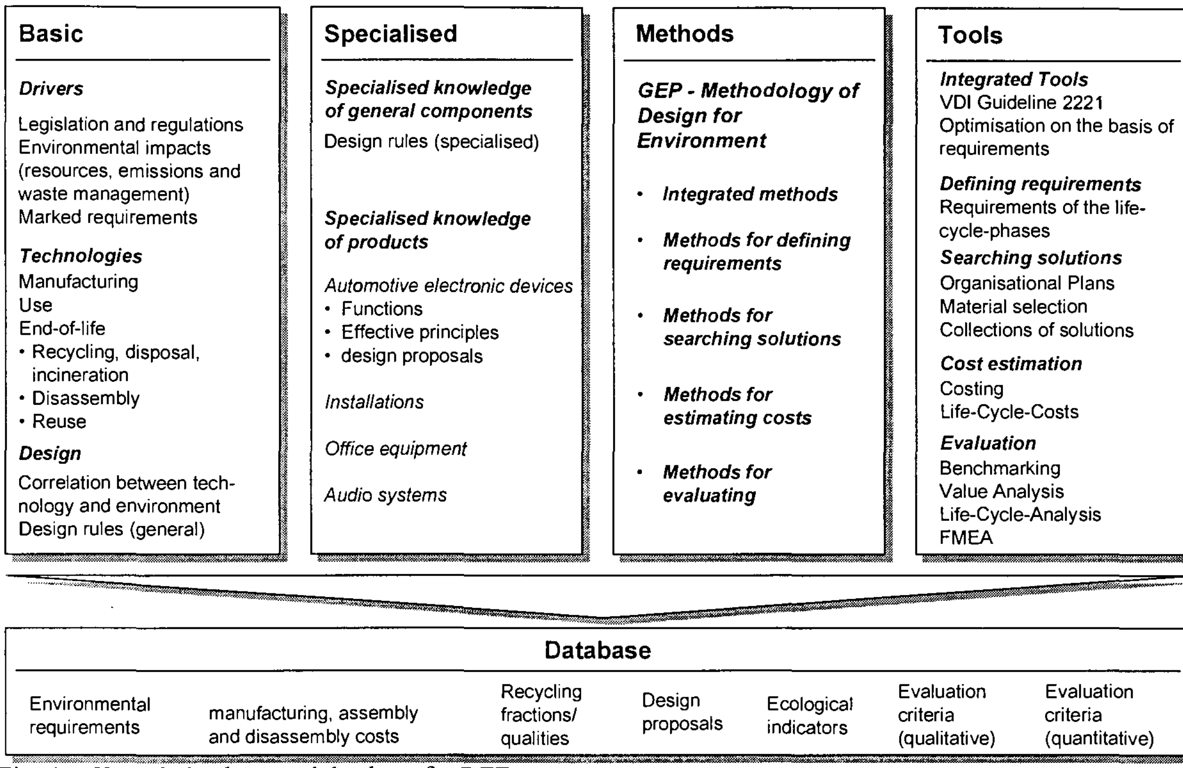

Fig. 4 Knowledge base and database for DFE

2.2.1 Knowledge

Aspects of the "Closed substance cycle and waste management act", of technologies (such as manufacturing, recycling etc.) and design as well as correlations between them are described in the "Basic knowledge". The drivers in the first column explain the system of the closed substances cycle and waste management, the necessity of eco-friendly products as well as acts and ordinances which are relevant for the designer. Descriptions of the environmental impact of the product in the life cycle phases, the different technologies concerning reuse, disassembly, waste processing, and waste disposal are given under "Technologies". General design rules for DFE (such as material selection, disassembly, reuse and recycling) are described under "Design".

The "Specialised knowledge" is classified according to general components and products. The specialised knowledge of general components is stored as design rules for e.g. printed circuit boards. The specialised knowledge of products is divided in automotive electronic devices, installations, office equipment, installations and audio systems. This specialised knowledge is structured in functions, effect principles and design proposals. In practice, the design know-how of the company will be concentrated as a collection of product specific requirements and solutions.

Apart of the "GEP-Methodology of Design for Environment", knowledge on further methods is necessary, like methods for defining requirements, searching solutions, cost estimation, design evaluation and other integrated methods. These are needed for a successful application of the methodology.

2.2.2 Data base

To use the environmental knowledge, a lot of different data are necessary. They are stored in several data bases. The data are classified according to two characteristics. First, there are data like CAD-files or requirements which are required for the collection of solutions. Secondly, we have basic data, which are demanded for evaluation and cost estimation. These are evaluation criteria, manufacturing costs, disassembly times for different disassembly operations, costs and benefits for recycling fractions and ecological indicators.

2.2.3 How to use the methods and tools

For an effective use of the knowledge, a couple of different software-tools and paper-tools are provided.

To optimise the environmental properties of a product in the embodiment design phase, the method "Product optimisation based on product requirements" has been developed. Steps for optimising a product according to special requirements have been defined, and a support for designers can be given from the data bases or tools (e.g. disassembly times, ecological indicators, material lists, ...).

The procedure to define "Requirements of the life-cycle-phases" supports the definition of environmental requirements for the clarification of the task in phase 1 of the design process. Priorities has to be given, too. First, the general environmental properties, which are to be optimised (e. g. disassembly, recycling), have to be defined. Subsequently to these general properties, concrete requirements are derivable. At last, these requirements have to be weighted.

To search for solution principles, above all, the discursive methods like organisational plans, material selection or collections of solutions are suitable. To select function carriers according to economical and ecological criteria a collection of solutions is realised as a knowledge based system. It is structured into main function carriers as standardised variants, so this collection is applicable for different products. The characteristics of the variants, e.g. type, material, manufacturing method and connection are described. They are evaluated according to the life-cycle-phases production, manufacturing and reuse as well as disassembly and recycling. Special design rules are given. This collection of solutions is a system of environmental design knowledge including geometric data (generated with CAD tools), which can support the designer in new projects: a selection of design proposals can be made with respect to technological, economical and ecological characteristics. A collection of solutions has been realised exemplarily for main function carriers of automotive electronic devices in this project. Fig. 5 as shows as an example of possible solutions for housings given by the respective data base.

Methods for estimating costs are necessary to get the disassembly and recycling costs or the entire Life-Cycle-Costs. So the economic consequences of the Design for Environment are determinable. For that, different tools are available.

Evaluating methods are needed for checking the results in the different design steps. The evaluation criteria are to be adapted to the current results of work. Benchmarking is useable in the early conceptual design phase to evaluate effect principles qualitatively concerning environmental criteria. The method of value analysis can be applied in the conceptual design phase and the embodiment design phase, because both qualitative criteria as well as quantitative criteria can be taken into account. Using the several methods of Life-Cycle-Analysis (LCA) ecological effects can be calculated, if the geometry of the parts is described and the materials are selected. For that, different LCA-tools are available. To check the performance of the requirements, the overall design can be analysed using the Failure Mode and Effect Analysis (FMEA).

With this DFE-Methodology, based on a widely accepted design method, environmental aspects have been included into the design process. This gives the chance that design engineers will accept the implementation of this additional task into their daily work.

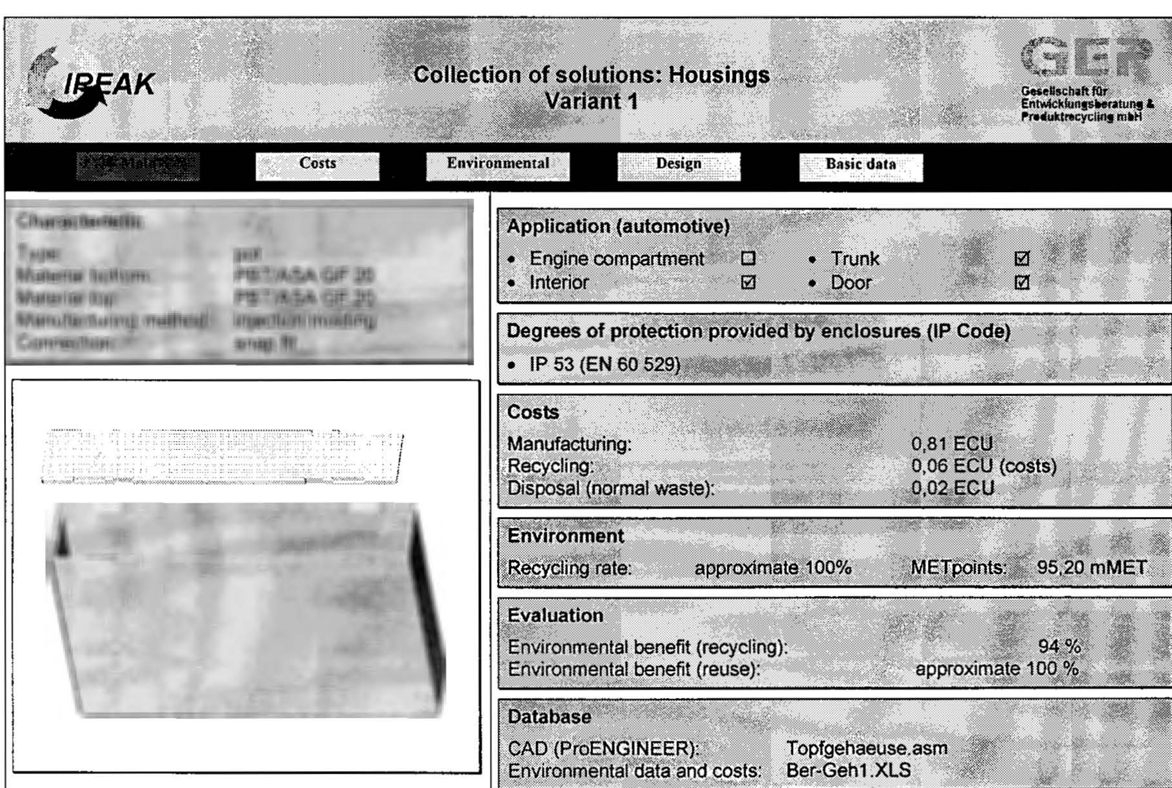

Fig. 5 Possible solution for housings, given by the respective data base

3 DEVELOPMENT OF ALTERNATIVE DISASSEMBLY SYSTEMS (IAT)

In order to plan alternative disassembly systems which meet all requirements of a wide spectrum of electronic appliances in the range from card readers or electronic control devices for cars to copiers, above all an analysis of the disassembly proceeding of some representative products has been made and documented in a so-called disassembly precedence graph. The disassembly precedence graph has been used as an auxiliary to identify recyclable materials, reusable assembly groups and components of an appliance and also the required disassembly operations. In Fig. 6 the disassembly precedence graph of an electronic control device is shown.

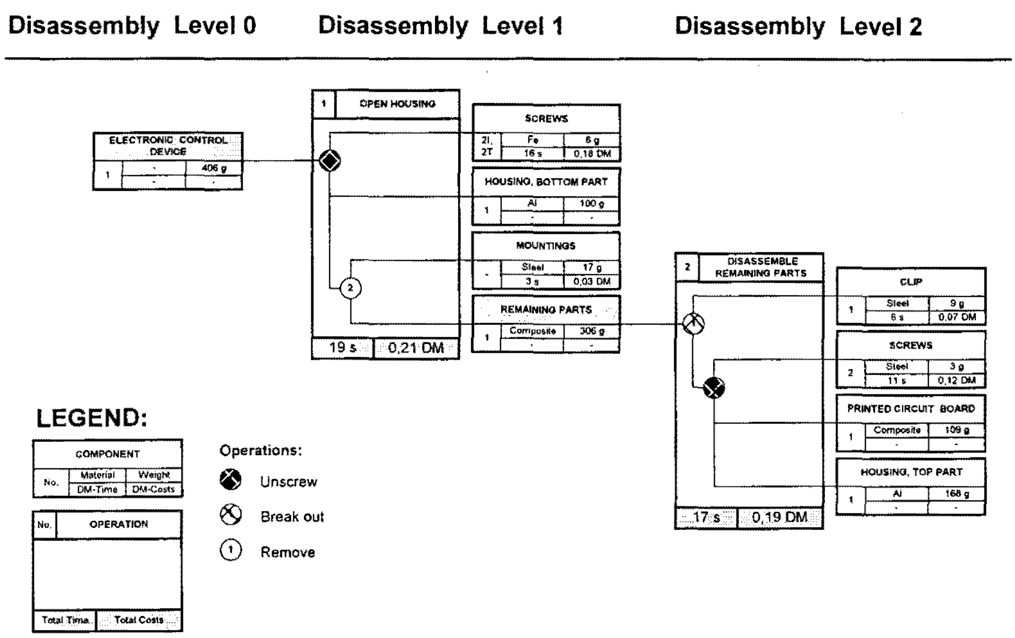

Fig. 6 Disassembly precedence graph of an electronic control device

In addition to the requirements resulting from the analysis of the products which have to be disassembled, the focus has also been put on the boundary conditions given by the recycling enterprise. The estimated product mix, mass flow and batch size are the parameters on which the economic efficiency of an investment in a disassembly system depends.

In order to propose a wide range of technical solutions that covers the requirements of small and medium-sized enterprises as well as large-scale facilities, a module system of working places and possibilities to link them has been developed. Thus any recycling enterprise may choose a system alternative or combine modules according to their own requirements and within their reach.

Among others there are single working places with or without linked transport, a conveyor table system, a line system based on division of labour and a flexible work piece carrier system.

Furthermore, a disassembly system in which the different working places are linked by a flexible work piece carrier system will be presented. On the one hand, this design allows the maximal mass flow and covers a major part of the above-mentioned spectrum of appliances. On the other hand, it is the most expensive one.

On the basis of the identified operations for disassembly and the estimated mass flow the disassembly system for multipurpose electronic products, i. e. the working places for the operators and their linking, has been planned and the resulting layout has been documented by means of ERGOMAS, a tool for the planning and visualisation of working systems.

The disassembly system based on a flexible work piece carrier system shown in Fig. 7 consists of three parts.

The work places in the centre are used for disassembling big electronic appliances and separating materials for recycling, which are transported to the left by a conveyor belt, and components as well as single parts, which are transported to the right by the work piece carriers. In order to be able to place also heavy appliances like copiers up to 80 kg on the work piece carriers, a pick-up has to be installed.

On the right-hand side there are work places used to rework single parts and components, to disassemble small appliances or to assemble products consisting of used parts and components. Therefore places have to be equipped with gadgets and tools, that enable all kind of mechanical and electronical tests.

The work places on the left-hand side are required for sorting of materials e. g. metal or plastic. Pure materials as for example metal may go directly into a container. Others, as for example plastic, have to be sorted on a rotary table before.

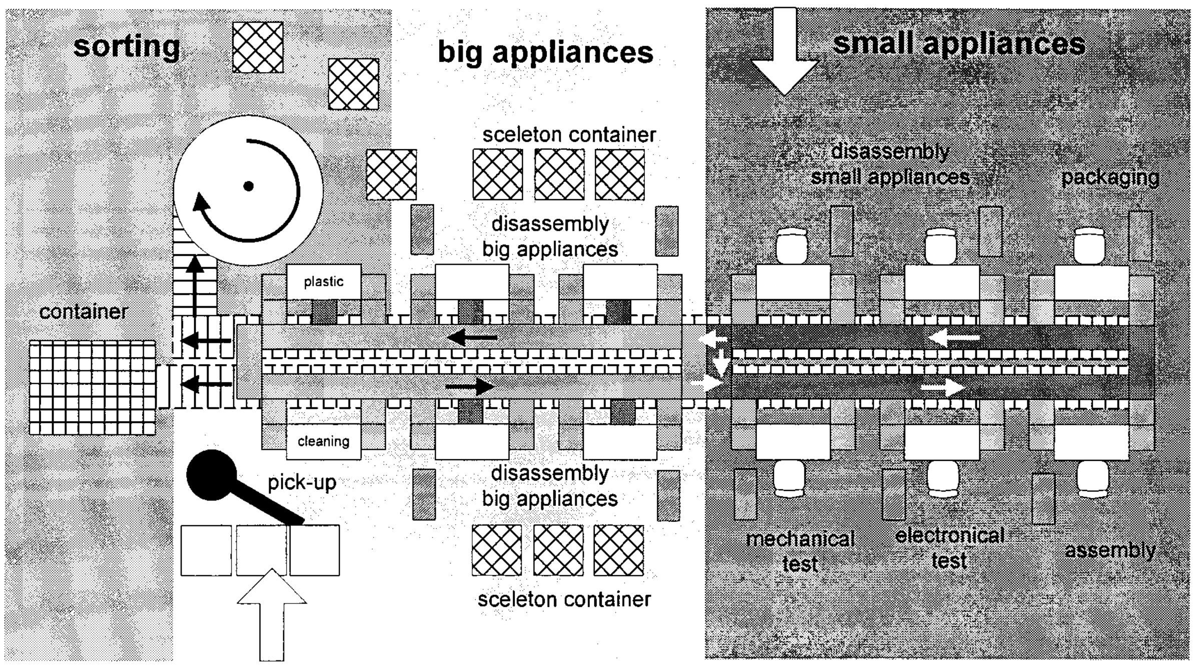

Fig. 7 Layout of a disassembly system for multipurpose electronic products

4 REALISATION OF AN INDUSTRIAL ELECTRONIC RECYCLING ENTERPRISE (HER)

The aim of IREAK is an industrial recycling enterprise that makes the ecological advantages of orderly disassembly economically competitive and therefore helps to increase the amount of electronic appliances that are recycled in a proper way. In the centre of such an enterprise stays the disassembly facility. The used disassembly strategy decides about the further way of appliances, components, parts and materials.

The idea of the IREAK-module-system for the disassembly facility was already described in chapter 3. To realise a recycling plant based on this module system it is important to choose the different modules appropriate to the individual conditions (type of appliances, number of pieces, working steps). This will be described in the following.

4.1 Mixed charges

Today's electronic recycling companies very often have to deal with mixed charges. These charges contain not only different appliances, but also partly disassembled appliances and material fractions like printed circuit boards, batteries or plastic parts. The best way to treat these charges is the single-working-place-module of the IREAK-module-system. This module corresponds in its general conception to the today's disassembly companies. In the centre there are single working places. Recycling workers are disassembling the old appliances into their different material fractions. These fractions are brought to the corresponding collection container. The working places, designed corresponding to ergonomic aspects, are equipped with suitable tools. Additional specialised working places are built up, e. g. to test and sort plastics, to handle harmful materials, to open picture tubes and to test and clean reusable appliances and components.

4.2 Small-appliances-mixed-charges

By collecting household appliances for example, the charges usually consist of different small appliances like coffee makers, toasters, irons and hair dryers. For an efficient disassembly of these appliances sorting is necessary. This job can be done by the IREAK-sort-module. In this module a number of single working places is linked by a transport system (e. g. a conveyor table system). This transport system does the sorting: The different appliances are brought into the system piece by piece, each recycling worker takes out only his specific type of appliances and disassembles them on his working place. Of course it is also possible to use this transport system in order to transport material fractions from the working places to other specific working places or to collection containers (e. g. plastics, harmful materials, reusable components).

4.3 *Big appliances*

It is not possible to disassemble big appliances on usual working places. Therefore the IREAK-module-system contains a specific module for these appliances: a mobile working place. This working place can be moved to the appliance, it is equipped with all tools that are necessary for disassembly. Because of that disassembly becomes very flexible, usual working places are not blocked with big appliances standing around.

4.4 *Copiers in huge amounts*

Copiers are an example for all appliances that are built up in a complex way. Furthermore it must be possible to divide their disassembly into different steps that can be coordinated and clocked. Their construction and their dimensions should be comparable. For the treatment of such appliances the IREAK-line-module is a practicable solution.

In this module the appliances are disassembled in division of labour. The appliances are put on carriers, the carriers are transported on an driven roller conveyor. The disassembly is done while the appliances are on the carriers. The height of the roller conveyor can be changed to adapt it to different appliances. Furthermore it is possible to turn the carriers at the working places in order to allow disassembly from all sides.

4.5 *Comparable appliances in huge amount, with product recycling option*

Such conditions are not found in today's electronic recycling companies. But in the future closer cooperations between manufacturers and recycling enterprises will appear– mainly because of new recycling laws in the European countries. These cooperations will help to enable more and more product recycling instead of material recycling. Such a mass stream of products that have complex demands on recycling strategy because of reuse options (e. g. testing of the function is necessary, cleaning of the components, and so on) can be treated in a complex disassembly system as it is described in chapter 3 (see Fig. 7). Because of the high investment the general conditions for building up such a system must be checked very carefully.

As a whole the realisation of an industrial recycling enterprise is a complex interdisciplinary task. Besides the described modules for the disassembly facility an extensive company computer system has to be built up and suitable concepts for company organisation and instruction and development of personnel have to be realised. Furthermore an ecological and economical controlling system in the recycling company is very important to enable decisions based on objective data.

5 AN INTRANET-BASED INFORMATION SYSTEM FOR MANUFACTURERS AND RECYCLING COMPANIES (IAT)

As shown in chapter 1, innovative strategies for recycling must not only regard the flow of material but also the flow of information. Therefore one duty of the IREAK project is to develop an intranet-based information system for manufacturers and recycling companies, i. e. for the partners Telefunken Microelektronik and Hetzel Elektronik-Recycling. Both act mutually as user and provider of the information system.

Thus the intended information system has to cover an internal and an external aspect. The internal aspect concerns the supply of information within one enterprise, i. e. the manufacturer respectively the recycling company acts as provider and user in "personal union". Possibly there could also be an exchange with other information systems like production planning or data management systems. The external aspect concerns the exchange of information between manufacturer and recycling company.

The systematic proceeding for the development comprises three steps: specification, conception and realisation of the information system.

5.1 *Specification of the intranet-based information system*

In order to cover the requirements of the manufacturer as well as the recycling company completely, an analysis of the demand for information of the concerned partners has been made and documented in a performance specification. Their possible input has been inquired simultaneously.

In order to enable an efficient recycling and reuse, manufacturers of electronic appliances have developed construction guidelines taking into account not only an efficient assembly but also the disassembly and recycling of a product. For the manufacturer therefore the main object of the information system is the supply of the acquired knowledge base in form of design rules dealing for example with design in modular system, avoidance of toxic substances or assistance in design for environment to their design engineers. Moreover, the manufacturer intends to draw from the data base information like recycling costs or the recycling ability of his current products, which is generated by the recycling enterprise.

Besides, recycling enterprises have an increased demand for information concerning the electronic appliances, which shall be recycled, their components and the materials inside and all other boundary conditions, so that a multipurpose disassembly system for electronic products as described in chapter 3 works profitably. The required information input by the manufacturer from which the recycling company will benefit could – among others – be the identification of their products and assembly groups with bar codes etc., CAD-drawings, parts lists of all assembly groups, the classification of the used materials, maintenance documentation, assembly instructions and all kind of technical data like dimensions, weight and performance.

The recycling company itself should provide all kind of particular disassembly information like precedence graphs, problems occurring during disassembly or the costs of recycling specified for the different types of appliances.

In addition to that another requirement of the manufacturer is the support for offering recycled electronic products or components for sale via internet. After mechanical and electronical tests appliances or components of them could be sold for example as second-hand products respectively spare parts. Components like for example electric motors could be reused in completely different products. Moreover, materials like iron, copper or plastic could be offered for sale to ironworks or other enterprises of the processing industry.

As result of the analysis of requirements and possible input the following three modules of an intranet-based information system have been defined:

- ❑ Support for design engineers of a manufacturer during the R&D process
- ❑ Support for a recycling enterprise during the disassembly process
- ❑ Offering for sale of electronic products or components

Each of the modules can be realised independently from the others. Also their allocation may vary. That means for example, that the data base containing product relevant information could be allocated by the manufacturer as well as by the recycling enterprise.

5.2 Conception of the intranet-based information system

The second step was the conception of the intranet-based information system. Therefore, based on the results of the above-mentioned analysis of the information demand, a semantic model of the data base system was made and documented in form of an entity-relationship-diagram as shown in Fig. 8. The drawing up of the data base model included the definition of the entities, the relations between each of them (0:0, 1:1, 1:n or n:m) and their attributes (see Chen 1991, Dreßler 1995, Radermacher 1990).

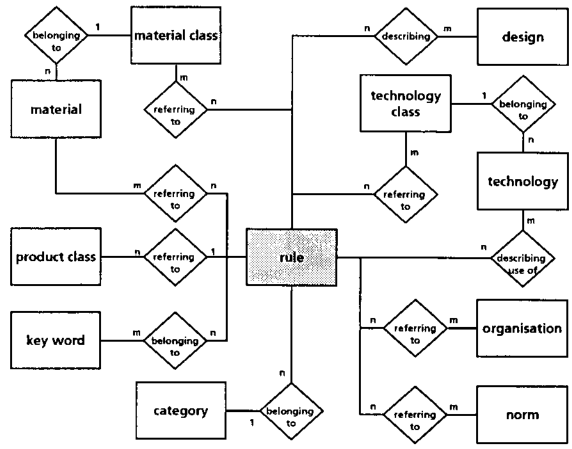

Fig. 8 Detail of an entity-relationship-diagram

This model is general and independent of the type of the data base – i. d. a hierarchical, network or relational model – which will be realised and the software platform that will be chosen.

5.3 Realisation of the intranet-based information system

For the realisation of the prototype it was decided to use a relational data base model. Therefore the semantic entity-relationship-model had to be transformed into a relational table structure and to be implemented in a data base software. Fig. 9 shows an example for a relational table which describes an entity with its attributes and their data type.

RULE			
	Attribute Name	Data Type	Description
🔑	RULE_NR	Long integer	Primary key
	RULE_NAME	String (255)	Name of the rule
	RULE_DESCRIPTION	Memo	Description of the rule
	RULE_LINK	Hyperlink	Link to the rule
	RULE_AUTHOR	String (50)	Name of authors
	RULE_DATE	Date	Effective date

Fig. 9 Relational table of an entity

As data base software for the prototype has been chosen Microsoft Access, in order to have a low-cost technology within anyone's reach.

To reach the aim of a world-wide availability of the data an access to the data base via internet by means of the Microsoft Personal Webserver as well as the Microsoft Internet Information Server (see Microsoft Corp. 1998) – both available with the operating systems Windows 95/98 respectively Windows NT – and the Microsoft Internet Database Connector (see Assfalg 1998) has been realised. As browser technologies the Microsoft Internet Explorer and the Netscape Communicator were employed.

Besides the realisation of the data base and its connection to the internet, the design of the user interface is another point of emphasis for the further proceeding. To guarantee the acceptance amongst users, the surface design has to correspond to the requirements of modern software ergonomics. Particular efforts have to be made to develop algorithms that facilitate navigating in a huge data base, adapted to the demands of the users.

6 CONCLUSION

The IREAK project is still in progress. Final results will be available in August 1999. Nevertheless the outline of a future industrial recycling factory and the R&D processes of manufacturers of electr(on)ic appliances are already recognisable.

In comparison with the point of departure nowadays a major part of the mass flow in recycling enterprises goes into material recycling, but the reuse of electr(on)ic products or components, i. e. the product recycling, is still hardly pronounced. Therefore future research activities should be focused particularly on the R&D processes of the manufacturers.

Product design has not only to take into account the suitability for disassembly and the avoidance of toxic substances, but also the life cycles of the different components of a product. That means that the life cycle of different components permits to define in advance the future use of long-lived components as spare parts in a product of the same type or in a completely different product.

With the work done in the framework of IREAK, the requirements of an efficient industrial recycling factory concerning organisation and information technology have been satisfied as well as the foundations for the reuse of electronic appliances have been laid.

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End of life scenario assessment based on product features of building components

Abstract

Reuse of products is often seen as a better alternative than reuse of materials, or landfill, or incineration. Although this may be true in general, it is doubtful whether this is also true for building products. Because of their long lifespan and the quickly changing demands on buildings, it is questionable if it is a wise decision to aim at the reuse of products. What is lacking is a good tool to decide what is the best eco-efficient end of life for a certain building product, taking into account both environmental impact and life cycle costs.
This research project aims to develop a tool that would enable us, to asses both qualitative and quantitative aspects of the end of life of a building product that affect the product's environmental impact and life cycle costs. This article describes the first steps; inventorying product features that affect the end of life of a building product, and choosing a computerized environmental impact model that can be integrated in the tool.

1 Introduction

In the Netherlands, 14 million tons of building and demolition waste are produced every year, of which more than 70% percent is recycled on a material level [BRBS, 1994a, 1994b], e.g. stony waste material is used for road subbases. The Dutch government however, prefers reuse of products above recycling to materials to landfill or incineration, but at the same time a good tool is lacking for making a considered choice for the most eco-efficient end-of-life scenario for a building product. Building products are products or components that together make a building except for the building interior.

The life cycle of a building can be roughly divided into four stages: design of the building, its construction, its use and finally its abandonment. The last stage can be subdivided in the following stages:

- demolition/disassembly;
- transport;
- sorting, cleaning, repairing and storage of products and materials;
- landfill, incineration, materials recycling and product reuse (See also Figure 1).

These various scenarios for the end of the life of a building are called End of Life Scenarios (ELS).

Optimizing for the end of life of a building has its consequences for the design process. When an architect tries to design for a certain ELS, he must choose the appropriate products and optimize the connections between those products. Suppose, an architect wants to design a building that is very easy to disassemble and that consists of building products most of which are suitable for reuse. Of course he does not want to reach this aim at any price and therefore seeks a balance between environmental profit and the life cycle costs of a design. The relation between environmental impact and life cycle costs, is called Eco-Efficiency (see also paragraph 4).

Let's consider a window frame as an example. This building product can be treated in several ways:

- The building is demolished and the window frame is dumped or incinerated;
- The building is demolished and the window frame is separated and the wood is recycled in layered wooden beams;
- The building is disassembled and the window frame can be used again in a new building.

Notice that the window frame may be depending on how it was connected to the rest of the construction, and is therefore not suitable for the ELS 'recycling of materials' or 'reuse of products'. This means that product features influence the environmental impact and the life cycle costs (the Eco-efficiency). Because, due to the very large variety of products used in buildings, this is a very complex matter, a tool is required for making the right choice between alternative end-of-life scenarios [Nilsson, 1998].

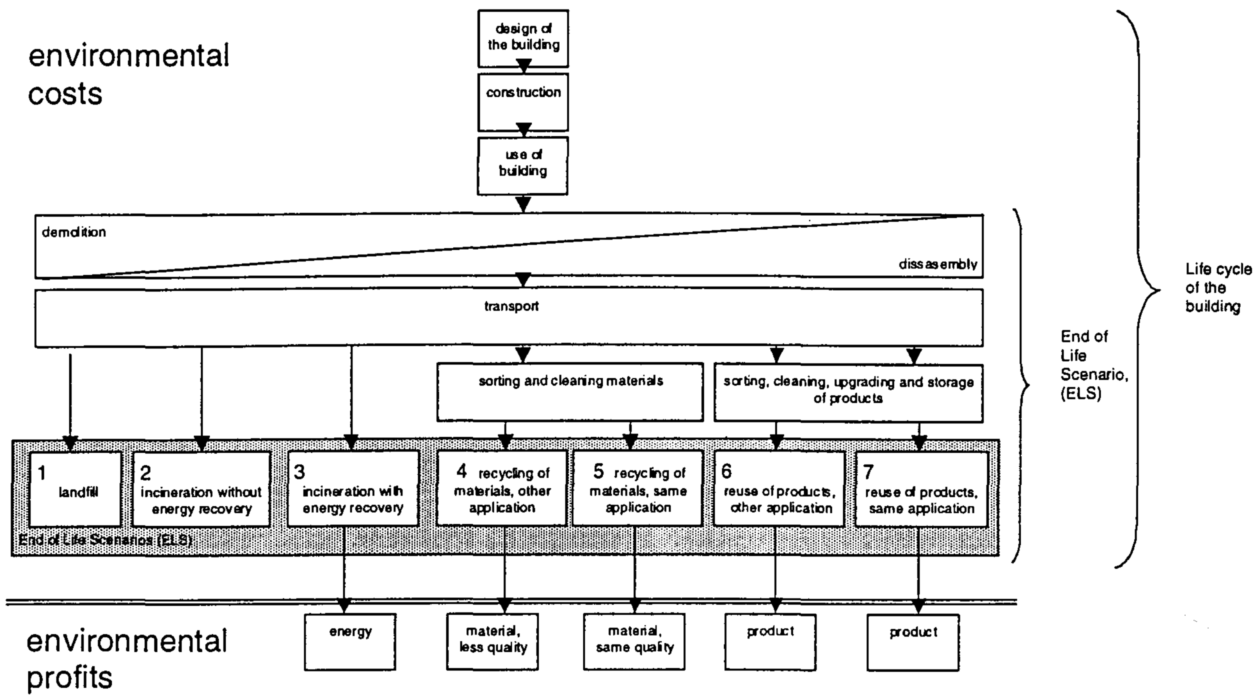

Figure 1: End of Life Scenarios (ELS)

The goal of my PhD-research project is to develop a decision support instrument called BELCANTO (Building End of Life Cycle ANalysis TOol) that should enable an architect to determine the eco-efficiency of various end of life scenarios for building products on the basis of product features.
A first step is to compare tools that can determine the eco-efficiency of building products. But, because there are no suitable tools yet, this article first concentrates on the product features that influence the ELS and than it describes the choice of a tool that can be used to evaluate a major factor determining the eco-efficiency: environmental impact.

Today, a wide variety of assessment methods are available for inventorying the environmental impact of a product or a process. In general, most of the assessment methods concentrate on the first stages of the product life, such as the production and the use of products. Less information is available on the end of life of building products, like data on demolition and disassembly of such building products.

Recycling concrete foundation piles illustrates the shortcomings of the available environmental impact methods. In situ mounted piles cannot be removed easily because they will break when they are taken out, so that parts of it will remain in the ground. Prefabricated piles, by contrast, can be pulled out easily. Both types of piles require the same amount of material and energy and will receive from LCA-programs the same score unless you know, only the prefabricated pile can be reused or recycled in its whole. Therefore, the reusability or recyclebility of building products is influenced by more product features than those that are measured in current LCA-methods.

2. BELCANTO (Building End of Life Cycle ANalysis TOol)

Figure 1 shows the life cycles of building products and buying special attention to the end of life scenarios (ELS). For all scenarios, the beginning of the life cycle is the same: it starts with the design, the construction and the use of the building. Only the final stage, demolition and/or disassembly, differs for each ELS. Products that are suitable for reuse in the same application have to be disassembled very carefully, whereas it is not very profitable to carefully disassemble a product that will end its life on a landfill.
After the demolition/disassembly stage the products and materials are transported to a landfill, an incinerator, a recycling plant, or a product repair plant. At present, reuse of building products occurs less often than materials recycling or incineration and landfill.

The following 'End of Life Scenarios' can be distinguished:
1. Landfill: The government of the Netherlands forbids the dumping of materials that can be incinerated or recycled (e.g. wood);
2. Incineration without recovery of energy;
3. Incineration with recovery of energy;
4. Recycling of materials in a different application;
A good example of this scenario is the use of crushed concrete in new concrete products. In the Netherlands, it is allowed to substitute 20 percent of the gravel by

crushed concrete, without the need of additional tests on deformation. Higher percentages may be used, but should be proved prior to construction. Other examples are the use of wood in chipboard or layered wooden beams;
5. Recycling of materials in the same application is very common for metals. Metals that are used in the building industry are copper, zinc, and lead. Another example is the collection of glass wool and rock wool at building sites that is returned to the producer. This scenario is also possible but still not common, for synthetic products like PVC pipes;
6. Reuse of products in another application: This scenario does not occur in the Dutch building industry;
7. Reuse of products in the same application: At present, this occurs for tiles, beams, old bricks, and curiosities like old sanitary facilities.

The final tool BELCANTO will calculate all environmental and economic costs of the ELS, described above. Figure 2 shows a schematic representation of BELCANTO. During the design process an architect decides to use certain products in a building. These products have features that influence the possibilities for recycling or reuse at the end of life of a building. The features of a building product are imported into the tool and result in an output that can be divided into two categories: environmental impact, and life cycle costs.
At the same time the architect can use the method to create a *demolition specification*: a scenario for the demolition of the building. Products suitable for reuse must be removed very carefully, while products only suitable for landfill or incineration can be removed without care.

3. Input: Product features related to End of life scenarios

This section discusses various product features that influence the scenarios at the end of the life of a building. Because of their overlap, the seven categories of figure 1 are combined into three categories reuse of products, reuse of materials, and landfill/incineration.

3.1 Reuse of product

The reuse of a product requires that the product is as undamaged as possible. This requires a careful way of disassembling and a well-considered way of designing and constructing a building.

- **Building components sequence**

The sequence of building components influences the ease with which they can be disassembled. The following sub-division can be made:
1. It is possible to remove a single product, which makes repair, replacement and disassembly possible as well. A roofing tile is a good example of this category.
2. It is possible to remove a product, but since all the same products must be removed at the same time, repair, replacement and disassembly are a large project. For instance, although concrete frames (like the CD-20 system) can be disassembled, it is impossible to remove the columns of the first floor without removing the entire second floor.
3. It is not possible to remove a product without damaging another product. Repair, replacement and disassembly are not possible without distortion of another function of the building. For example, due to today's very strong mortar, bricks cannot be removed without damage.

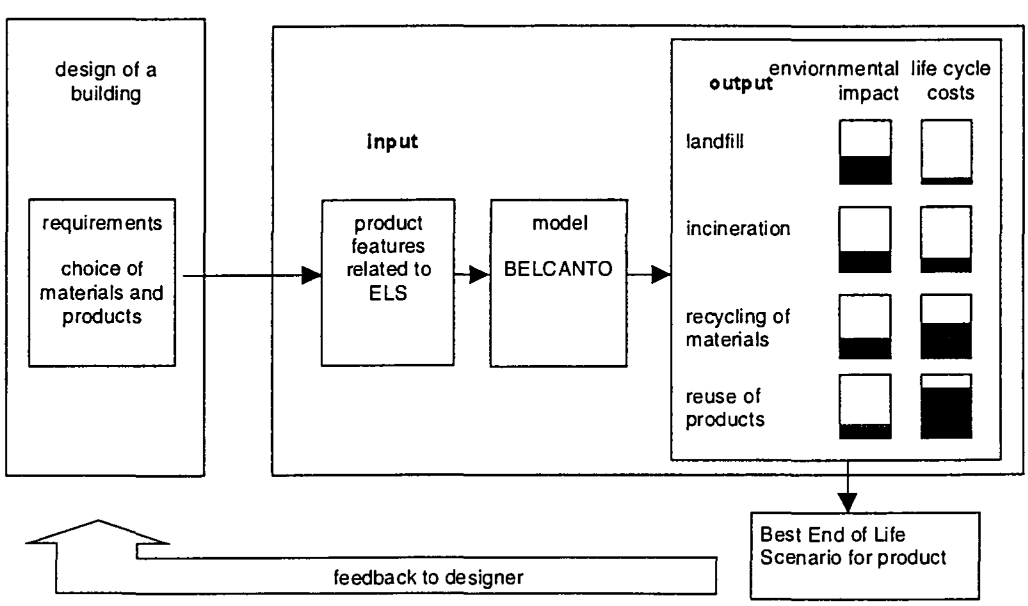

Figure 2: Schematic representation of BELCANTO

- **Connection to other components**

There are three types of connection: fixed, half-fixed, and non-fixed.
Fixed connections can be divided into two types: *chemical fixed connections* like glue, cement, PU foam, and solder, or *mechanical fixed connections* like clicking. Characteristics of this type of connection are that either the product is damaged by the connection, or the product is covered with the material used for the connection. In either case, the product has to be cleaned or repaired before reuse is possible.
Half-fixed connections are connections that can be disconnected, but not as easily as non-fixed connections. An example of this type of connections is when nails are used, or screws are rusted. It is not certain that the product is intact after disconnection. A percentage will be damaged, dependent on the type of connection. The connection itself will most likely to be damaged as well.
Non-fixed connections are easy to undo. Examples of this type of connection are screwed connections that are not rusted and click-connections that can be unclicked (mechanical non-fixed connections). The connection is not damaged and can be reused. [Timmermans, 1985]

- **Quality**

The building products that will be reused in another building must have a guaranteed quality. The quality may be less than a new product but a certain minimum quality must be guaranteed. To determine the quality, it is possible to make use of representative samples.

- **Remaining lifespan**

The lifespan of a product depends on external aspects like climate, its use, and environment, and on inherent aspects like material qualities, design details and quality of the building process [Huffmeijer, 1995]. For any reuse of a product, it is essential to know its remaining lifespan. In the case of product A (Figure 3) there is no lifespan left and hence this product should not be reused.

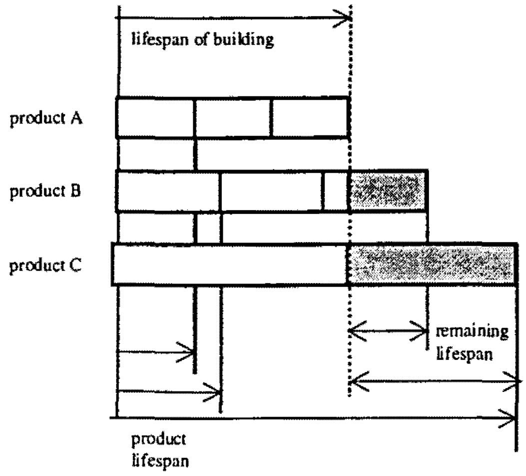

Figure 3: Remaining lifespan of reused products

- **Reliability**

Apart from a shorter lifetime, an older product also has a greater risk to fail. Figure 4 shows the chance of replacement. The standard deviation is assumed to be one sixth of the average lifespan [Huffmeijer, 1995].

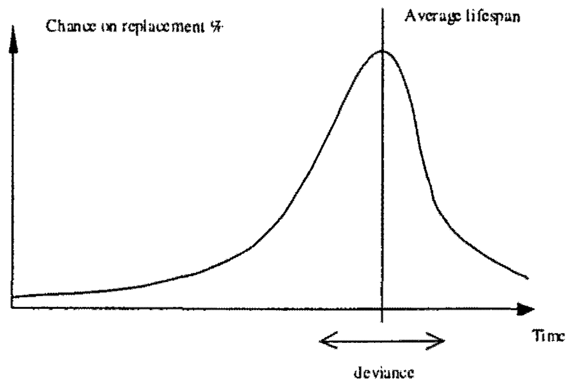

Figure 4: Reliability of reused products

- **Out-dated products**

Some products will be of no use in the future. A good example is glass. Nowadays, single-glazing is not allowed anymore, and only double-glazing is applied. If this trend continues, even double-glazing may not be sufficient in the future anymore. Similar problems occur with installation products. All products that have a function in the energy balance of a building (installation and isolation) have a reasonable chance of becoming outdated sooner or later.

- **Ergonomics and safety**

Disassembling buildings to obtain building products requires more work than demolishing buildings and this work must be done in a safe and healthy way, because it concerns human activity. During disassembly, large and generally heavy objects have to be moved. Since this is accurate work, people will be close to these objects and will run the risk of becoming injured. Furthermore workers may get ill by prolonged exposure to noise and dust, caused by for example the sawing of stony materials.

3.2 Recycling of materials

Recycling of materials involves fewer demands in comparison with reuse of products as described above. Besides, connections between parts are now more important than the connections between products.

- **Connection with other materials**

In the case of materials recycling, we do not describe the connections between building products but between materials. It is possible to classify connections in the same types as in the case of product reuse: fixed, half-fixed and non-fixed connections.
Fixed-connections and *half-fixed connections* may cause pollution of the material and thus disturb the

recycling process. In general, damage of the product (and of the material) is less important because the materials are being recycled anyway.

- **Quality of the material**

The quality of the material is determined by pollution and by aging.
In the case of reusing recycled concrete aggregates for new concrete, e.g. wood remains and gypsum may potentially deteriorate concrete quality. Steel recycling is effected less by pollution, since most of the pollution here (e.g. paint) will be removed in the recycling process adopted.

- **Quality of the recycled material**

Some materials may be recycled over and over without a significant quality loss, while others may be recycled only once, or a few times at most. In some cases 100 percent of recycled material is reused in the new material, in other cases only smaller percentages may be applied.

- **Ergonomics and safety**

In materials recycling the same aspects play a role as in reusing products. But accuracy is less important than in the case of product reuse, because only a limited number of materials are used in buildings. For that reason, safety and heath aspects are much less of crucial importance here.

3.3 Landfill and Incineration

- **Construction**

The construction is of no importance for the end of life scenario (ELS) 'landfill and incineration'. All kinds of material can be dumped, while incinerators can only process combustible waste. Therefore the materials should be divided into combustible and non-combustible in the case of the ELS 'Incineration' (with or without recovering energy).

- **Design**

Design is of no importance for landfill or incineration.

- **Ergonomics and safety**

The 'landfill and incineration' scenario requires no special procedures for safety and health are needed during the demolition process.

4. Output: Environmental impact and life-cycle costs related to End of life scenarios

The output of BELCANTO is twofold: environmental impact, and life cycle costs, of each ELS (Figure 2). The environmental impact, and the life cycle costs, are a sum of costs and proceeds. The results of these calculations must found the considerate choice of building products by an architect concerning in a new building or a demolition specification. In the following paragraphs the results are described that are expected en needed for choices during the design of the building.

4.1 Reuse of products

The environmental impact the ELS 'product reuse' is the sum of all the processes from the moment of disassembly of the building including the reuse of the building (Figure 5). Disassembly, transport to a product repair plant, cleaning of the product, repairing, and storage of the product cause environmental costs. Storage takes longer because it takes longer to find a building in which the product can be reused and therefore causes a greater environmental impact. Transport to the new building site will not be part of the environmental impact, because a new product has to be transported as well. Environmental proceeds arise from the fact you don't need to make a new product and can be defined as the total environmental impact of the product: the total sum of all the processes that are needed to make the product.

The life cycle costs for the ELS 'product reuse' are the costs made for disassembly, transport towards a place where upgrading is taking place, cleaning and upgrading and storage. The profits that can be made are the costs saved by using a second hand product instead of a new product. Further, no costs are made for waste disposal.

4.2 Recycling of materials

The environmental impact of materials recycling is the sum total of the environmental impact of demolition/ disassembly, transport to a recycling plant, cleaning, and repairing (Figure 6). Transport to a building site is not included because a new material has to be transported as well and the same is true for the storage of materials. Environmental proceeds come from the material that is saved.

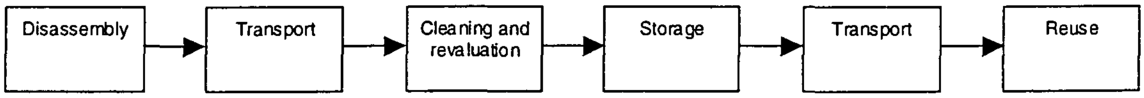

Figure 5: Reuse of products

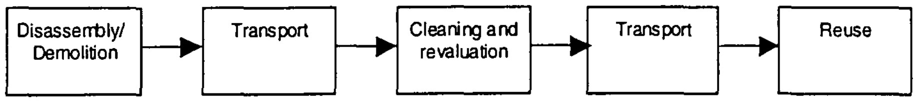

Figure 6: Recycling of materials

The life cycle costs are the sum of costs for demolition/disassembly, transport towards a recycling plant, cleaning and repairing. Saving material in a new product makes some profit.

4.3 Landfill and incineration

The environmental impact is the sum of the environmental impact of demolishing, transport towards a landfill or incinerator, and landfill /incineration (Figure 7). The environmental profit is energy that raises from incineration.

The life cycle costs of these scenarios are costs of demolition, transport, landfill and incineration. The released energy, caused by incineration, yields a profit.

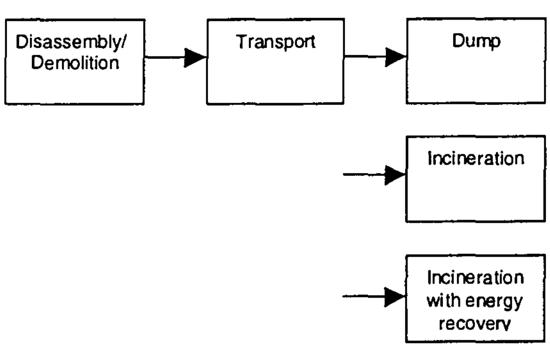

Figure 7: Landfill and incineration

5. Assessment of the environmental impact

The first step to make BELCANTO is to choose a tool, preferable a computer model, which can be used as a part of this environmental impact method. Furthermore, the method will also include a qualitative part, also based on product features. This qualitative part will not be described in this article. The computer model has to meet certain criteria as described in the following paragraph.

5.1 Criteria for Environmental Impact methods

1) The method must have a structure that makes it possible to compare different End of Life Scenarios.
2) The method must have a structure with no preferences for certain ELS, for example no preferences of reuse of products above reuse of materials.
3) The method must have data of the production of building materials.
4) The method must have data available of processes like demolition and crunching or must have the opportunity to add the data.
5) The method must have data of recycling processes of building materials.
6) The method must have data of landfill and incineration.
7) The method must have a fair way of ascribing environmental profit in case of recycling.

5.2 Environmental Impact methods

The most suitable environmental impact methods often called Life Cycle Assessment methods (LCA), which are used in the Netherlands, are described below. Initially the purpose is to make a tool for the Dutch situation; therefore it would be an advantage to use a Dutch Environmental Impact method as well. Table 1 gives an overview of all the criteria, and how they meet the criteria mentioned in 5.1. The paragraphs below describe in short the computer models, followed by the disadvantages of the models.

5.2.1 Eco-Quantum

Eco-Quantum is an environmental impact method or LCA developed in order of the SBR (Foundation of Building Research) and the SEV (Foundation Experimental Public Housing) [Eco-Quantum 1, 1997]. The method is developed to support architects in the design process and contains a lot of data of building products and materials.

Eco-Quantum has two major disadvantages:
1) Although Eco-Quantum discriminates for each building material four possible scenarios: landfill, incineration, low level materials recycling, and high level recycling, it is not possible to choose one scenario. Eco-Quantum assumes that every material has in reality different ELS. For wood the division is

	Eco-Quantum	CML/Simapro 4	TWIN/Greencalc	MATTER
1) The method must have a structure that makes it possible to compare different ELS	No*	Yes	No	Yes
2) The method must have a structure with no preferences for certain ELS.	Yes	Yes	No	Yes
3) The method has data of the production of building materials.	Yes	Yes	Yes	Yes
4a) The method must have data available of processes like demolition and crunching, 4b) or has the opportunity to add the data.	No, No	No, Yes	No, No	No, Yes
5) The method must have data of recycling processes of building materials.	Yes	Yes	No	?
6) The method must have data of landfill and incineration.	Yes	Yes	No	Yes
7) The method must have a fair way of ascribing environmental profit in case of recycling.	Yes	Yes	No	Yes
* Seems to be possible in a research version, but it is not sure if this version will be available in the future.				

Table 1: Environmental impact methods and criteria

as follows: 0% landfill, 70% incineration, 20% material reuse on a lower level and 10% material reuse on a higher level. In the computer model the percentages are fixed and cannot be changed.
2) Eco-Quantum is provided with data of producing materials and the energy needed for producing the material, but there are no data available of e.g. applying the materials like energy needed for making a bitumen roof. Furthermore, data of demolition processes like crunching concrete are not available, and cannot be added as well.

5.2.2 LCA method of CML/SimaPro 4

In 1992 the CML (Center of Environmental Knowledge, University of Leiden, the Netherlands) published the LCA-method (Life Cycle Assessment method) [Heijungs, 1992]. This method was followed all over the world. The method inventories all possible processes that occur in the course of life of a product. These processes are summarized in a process tree. Lots of data are collected of these processes and are used to determine the environmental impact of a product. SimaPro 4 [Pré Consultant, 1997a, 1997b] is a computerized model based on the CML method, and helps a designer to evaluate a product. SimaPro 4 is more difficult to use, compared to EcoQuantum, but has more opportunities for the user to adapt. Although SimaPro 4 is developed for designers of products and not for architects, and therefore contains no ready-made building products, it contains lots of data that are used in the building industry. Besides, a database is recently added by the ENCI (First Dutch Cement Industry), which contains data of concrete products [Lanser, 1998].

SimaPro 4 is not suitable for architects without knowledge of industrial design and engineering. Therefore, it has to be integrated in BELCANTO, in such manner, that it can be used also by architects. Nevertheless, it meets all the criteria stated in section 6.1. Data of producing a building product are available in SimaPro 4, just like data about recycling and disposal. Data of the demolition process are not available, but can be added.

5.2.3. TWIN-model/Greencalc

The TWIN-model [Haas, 1997] tries to measure the environmental impact in both a quantitative way and a qualitative way. The TWIN-model tries to complete the shortcomings of the normal LCA by adding aspects of health, corrosion and a method of weighing all the various aspects of the life cycle. Greencalc is a computer model based on the TWIN-model but less complete.

The TWIN-model considers two strategies for the end of life of a building: waste and recycling. Waste can be divided in chemical waste, final waste and waste that can be processed further. Final waste is not suitable for reuse and the possible end is dump or incineration. Chemical waste is too dangerous to dump or incinerate. Unfortunately, no distinction is made between dump and incineration, which is a major disadvantage of this model.

Recycling can be divided in 'product reuse' and 'material reuse' and both can be divided again in 'reuse in the same application' and 'reuse in another application'. It is regrettable that an order of preference is made between certain reuse strategies. Product reuse, for example, is judged more positive than material reuse. Therefore, the TWIN model is not useful as a tool to judge different ELS in BELCANTO.

Greencalc, the computer model based on the TWIN-model, is even less complete and includes not even different end of life strategies of the building.

5.2.4 MATTER - Building materials and CO2

This new and interesting method measures the environmental impact with only one, but important factor, the emission of CO_2. A computer model will be developed in one year and can be useful in measuring the environmental impact of the various ELS. It will contain detailed information about recycling, incineration and landfill of different building materials. Although, the model is not yet available, it is interesting to follow future developments [Gielen, 1997].

5.3 Selection of an environmental impact method

The information described above is presented in table I to make a selection of the environmental impact assessment methods. SimaPro 4.0 seems to be the best choice to use in the End of Life Scenario method because it is flexible in its use and can be extended with more data. The MATTER method is still in development and promises to be very interesting. The main problem of TWIN/Greencalc is the built-in preference for a certain ELS and therefore it is not possible to make a fair deliberation between ELS. Eco-Quantum has a lot of positive aspects, but because it is developed for a quick scan of a building not enough parameters can be changed. This might change when a research version will be available.

6. Conclusions

Product reuse is often seen as a better alternative than material reuse, landfill, and incineration. However this may be true, for building products is not yet proved. Because of their long lifespan and the quickly changing demands on buildings it is the question if it is a wise decision to do so. A good tool to decide what is the best eco-efficient end of life scenario of a certain building product is still not available, taking into account environmental impact as well as life cycle costs of the End of Life Scenarios. Such a tool will be developed during my PhD-research project and is called BELCANTO (Building End of Life Cycle ANalyseTOol)

BELCANTO can be described as follows:
On the input side product features will be imported in relation to end of life scenarios (ELS).
For the end of life scenario 'product reuse' the following product features are of interest: order of building components, connection with other products, quality, remaining lifespan, reliability, out-dated product features, ergonomics and safety, and design.
The ELS 'material recycling' requires fewer demands in comparison with the ELS 'product reuse'. Features of importance are connection with other materials, quality of the material, quality of the recycled material, and ergonomics/safety.
The ELS 'incineration' and 'landfill' require no special product features, but of course hazardous materials should be avoided.

Design is of no interest, except in case of the ELS 'product reuse'. Even than it is only important if a product does not have to be repaired combined with a trendy design, and that is not very often the case, in building industry. Ergonomics and safety play a stronger role as the accent shifts from demolition towards disassembly. In case of disassembly people tend to be closer to the products they have to remove out of the building, and in case of product reuse, the objects are bigger so that they can cause more damage.

The output of BELCANTO will be bipartite and will result in the environmental impact and life cycle costs for each end of life scenario. Together these two elements determine the eco-efficiency of an ELS for a building product. It is possible for an architect to use this tool as an aid in the design process of a building, or as an aid for making a demolition specification.

In this article I made a choice to integrate a current environmental impact method as a part of the BELCANTO because of the complexity of this matter and the enormous amount of data needed for these kind of deliberations.

The best environmental impact method for this purpose is SimaPro 4:
- It makes it possible to compare different end of life scenarios of building materials;
- It does not give preference to one of the end of life scenarios;
- It has the opportunity to ascribe the environmental impact of recycling of a building product in different ways;

- It has data available of production processes, recycling processes of building materials and data of landfill and incinerating;
- It has the opportunity to add data on demolition processes.

7. Further Research

BELCANTO is further developed on the basis of a case study: Office XX, a building that is now in construction in Delft, the Netherlands. This building is designed to have a life span of only twenty years, and will be completely dismantled afterwards. Because this building is small, and has therefore only few parts, it is attractive to take as a case study. Furthermore, its demountability implies for each part all possible 'end of life scenarios'.

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Remanufacturing Production Planning and Control: U.S. Industry Practice and Research Issues

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Abstract
Remanufacturing is a viable form of waste prevention with a much wider scope of industrial practice than previously thought. In the United States alone over 73,000 firms are engaged in some form of remanufacturing. The tasks of planning, controlling and managing the operational tasks in a remanufacturing environment are more complex than for a traditional manufacturer. This research identifies seven complicating characteristics that significantly affect production planning and control activities for remanufacturers. The current state of production planning and control activities at remanufacturing firms in the United States is presented and discussed in the context of these seven characteristics. A research agenda is also presented, showing where present research has failed to address many issues of importance for a successful planning and control system.

Remanufacturing Production Planning and Control: U.S. Industry Practice and Research Issues

Introduction

Remanufacturing is an environmentally and economically sound way to achieve many of the goals of sustainable development. Remanufacturing closes the materials use cycle and forms an essentially closed-loop manufacturing system. Remanufacturing focuses on value-added recovery, rather than just materials recovery, i.e., recycling. There are estimated to be in excess of 73,000 firms engaged in remanufacturing in the United States directly employing over 350,000 people (Lund 1998). Remanufacturing operations account for total sales in excess of $53 billion per year (EPA 1997).

The results of our recent survey of North American remanufacturing firms shows that planning, controlling and managing operations are significantly different from traditional manufacturing production planning and control. We identify and discuss the essential characteristics that contribute greatly to the complexity of managerial tasks, and discuss current managerial practice. We also identify critical research issues and needs for each of the areas. We begin with a detailed discussion of remanufacturing, and in following sections we describe the survey instrument used and provide details on the firms that participated. We then present seven complicating characteristics and discuss how these characteristics affect production planning and control activities. We identify and discuss the essential research needs following our discussion of the complicating characteristics.

Remanufacturing

Remanufacturing is "...an industrial process in which worn-out products are restored to like- new condition. Through a series of industrial processes in a factory environment, a discarded product is completely disassembled. Useable parts are cleaned, refurbished, and put into inventory. Then the new product is reassembled from the old and, where necessary, new parts to produce a fully equivalent - and sometimes superior - in performance and expected lifetime to the original new product." (Lund 1983). Remanufacturing is a form of waste avoidance since products are reused rather than being discarded, usually landfilling. Remanufacturing also captures value-added remaining in the product in the forms of materials, energy and labor. Remanufacturing is also profitable, Nasr, et al. (1998) reports average profits margins of 20%.

Given the profitability, and growing consumer awareness, the time is right for the formal development of systems for managing remanufacturing processes. These systems exist on a number of scales presently, but lack an integrated body of knowledge of how to design, manage and control their operations. In the next section, we present the characteristics that complicate production planning and control (PP&C) activities.

Complicating characteristics of remanufacturing

Nasr, et al. (1998) report there is a significant lack of specific technologies and techniques for remanufacturing logistics. Our research agrees with these findings, and we identify seven major characteristics of recoverable manufacturing systems that significantly complicate the production planning and control activities. The characteristics discussed here were developed from the data from our survey, on-site facility visits, and reviewing the current literature (see Guide et al. 1998). We present each of these characteristics and in following sections we fully examine the effects of these complicating characteristics on current production planning and control practices, and discuss research needs.

The seven characteristics are (1) the uncertain timing and quantity of returns, (2) the need to balance returns with demands, (3) the disassembly of returned products, (4) the uncertainty in materials recovered from returned items, (5) the requirement for a reverse logistics network, (6) the complication of material matching restrictions, and (7) the problems of stochastic routings for materials for remanufacturing operations and highly variable processing times.

Before we discuss these characteristics in detail, we present the background on the survey instrument used.

Survey Design and Overview

The survey instrument consisted of 75 questions covering several areas: general company information, demand management, materials management, production planning and control, and miscellaneous information. We do not list the full survey for the sake of brevity (the full survey ran over eight pages); a copy is available upon request from the author. Most of the questions asked managers to responding by providing details on specific applications (e.g., disassembly operations) and required considerable time on the part of a manager. The American Production and Inventory Control Society Research and Education Foundation (APICS E&R) provided funding (Grant #97-14) for the survey and access to the Remanufacturing SIG membership list. The membership list yielded 320 firms actively engaged in remanufacturing. The response rate was 15%, or 48 useable surveys. The vast majority of firms responding (95%) are not original equipment manufacturers (OEMs), and this finding is consistent with the results obtained by Nasr et al. (1998). Firms remanufactured a variety of products ranging from simple industrial goods (roller bearings) to commercial jet aircraft. The majorities of the respondents' positions were in materials management (25.6%), and production (28.2), but several were plant managers (12.8%), or vice presidents (12.8%). Before we discuss the specifics of the complicating characteristics, we provide an overview of the production planning and control environment for a remanufacturing firm.

An overview of PP&C for remanufacturing

Remanufacturing firms commonly serve a number of smaller niche markets, and use diverse product offerings and strategies to serve these often dissimilar markets. However, even serving smaller niche markets is profitable; the majority of firms responding had sales in excess of $21 M per year. Firms reported remanufacturing, on average, over 1,400 product types and over 50,000 part types per facility. The majority (80%) of remanufacturing firms use a mix of make-to-stock (MTS), make-to-order (MTO), and assemble-to-order (ATO) strategies, within a single remanufacturing facility. Only one-fifth of firms surveyed reported having pure MTS, MTO or ATO strategies. Further, almost a quarter of the firms' report that the mix of MTS, MTO, and ATO changes based on market conditions. In order to manage this amount of product diversity all remanufacturing firms surveyed report using hybrid PP&C systems.

Remanufacturing firms have a more complex shop structure to plan, control and manage. A typical remanufacturing facility consists of three distinct sub-systems, disassembly, processing and reassembly, that must be carefully coordinated. Disassembly operations are the first steps in remanufacturing operations and provide the parts and components for processing. Remanufacturing operations layouts are most commonly in a job-shop form because of the use of general-purpose equipment, and the need for flexibility (Nasr et al. 1998). Reassembly is the final stage in a remanufacturing system. Careful coordination is needed between the sub-system to provide high levels of customer service.

Remanufacturing firms must be able to manage the additional variety inherent in their environment. The nature of multiple product positioning strategies to serve niche markets, and the resulting need for production planning and control systems capable of managing diverse objectives place significant demands on any PP&C system.

Affects of the Complicating Characteristics

In the following sub-sections, we discuss how the complicating characteristics affect production planning and control activities. In the following section we identify and discuss the essential research issues.

Uncertainty in the timing and the quantity of returns

The product returns process is highly uncertain with respect to timing, when cores are available for remanufacturing, and quantity, how many cores are available. Firms report activities that assist in the control of the timing and quantity of returns, but not both. Over half (61.5%) of the firms report that they have no control over the timing or quantity of returns. Firms reporting some degree of control mainly used some form of core deposit system. Core deposit systems are intended to generate a core when a remanufactured product is sold. Most companies report requiring a trade-in, or charging a premium if no core is returned (80%). A small percentage of firms (5%) use leasing to reduce timing uncertainties. However, these activities only reduce the quantity uncertainty of returns. This does little to reduce the timing aspect of returns since a return generates a sale - a stochastic event itself. Leased equipment may have the lease renewed or the equipment purchased. Because of this uncertainty in returns quantities and timing, remanufacturing firms report core inventories account for one-third of the inventory carried (Nasr et al. 1998). Presumably, higher levels of cores are held to buffer against variation in the supply of cores and the variability in demands.

Balancing returns with demands

Remanufacturing firms seek to balance return and demand rates to avoid excessive amounts of inventory from building up (where returns exceed demands), or low levels of customer service (where demand exceed returns). Almost half of the firms report that they attempt to balance returns with final demand. The remaining firms report making no efforts to balancing returns with demands. Firms usually base core acquisition based on a mix of actual and forecast demands, but one-third of firms report using only actual demand rates. Firms using only demand-based rates to acquire cores generally use MTO or ATO strategies, and generally use work-in-process inventory to buffer against lead-time and demand uncertainty. The MTS firms relying solely on actual demand rates reported no difficulties obtaining sufficient cores. However, one-quarter of firms' report that no excess of cores exists and their major product acquisition management problem is identifying reliable sources of sufficient quantities of cores. The remaining firms report several methods of dealing with excess materials, including using excess parts as spares (5%), placing excess cores into a holding warehouse (22.7%), trading with other remanufacturing firms (10%), and scrap dealers (41%).

Disassembly

Disassembly is the first step in processing for remanufacturing and acts as a gateway for parts to the remanufacturing processes. Products are disassembled to the part level, assessed as to their remanufacturability, and suitable parts are then routed to the necessary operations. Parts not meeting minimum remanufacturing standards may be used for spares, or disposed of. Purchasing requires information from disassembly to ensure that sufficient new parts are procured. Our survey findings indicate that three-quarters of products remanufactured were not designed for disassembly, and this has a profound impact on operations. Products not designed for disassembly have less predictable material recovery rates, higher disassembly times, and generate more waste. Parts may be damaged during disassembly, especially on products not designed for disassembly, and this often has a negative impact on material replacement rates. Gungar and Gupta (1998) provide an extensive review of disassembly literature on sequence generation and economics and we refer the interested reader to them.

In general, disassembly operations are highly variable with respect to the time required. Our respondents reported that disassembly times ranged from minutes to weeks, with very large variances in required times to disassemble like units. The average times reported to disassembly a product range from a low of 5.54 hours to a high of 300 hours, and all products have a wide range of average times for the disassembly of identical products. The variances associated with disassembly times may be very high, with coefficients of variance (CVs) as high as 5.0. This uncertainty makes estimating flow times difficult and setting accurate lead times almost impossible. The majority of remanufacturers stated that they were under constant pressure to reduce lead times in order to remain competitive with OEMs.

One of the decisions facing a planner is how to release parts from the disassembly area to the remanufacturing work centers. Firms report using pull, push, and push/pull release mechanisms. Our experience has shown that careful coordination is required between disassembly and reassembly to provide short, responsive lead times. Disassembly activities are also labor intensive with no automated techniques reported.

Uncertainty in materials recovered

One of the major sources of uncertainty facing a remanufacturer is material recovery uncertainty. Since no two units will be exactly alike with respect to the time in service, the conditions of use, and the level of maintenance, what parts will be useable will vary from identical unit to unit. Material recovery rate (MRR) is defined as the frequency that material recovered off a core unit is remanufacturable (Guide and Spencer 1997). The majority (95%) of remanufacturing firms use simple averages to calculate MRR, although at least one firm responding used more sophisticated multiple regression models. However, firms reported a wide range of stability for most MRR, ranging from completely predictable to completely unpredictable. Products are equally likely to contain parts with known predictable recovery rates, as to contain parts with no known pattern of recovery.

Material recovery rates may be used in determining purchase lot sizes and remanufacturing lot sizes, and play an important role in the use of material requirements planning systems. Firms are almost evenly split with respect to incorporating MRRs into purchase lot sizing. Firms must purchase replacement parts and materials to use when original parts may no longer be returned to serviceable condition. Purchased replacement parts account for, on average, one-third of parts on a fully remanufactured item (Nasr et al 1998). The average purchase lot size for remanufacturing firms is relatively small, only 334 units, and the average cost of a purchase order is $11k. Of the firms using recovery rates in calculating purchase lots, three-quarters use the historical rates and the remaining firms report that planners use subjective judgement. This is surprising, since if a fixed schedule of end items is known in advance, the required replacement materials may calculated with certainty, given the appropriate MRRs. Many managers reported not being aware of such information, suggesting a lack of communication between engineers and materials managers. Purchase lot sizing is done using a variety of techniques, and over one-quarter of the managers reported using multiple lot sizing techniques. The most common purchasing lot sizing techniques are dynamic lot sizing rules where historical consumption patterns, price breaks, and service level requirements may be taken into account. Lot-for-lot purchasing is also common because of the simplicity and perception of holding lower amount of inventory. Finally, one-fifth of firms routinely use fixed purchase lot sizing; the reason most cited being a vendor's minimum purchase requirement. Purchase lot sizing provides a level of protection against variability in material recovery rates since orders are commonly planned to cover multiple periods. Managers cited a number of concerns with purchasing, the most common ones are: (1) long lead times (90%), (2) sole suppliers for a part or component (75%), (3) poor visibility of requirements (65%), and (4) small purchase orders and, as a result, unresponsive vendors (55%). Purchase lead times reported are highly variable, the mean time to receive an order ranged from 0.5 to 90 weeks. The variation in lead times is also very high, with coefficients of variation as high as 3.0 not uncommon. Purchased parts also cause a high percentage (~45%) of late orders.

A final area that merits discussion is the use of material requirements planning (MRP) in a remanufacturing environment. The use of MRP is widespread among remanufacturers and three-fourths report using some form of MRP. A high percentage (86.2%) of firms report the system is customized to some extent, and the uses of MRP vary greatly in this environment. Firms commonly use MRP for planning purchase and remanufacturing order releases, maintaining bills of materials, and materials tracking. There was no evidence that firms using MRP systems were less likely to experience significant problems with purchase orders, inventory control, or due-date performance. Firms that incorporated MRRs into the purchase order release calculations were less likely to cite concern with poor visibility of requirements, but still cited visibility as problematic. This poor visibility is a function of the short planning lead times (average less than 4 weeks) and dependence on actual demand rather than forecasts. Few firms report being satisfied with their MRP systems, yet few use alternatives.

Reverse Logistics

Reverse logistics activities are primarily concerned with how the products (core) are returned from the user. A large portion of reverse logistics is concerned with core acquisition management, which we have discussed briefly previously. This area is responsible for core acquisition and ensuring an adequate supply of cores for remanufacturing. Most firms acquire cores directly from the customer (81.8%) by requiring a trade-in when a remanufactured item is purchased. Since the majority of products remanufactured by the firms surveyed were relatively high value, customers were motivated to return the products themselves. This is an important distinction from reuse networks for relatively low value items (e.g., recycled goods), where the consumer may require incentives to even provide the products for collection. The design of a returns network in a value-added remanufacturing system may not be as critical for success as in material-recovery operations; further investigation is certainly needed. The other three methods to acquire cores were core brokers (9.2%), third party agencies (7.3%), and seed stock (1.7%). Core brokers act as middlemen, speculating on cores that have no formal market presently and serving as a consolidator for smaller volume core collectors. Managers reported that core brokers charged a premium for their services, and that cores obtained were often very costly to remanufacture due to poor condition. Third party agencies are information brokers that provide information about cores, arrange for a core exchange, or connect buyer and seller. These third party agencies do not exist for many remanufactured products, but are extensive in the automotive parts industry where there is a large, established trade organization. Leasing is an option that more remanufacturers are taking advantage of, but it represents a relatively small portion (5%) of returned products for the firms surveyed. It may be worthwhile to note that leasing does reduce timing uncertainty, but it does not eliminate it since a lessee has the option to renew. Finally, in order to provide remanufactured products where the original products have not been in use long enough to provide sufficient returns, seed stock may be used. Seed stock is composed of products that failed OEM specifications at the manufacturing plant and is purchased by a remanufacturer to provide customers with current product designs or features. If the remanufacturing firm is an OEM subsidiary, seed stocks may be provided as part of customer service. Core acquisition management controls how products are acquired and from what sources, to meet customer demand. As discussed earlier, balancing return rates with demand rates is a related function.

Materials matching requirements

The requirement for parts matching (customer-required returns of the same item) compels the firm to carefully coordinate disassembly operations with repair/remanufacture operations and reassembly. This requirment is common for remanufacturers practicing a make-to-order product position strategy where the customer retains ownership and provides the product to be remanufactured. A full 15% of firms reported depending solely on customer-owned assets. This dependence on customer-owned assets has the advantage of no risky core acquisitions based on projected demands. However, the major disadvantage is a very short planning horizon with very low visibility for replacement parts. Replacement parts and components are more expensive for customer-owned assets, almost 25% on average, greater than for MTS parts. Remanufacturers' report offering customer required returns as a service to customers for a variety of product types, including copiers, network equipment and avionics.

The other major impacts of this characteristic are on scheduling and information systems. In order to provide the same unit back to the customers, parts (up to 40k parts on a relatively simple product) must be numbered, tagged and tracked, placing an additional burden on the information systems. The reassembly of a unit composed of matched parts may be easily delayed since a specific part, not just a specific part type, may delay the order. Remanufacturing firms relying on a MTO strategy are less likely to use an MRP system for material procurement. The majority of firms used simple re-order point systems for inexpensive parts, and ordered more expensive replacement parts as-needed. The purchase lead times for these firms were among the highest of all remanufacturers, averaging almost a full year. Make-to-order firms also reported some of the shortest planning horizons, with many firms planning materials and resources requirements only after products are returned from the customers. Order release is exclusively one-for-one and this makes set-up reduction programs popular. However, in order to provide reasonable remanufacturing lead times, firms routinely carry excess capacity at critical resources.

Firms report using a variety of methods to track materials and parts, including MRP, in-house developed database systems, and manual tagging and tracking. Remanufacturing lot sizing when this characteristic is present is most commonly lot-for-lot because of the unique requirements of remanufacturing operations (we discuss this fully in the next section). Priority control of parts to provide a predictable arrival of parts in the reassembly area is also a common concern among remanufacturers. Firms report using a set buffer size for common parts where service levels trigger replenishments. Parts that are more expensive are pushed to the reassembly area by the use of priority dispatch rules or pulled by a final reassembly schedule. Purchase orders are often problematic for reasons discussed earlier - low volume and visibility. These two factors are often more pronounced in a MTO environment.

Routing uncertainty and processing time uncertainty

Uncertainty results from stochastic routings for returned products and from highly variable processing times. Stochastic routings should not be confused with purely probabilistic routings common in repair shops or in modeling of job shops. In remanufacturing operations, certain tasks are known with certainty, e.g., cleaning; however, other routings may be probabilistic and highly dependent on the age and condition of the part. Routing files are a list of all possible operations, and for planning purposes, the likelihood of an operations being required is maintained. Not all parts will be required to route through the same set of operations or work centers, indeed, few of them would go through the same series of operations as a new part. This adds to the complexity of resource planning, scheduling and inventory control. Shifting bottlenecks are common in this environment because material recovery from disassembly will vary from unit to unit (hence remanufacturing volumes), highly variable processing times, and stochastic routings. This makes resource planning (both machines and labor) and estimating product flowtimes difficult. This characteristic is cited as the single most complicating factor for scheduling and lot sizing decisions. Order release mechanisms are limited to one-for-one core release, except for some common parts which release may be delayed in order to provide a minimum batch size.

Remanufacturing lot sizing is complex and there is no agreement on the best method. A standard lot size of one unit was reported in over one-third of the firms because of the unique requirements of remanufacturing; that is, unique routings for identical part types. Only one-quarter of firms reported using a fixed lot size, usually based on the EOQ. Almost one-half reported using dynamic lot sizing techniques based on capacity constraints, projected demand, or service fill rates.

Research Issues

The discussion of the complicating characteristics shows that remanufacturing firms must be able to manage complex tasks that are significantly different from tasks in a traditional manufacturing environment. In the following sub-sections, we discuss major research needs for each of the complicating characteristics. It should be noted that, in general, there is a need for detailed case studies of all the operational aspects of remanufacturing.

Uncertainty in the timing and the quantity of returns

Essential research issues in this area include a need to develop strategies that develop tools and techniques to manage both quantity and timing uncertainty. Forecasting models designed to predict the availability of returns are needed to reduce some of the uncertainty. There is a body of reliability literature addressing repairable products (Ascher and Feingold 1984), and the development of models considering multiple product life cycles could provide reliability-based models for returns.

The research literature in this characteristic has focused mainly on inventory models that assume that returns are exogenous variables (see van der Laan 1997 for a complete discussion of inventory models in remanufacturing). More research is needed on systems for inventory control and management since much of the previous research has assumes individual, rather than batch arrivals. Additionally, models and managerial systems that link inventory systems with reverse logistics are needed.

Balancing returns with demands

Critical research issues for this characteristic involve better methods to balance return rates with demand rates. There are also very few reports of systems designed to handle the complexity of multiple sources and uses for parts in a dynamic environment. Research regarding the most effective product positing strategies, and corresponding PP&C systems, to serve such diverse markets would also be welcome. Aggregate production planning models detailing alternatives between core acquisition, parts disposal, and purchased parts would be of benefit to practicing managers. This characteristic has mainly been addressed by inventory theory models (see van der Laan 1997), but little has been done to formally integrate these models into a production planning and control system.

Disassembly

There are a number of interesting research questions dealing with disassembly operations. First, disassembly acts as an information gateway, and this information is used in a number of decision areas including, purchasing, resource planning, final assembly, scheduling, and product design. Our research indicates that much of this information is not being exploited to the fullest extent possible. Disassembly operations provide data on material recovery from individual units, and there are often lengthy delays in data entry into a tracking system. Nasr et al. (1998) reports that although specifications may be changed substantially because of information from disassembly, few of these changes are communicated to engineering. Formal models of information systems could help understand the cross-functional information requirements, and the potential benefits of such information systems. For example, information on a product's performance obtained at disassembly should be fed back to design engineers to provide improved designs.

Scheduling systems that enable closer coordination between disassembly and reassembly are also needed to provide more predictable lead times and provide better customer service, while minimizing the investment in unnecessary inventory (see Guide and Srivastava 1998). The research on the release policies for materials is inconclusive and better models are needed to fully understand the gating of materials from disassembly operations. The disassembly process itself is an uninvestigated area; no models or guidelines exist for disassembly center design or staffing. Alternative structures require investigation, including disassembly line design and flexible worker allocation schemes

Uncertainty in materials recovered

No research has used reliability models to aid in predicting material recovery rates. There is a body of reliability literature specific to repairable products (Ascher and Feingold 1984) and efforts are needed to incorporate these results into improved predictive models of materials recovery. MRR provide the foundation for other decision-making activities, and more accurate predictive techniques are of great interest.

There are no models that take into account the added protection from this purchase lot sizing effect, although preliminary research by the author has shown that some purchase lot sizing techniques may help provide more predictable remanufacturing schedules. The use of purchase lot sizing techniques that provide for several periods of coverage buffer against the likelihood that recovery rates will often be lower than expected. However, techniques that allow managers to examine the trade-off between inventory holding costs and customer service must be developed. Certainly, the complications reported by managers (i.e., low visibility of requirements, long lead times) contribute to lower levels of customer service, and all of these areas deserve further investigation.

The use of MRP in this environment, with high amounts of variation and the extensive modifications requires considerable research. The use of MRP combined with other forms of materials planning was reported by many firms, but no clear guidelines exist for inventory planners in this environment. Other resource planning activities, such as flexible worker assignments policies, capacity planning and machine scheduling, should be documented and modeled.

Reverse Logistics

Nasr et al. (1998) report that slightly less than half of remanufacturers report using the same distribution channels as new products providers. However, there are no details available as to what channels are used. This requires further investigation to what channels are used, and how these differ from traditional manufacturing distribution. Remanufacturing executives expressed an interest in decision-making tools that help evaluate choices among sources for cores and to aid the core buying process itself. A clear model of how core acquisition management activities coordinate between purchasing, production, and other functional areas would be of benefit to streamlining operations. Information systems using electronic commerce (i.e., the Internet) could be beneficial in bringing buyers and sellers of cores together. The development of value-added reuse reverse logistics networks requires special attention since previous reverse logistics networks reported have focused mainly on material recovery (recycling) returns. A complete discussion of reverse logistics models is available in Fleischmann et al. (1997).

Materials matching requirements

Fundamental research issues include providing remanufacturers with greater visibility in requirements for very expensive materials, and developing cooperative relationships with suppliers. Hybrid inventory control models are commonly used in this environment and there is no research investigating the effectiveness of these tools. The unique requirements for materials tracking and control place a strain on current shop floor control systems because of the additional need for tight coordination between disassembly and reassembly. Models investigating the benefits of lot sizing models and guidelines for managerial use are also needed. Customer-driven returns may be a successful tool for green marketing, and help to encourage reconsumption by consumers. Cooperative research with marketing would provide hard evidence in the potential of this option.

Routing uncertainty and processing time uncertainty

There are no decision-making tools to assist a manager in deciding whether the set-up saving from remanufacturing lot sizing are greater than the added processing delays from parts not requiring particular operations. Other shop floor level decision models could address scheduling coordination between disassembly and reassembly activities, order release mechanisms, and priority control techniques. Bottleneck scheduling heuristics may be able to exploit the high amount of time spent in cleaning operations, but detailed cases of cleaning operations are first needed.

Conclusions

Remanufacturing executives were asked to identify the greatest threats to industry growth over the next ten years. The majority (60%) cited the increased pressure to continuously reduce remanufacturing lead times, and many (38%) others cited the lack of formal systems (e.g., operations, accounting, logistics) for managing their businesses. Other threats identified included lack of cores (50%), products designed for disposal (34%), and rapid technological changes (28%). The need for academics to develop new systems and evaluate the applicability of present systems is clear.

We have identified seven complicating characteristics of production planning and control activities for remanufacturing firms. The characteristics give focus to efforts in developing new systems for remanufacturing production planning and control. Firms use hybrid production planning and control systems to control operations catering to a diverse market. Most firms use a variety of product positing strategies and this further complicates the problems of planning, controlling and managing operations. We also note that remanufacturing represents a much larger industrial segment than previously thought, and is deserving of full attention by academics from all areas. These characteristics affect a variety of decisions by managers and the environment is inherently more complex that traditional manufacturing. Remanufacturing represents a higher form of reuse, and meets the requirements for sustainable development. We hope that this research forms a foundation for many other developments.

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A Queuing Network Model for a Remanufacturing Production System

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Abstract.

Developing models to study remanufacturing production processes is a difficult task due to the complexity of remanufacturing systems. A typical remanufacturing system consists of disassembly, remanufacturing, and reassembly operations. Previous models have been limited to simulation studies that require extensive time to develop, execute, and analyze. Given the complexity of most simulation models, it may be difficult to isolate specific cause-and-effect relationships required to develop effective manufacturing control techniques. We develop a queuing network model for a remanufacturing production system and present approximate solutions. A decomposition approach is used where the remanufacturing production process is decomposed into: a disassembly segment, a remanufacturing operations segment, and a reassembly segment. The disassembly segment is modeled as a simple queue, the remanufacturing segment is modeled as an open Jackson network, and the reassembly segment as a kitting process. The queuing model is compared with a simulation network model and error bounds are set. The advantages of an analytic model are discussed and applications are presented.

Key words: Remanufacturing, queuing models, manufacturing planning and control

A Queueing Network Model for Remanufacturing Production Systems

Introduction

A recoverable product environment seeks to increase product life with the help of: repair, remanufacturing (including technical upgrades), and recycling of products. A major part of the recoverable product environment is the remanufacturing system (Figure 1) that is designed to remanufacture products.

Remanufacturing systems are faced with a greater degree of uncertainty and complexity than traditional manufacturing systems. This leads to a critical need for developing planning and control

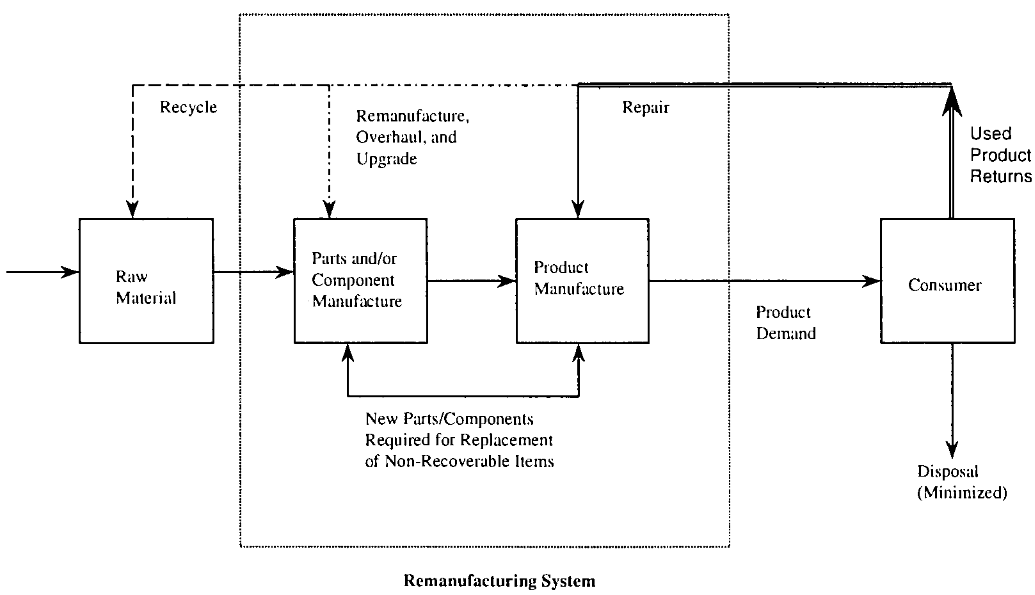

Figure 1 - The Recoverable Product Environment

systems designed to deal with this added uncertainty and complexity.

There are three distinct subsystems in a remanufacturing system: disassembly, remanufacturing, and reassembly. The coordination of these sub-systems is critical for a successful manufacturing planning and control system. In this paper, we develop an analytical (approximation) technique using an open queueing network model for the remanufacturing system in order to provide the foundation for further research into the development of formal manufacturing planning and control systems. We compare the results obtained from the approximation model with the results obtained from a simulation model and provide estimates of error bounds, and discuss implications for future research. We begin with a discussion of the remanufacturing environment and its unique problem structure.

Remanufacturing

Remanufacturing can be described as the transformation of used products, consisting of components and parts, into products that satisfy exactly the same quality and other standards as new products. The U.S. Environmental Protection Agency (EPA) considers remanufacturing to be a waste prevention activity, since it results in less waste than recycling activities. A recent report issued shows that remanufacturing can result in significant energy savings, in addition to the savings from the elimination of disposal costs (U.S. EPA 1997). Thus, remanufacturing is environmentally friendly and profitable. Note that remanufacturing has been successfully implemented in a number of products, including copiers, toner cartridges, medical equipment, automobile parts, computers, office furniture, aviation equipment, and tires (Guide et al. 1998).

Remanufacturing firms contend with several complicating factors that limit the effectiveness of traditional methods of manufacturing planning and control (MPC). The six major factors that significantly complicate the MPC functions are: (1) probabilistic recovery rates of parts from the inducted cores (a core is a product returned for remanufacture) which implies a high degree of uncertainty in materials planning, (2) unknown condition of the recovered parts until inspected, thus leading to stochastic routings and lead times, (3) the part matching problem (units are often composed of serial number specific parts and components, along with common ones), (4) the added complexity of disassembly operations, (5) the problem of imperfect correlation between supply of cores and demand for remanufactured units, and (6) the uncertainties in the quantity and timing of returned products (Guide et al. 1998).

Part recovery rate is a function of how often a part is in a suitable condition to be used in remanufacturing; parts which are not recoverable must be replaced by new parts. Part recovery rates are often highly variable which leads to variations into the remanufacturing system in the form of stochastic workloads.

A part's condition is not known until a unit is disassembled, cleaned and inspected, which leads to stochastic routings and processing times. The operations required for each like part may vary widely because of the different age, wear and operating conditions the units may have been subjected to. This uncertainty in the required operations (routings) makes scheduling and capacity planning more complex due to the higher degree of variability inherent in remanufacturing.

Another related factor that can significantly add to the complexity in a remanufacturing shop is the "serial number specific" reassembly operations. Any planning and control system used in a remanufacturing facility must be designed to coordinate the flow of material from disassembly with the reassembly of the unit. This coordination may be complicated when a unit is composed of serial number specific parts and components. A unit may also be composed of a mix of common parts and serial number specific parts and components. This mixture of common and serial number specific parts and components may be more prevalent with advances in modular design practices where components are common items, but the parts that make up these components are serial number specific. The presence of any reassembly operations makes coordination between disassembly and reassembly critical if customer due dates are to be met.

Remanufacturing requires that cores (returned products) are disassembled to the part level before any decisions may be made about the required processing, or if a part must be replaced. There are a number of possible shop structures available for a remanufacturing facility and there have been a large variety of shop structures reported ranging from highly repetitive type work (cellular telephones) to large job-shop type structures (U.S. Naval ship remanufacturing) (Guide 1998; Nasr et al. 1998). We present an overview of a typical remanufacturing facility in Figure 2. Nasr et al. (1998) report that the vast majority (85%) of remanufacturing firms use manual conventional equipment to process materials. Less than one-quarter of facilities reported using CNC or NC machines, and a very small percentage (~6%) reported using manufacturing cells. The most common type of remanufacturing facility will be a general purpose remanufacturing shop with characteristics of both open and closed (routings) job shops with reassembly operations (see Figure 2).

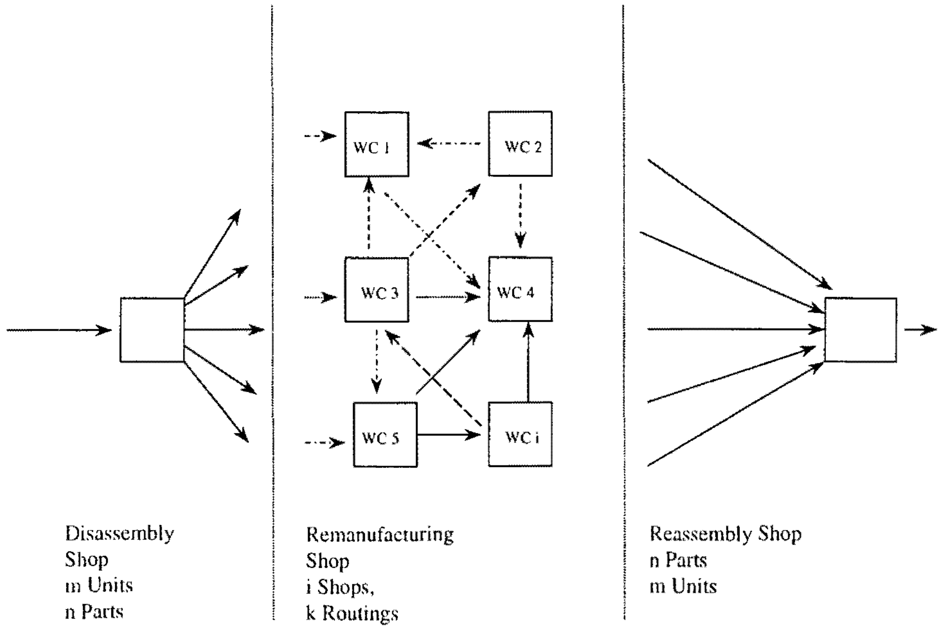

Figure 2 - A General Remanufacturing Shop

Demand management is an essential concern for a firm in a recoverable product environment since it is considerably more complex than in a traditional manufacturing environment. Because a firm engaged in remanufacturing may not operate in a closed-loop system, the problem of balancing the return of products with the demand for products may be quite complex. This problem is known as the problem of imperfect correlation between demand and returns and has been addressed in earlier studies by Muckstadt and Isaac (1981) and van der Laan, et al. (1996). The problem of imperfect correlation between demand and returns may lead to excess stocks of unwanted units, components and parts, and shortages of needed units, components and parts. A number of factors including the life-cycle stage of a product, and the rate of technological change will influence the correlation between product demand and returns. This problem of imperfect correlation also results in uncertainty with respect to quantity and timing for product returns. This uncertainty in the available quantity and timing of cores makes planning and control in remanufacturing environment more complex since this variability in source materials is rarely a factor in traditional manufacturing.

Modeling of Remanufacturing Production Systems

There have been a number of models of various aspects of remanufacturing systems reported in the literature. Various authors have investigated the problems associated with disassembly, including materials planning (Gupta and Taleb 1994; Taleb et al. 1997; Taleb and Gupta 1997), and optimal levels of disassembly (Lambert 1997). The models explicitly examining shop floor control systems are limited to simulation evaluations of actual production systems (Guide 1996, Guide and Srivastava 1998) or grounded theoretical models (Guide et al 1997). There have been no analytic models of remanufacturing production systems reported. This is understandable due to the complex nature of remanufacturing and the lack of detailed studies of relatively simple systems.

Simulation models have a number of advantages and disadvantages (see Law and Kelton 1992 for a complete discussion). A major disadvantage of a simulation model is the time required to collect the data, verify the code and validate the model. Analytic models typically execute faster and require much less data to develop and test. A queueing model of a remanufacturing facility could provide a number of benefits to researchers and practitioner alike by reducing the time required for building models of existing production systems and greatly simplifying the modeling process in general. In the following sections we develop a queueing approach for modeling a remanufacturing facility.

Queueing Network Model

Queueing models have been reported for a large number of production facilities (see Buzacott and Shanthikumar (1992) for a thorough discussion). We use decomposition to solve the problem of modeling a remanufacturing production system. The steps are as follows (Shanthikumar and Buzacott 1981):

Step 1: Analysis of the interactions (arrival and departure processes) between service centers.

Step 2: Decomposition of the queueing network into subsystems of service centers and their analysis.

Step 3: Recomposition of the results obtained from the decomposed single service centers.

We can see that the structure of a remanufacturing facility may be decomposed into three segments as shown in Figure 2. The three segments, the disassembly process, the remanufacturing process and the reassembly process will be discussed in the following sections. For our base case, we assume that there is perfect recovery (recovery rates are 100%), no blocking at any of the service centers (except at the reassembly center), and that the arrival process may be adequately described by a Poisson process.

The Disassembly Process

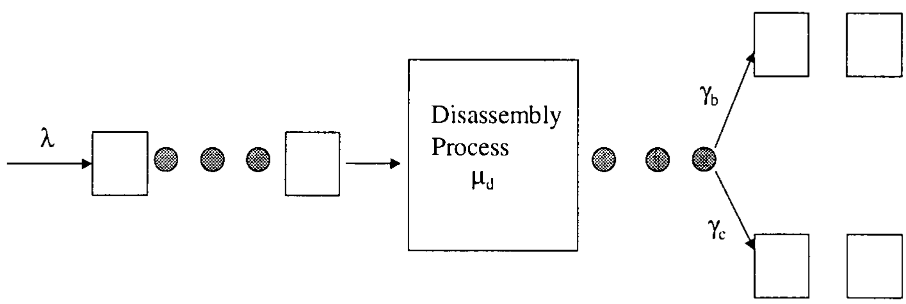

Figure 3 - The Disassembly Process

Assume that a single class of jobs arrive to the system according to a Poisson arrival rate λ. All jobs enter the system via a disassembly process and wait in a queue if the server is occupied. The disassembly process service times are iid exponential random variables with mean $1/\mu_d$. We assume that the disassembly process yields two streams of parts *b* and *c* to the remanufacturing process with rates γ_b and γ_c respectively. We limit our discussion to two part types; multiple part types may be modeled in the same fashion. The disassembly process is modeled as an M/M/c queue.

The Remanufacturing Process

Jobs arrive at machine center *i* (i=1,...,k) according to the Poisson arrival rate of either γ_b or γ_c from the disassembly process. Service times are iid exponential random variables with mean $1/\mu_i$ (i=1,...,k) for machine center *i*. The remanufacturing processes may be modeled as open Jackson networks via:

$$\lambda_i = \gamma_p + \sum_{j=1}^{k} r_{ji}\lambda_j \tag{1}$$

where λ_i is the mean flow rate into node *i* (from the disassembly center, γ_p ($p = b,c$) and from other nodes) and r_{ij} is the probability of a job completing service at node *i* going to node *j* (independent of the system state), i=1,...,k. The remanufacturing process nodes of the network behave as independent

M/M/c queues and simple closed form performance measures exist for calculating the number of jobs in the system, expected queue lengths and expected waiting times, global performance measures are defined in a following section.

The Reassembly Process

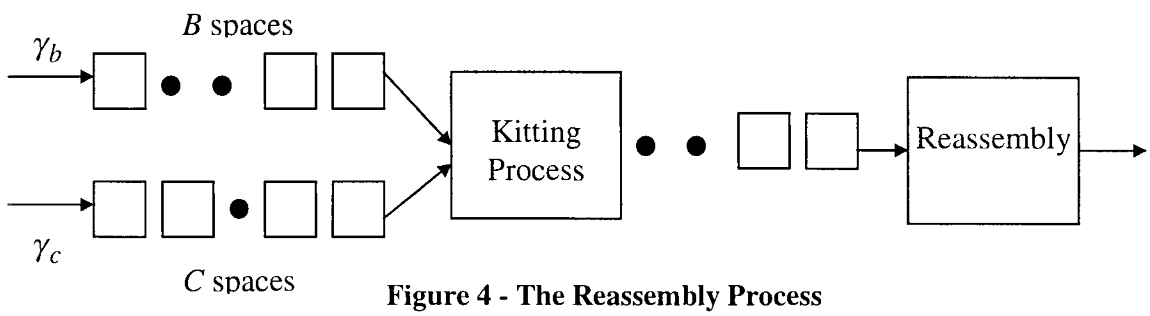

Figure 4 - The Reassembly Process

Parts b and c arrive from the remanufacturing process in two separate streams with rates γ_b and γ_c respectively and form separate queues. One unit of part b and one unit of part c are required to complete a kit. The kits then join a single queue for reassembly (see Figure 4). We approximate the kitting process as a double ended finite buffered queue and model the reassembly process as an M/M/c queue.

Next, we show how to model the kitting process. Assume that parts b arrive at the kitting area and form a queue, if parts c are not available. Parts c also arrive at the kitting area and pick up one unit of part b from the queue, if any, or else form a queue. Thus, at any given time, there is either a queue of parts b or one of parts c or of neither. Assume that there are limited buffer spaces; B units of parts b and C units of parts c. (Note that if either part b or part c arrives and finds the buffer full, it is considered lost to the system. However, by judiciously choosing B and C to be sufficiently large, this problem can be minimized). Let P_n denote the steady state probability that n units of parts b are waiting in the queue. We allow n to vary from $-C$ to B. We interpret the value of n as follows. When $n > 0$, it denotes that n units of parts b are waiting. When $n = 0$, it denotes that none of the parts are waiting. When $n < 0$, it denotes that n units of parts c are waiting. The steady state transition equations can be written as follows:

$$-\gamma_b P_{-C} + \gamma_c P_{-C+1} = 0 \qquad (2)$$

$$-(\gamma_b+\gamma_c)P_n+\gamma_b P_{n-1}+\gamma_c P_{n+1}=0 \qquad (-C<n<B) \qquad (3)$$
$$-\gamma_c P_B+\gamma_b P_{B-1}=0 \qquad (4)$$

Solving equations (2) through (4) recursively, we get

$$P_n=\gamma^{C+n}P_{-C} \qquad (-C\le n\le B) \qquad (5)$$

where $\gamma=\dfrac{\gamma_b}{\gamma_c}$.

Using the boundary condition

$$\sum_{n=-C}^{B}P_n=1 \qquad (6)$$

we get

$$P_{-C}=\frac{1-\gamma}{1-\gamma^{C+B+1}} \qquad (\gamma\ne 1) \qquad (7)$$

Substituting equation (7) into (5), we get

$$P_n=\frac{(1-\gamma)\gamma^{C+n}}{1-\gamma^{C+B+1}} \qquad (\gamma\ne 1) \quad (-C\le n\le B) \qquad (8)$$

Taking the limit as $\gamma\to 1$, we get

$$P_n=\frac{1}{C+B+1} \qquad (\gamma=1) \quad (-C\le n\le B) \qquad (9)$$

The probability that there are no parts waiting at the kitting area is

$$P_0=\frac{(1-\gamma)\gamma^{C}}{1-\gamma^{C+B+1}} \qquad (\gamma\ne 1) \qquad (10)$$
$$=\frac{1}{C+B+1} \qquad (\gamma=1) \qquad (11)$$

Kitting Performance Measures

The probability that there is a queue of parts b is

$$P_b = \sum_{n=1}^{B} P_n$$

$$= \frac{(1-\gamma^B)\gamma^{C+1}}{1-\gamma^{C+B+1}} \qquad (\gamma \neq 1) \qquad (12)$$

$$= \frac{B}{C+B+1} \qquad (\gamma = 1) \qquad (13)$$

The probability that there is a queue of parts c is

$$P_c = \sum_{n=-C}^{-1} P_n$$

$$= \frac{1-\gamma^C}{1-\gamma^{C+B+1}} \qquad (\gamma \neq 1) \qquad (14)$$

$$= \frac{C}{C+B+1} \qquad (\gamma = 1) \qquad (15)$$

The mean queue length of parts b is

$$L_b = \sum_{n=1}^{B} nP_n$$

$$= \frac{\gamma^{C+1}\left\{1-(B+1)\gamma^B + B\gamma^{B+1}\right\}}{(1-\gamma)(1-\gamma^{C+B+1})} \qquad (\gamma \neq 1) \qquad (16)$$

$$= \frac{B(B+1)}{2(C+B+1)} \qquad (\gamma = 1) \qquad (17)$$

The mean queue length of parts c is

$$L_c = \sum_{n=-C}^{-1} -nP_n$$

$$= \frac{C-(C+1)\gamma + \gamma^{C+1}}{(1-\gamma)(1-\gamma^{C+B+1})} \qquad (\gamma \neq 1) \qquad (18)$$

$$= \frac{C(C+1)}{2(C+B+1)} \qquad (\gamma = 1) \qquad (19)$$

Note that due to limited buffer space,

probability that parts b are lost = P_B ,

probability that parts c are lost = P_{-C} .

Also,

the mean number of parts b lost per unit time = $\gamma_b P_B$, the mean number of parts c lost per unit time = $\gamma_c P_{-C}$.

Note that Little's formula is also valid here. Thus,

$L_b = \gamma_b W_b$ and $L_c = \gamma_c W_c$,

where W_b and W_c are mean waiting times for parts b and parts c respectively.

If $\gamma_b = \gamma_c$, $B = C$ and B is sufficiently large, then the output of the kitting process can be approximated by a Poisson process with rate γ_b (Som et al. 1994).

Performance Measures for the Remanufacturing System

To provide an estimate of the time an average job spends in the system, $E[T]$,

$$E[T] = \sum_{i=1}^{k} \upsilon_i E[T_i], \; i = 1,\dots k \tag{20}$$

where:

$$E[T_i] = \frac{1}{\lambda_i}\frac{\rho_i}{1-\rho_i}, \; \rho_i = {\lambda_i}/{\mu_i} \tag{21}$$

and

$$\upsilon_i = \frac{\lambda_i}{\lambda}, \tag{22}$$

where λ_i is th arrival rate to the ith node and λ is the arrival rate to the system.
Similarly, the expected number of jobs in the facility may be found via Little's formula or directly from

$$E[N] = \sum_{i=1}^{k} \frac{\rho_i}{1-\rho_i} \tag{23}$$

and the variance of the total number of jobs in the facility (N) may be found since $N_1,\dots,N_k$ (the number of jobs at machine center i) are independent and since $\mathrm{var}(N_i) = \rho_i/(1-\rho_i)^2$, $i = 1,\dots,k$, by

$$\mathrm{var}(N) = \sum_{i=1}^{k} \frac{\rho_i}{(1-\rho_i)^2} \tag{24}$$

Model Performance

We show that this approximation model is quite robust. We examine the performance of the model for a facility that remanufactures a single type of end item, product a, composed of two parts b

and c. All jobs must first be disassembled at the disassembly center and the routed through one of two entry machine centers (cleaning operations) before remanufacturing operations may begin. Both parts b and c have the same expected number of processing operations. The expected utilization rates for the disassembly center, the machine centers, and the reassembly have the same expected utilization rate, which we examine at a number of intensity levels.

In the first experiment, we use a general, job-shop type layout. The remanufacturing job shop is symmetric, where each job leaving a machine center has an equal probability of going to one of the other k - 1 machine centers, or going to the reassembly center. That is, $p_{ij} = 1/k$; $i \neq j$, $i,j = 1,\ldots,k$; $p_{ii} = 0$, $i = 1,\ldots,k$. In all experiments for the job shop layout, we set $k = 10$, plus a disassembly center and a reassembly center. The calculations for the analytic models were built using MS Excel spreadsheets. These analytic results were compared with the true values for sojourn times, which we obtained via simulation models. The transient period for the simulations was carefully determined via Welch's technique (see Law and Kelton 1992) and each scenario was run five times using independent random number seeds for each run. We present these results in Table 1 below.

ρ	*0.95*	*0.85*	*0.75*	*0.65*	*0.55*	*0.45*
Analytic	207.35	68.43	38.88	26.76	19.96	15.66
Simulation	209.25	69.47	41.85	30.02	23.65	19.52
% Error	0.906	1.50	7.09	10.85	15.57	19.75

Table 1 - Flowtime Results for Job Shop

The analytic results are quite accurate, (the error is under 10% for $\rho \geq 0.75$), and start deteriorating when lower utilization levels are used.

In the second set of experiments, we use a flow-line layout for the facility. As with the job shop layout, all units, after disassembly, enter the remanufacturing operations via one of two machine centers (cleaning operations). The remanufacturing operations are carried out in a flow line, where there are two lines, one dedicated to part b and the other dedicated to part c. The flow of parts is in one direction only, and each job leaving a machine center has an equally likely probability of going to one of the remaining machine centers, or going to the reassembly center. That is, $p_{ij} = 1/(k_i - 1)$; $i \neq j$, i $= 1,\ldots k$; $j = 2,\ldots,k$, $j > i$; $p_{ii} = 0$, $i = 1,\ldots,k$. In all experiments, we set $k = 10$ for each line, and have disassembly and reassembly centers. We again compare our analytic results with simulation model output, and we present the results in Table 2. In this case, the results are accurate, with no error in excess of 5%, for $\rho \geq 0.45$.

ρ	*0.95*	*0.85*	*0.75*	*0.65*	*0.55*	*0.45*
Analytic	352.89	120.0	73.66	53.90	43.14	33.53
Simulation	344.20	121.80	73.78	52.52	41.35	33.75
Error	-2.46	1.49	0.15	-2.56	-4.16	0.65

Table 2 - Flowtime Results for Flow Shop

Conclusions

A queueing network approach for the modeling of remanufacturing production systems produces approximations to true system performance that are quite accurate. The queueing approach has a number of advantages over simulation modeling including obtaining performance measures much more rapidly. Queueing models require less data collection and may be developed in a short period of time. Further research is required to set error bounds on queueing network models for more complex scenarios, such as unequal processing times for components and general distribution times (G/GI models) for machine center time and arrival rates.

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Repair or Remanufacture: A Comparative Evaluation

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Repair or Remanufacture: A Comparative Evaluation

Abstract

A recoverable product environment, which includes strategies to extend product life, is an increasingly important method of waste prevention. A major part of this environment is the recoverable manufacturing system designed to remanufacture products. Strategies in recoverable manufacturing include repair and remanufacturing. A key characteristic of the recoverable environment is the high degree of variability inherent in it due to several complicating characteristics. In this paper repair and remanufacturing strategies are compared on various criteria to evaluate whether the activities are similar enough to be performed with the same manufacturing system and production planning and control system, or dissimilar enough that separate systems are needed. A simulation approach is used to make the comparison.

Repair or Remanufacture: A Comparative Evaluation

There are significant environmental costs to manufacturing, including material, energy, waste products, and pollution. The prevention of waste products avoids associated environmental costs before they can occur. An increasingly viable strategy for a range of manufactured products is to develop systems focused on recoverable product environments. Such systems, focused on the recovery of materials used to manufacture and deliver products, can reduce the environmental costs of manufacturing through reduced use of materials and energy, at the same time reducing the cost of waste products (such as landfill and disposal costs). Recoverable product strategies include repair, remanufacturing (including technical upgrades), and finally recycling of products (Vandermerwe and Oliff 1990, Thierry et al 1995, Guide and Srivastava 1997d). The strategies are operationalized through the recoverable manufacturing system, which is designed to extend product life by repair, and by remanufacturing. This environmentally friendly approach is profitable as well, as reported for various industries such as copiers, automobile parts, computers, and aviation equipment (Lund 1984, Graedel and Allenby 1995, Guide 1996, Thierry et al. 1995, Nasr et al. 1998). Recoverable manufacturing in the United States exceeds $53 billion in sales per year, with in excess of 73,000 firms engaged in some form of recoverable manufacturing (Lund 1996). The Environmental Protection Agency (EPA) cites remanufacturing as a major form of reuse activity and reports that less energy is used as also less waste is produced with such activities (EPA630-N-97-002 1997), and reports on a number of firms successfully engaged in recoverable manufacturing.

Recoverable manufacturing takes many forms and in Figure 1 we identify three distinct forms of operations as subsets of recoverable manufacturing. Repair operations are aimed at isolating and either

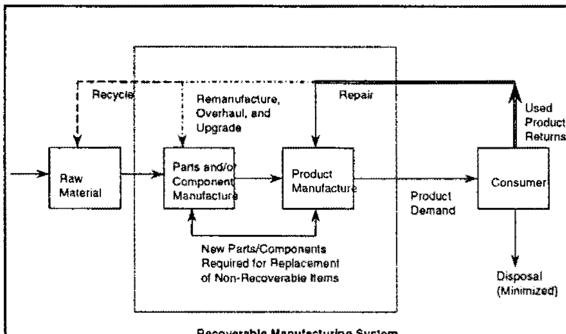

Figure 1 - A Recoverable Product Environment

reworking or replacing only the defective parts to get a product back into use. The original product form is preserved under this approach and minimum additional materials and energy are used while not discarding the product (minimizing waste). Remanufacturing operations utilize a combination of rework and replace on all components of a product to bring the product back up to its original specifications of quality and use. This approach will be more expensive than repair since more materials and energy would be utilized, however, it is expected to extend the product life longer than repair, as well as extend the mean time between failures. Finally, for every product a stage is reached where recovery of the product is not feasible with due economic consideration. At this stage, recycling still provides an environmentally sound way of reducing costs while recovering material in raw form.

In this study we focus on repair and remanufacturing subsets of recoverable manufacturing where the product form is retained and the aim is to extend the product life. The characteristics of both forms are examined. A framework is developed to compare the two forms of recoverable manufacturing. Our aim is to ascertain whether these two systems are sufficiently alike in their performance on various criteria that the two activities of repair and remanufacturing could be performed with the same manufacturing system, or separate systems are needed to enable effective planning and control.

Repair and Remanufacturing

Repair

Repair can be considered as a transformation process aimed at isolating and rectifying the defects in a product that cause it to become non-functional, such that the product is returned to functional form. There are a growing number of industries where repair, rather than replacement of the product, is economically feasible. Extended warranties require a manufacturer to assume financial, and often operational, responsibility for a product when it requires repair. These trends are a matter of simple economics as well as a growing interest in environmentally conscious behavior. Repair acts as a form of product life extension (see Figure 1), termed added value recovery, and is considered a first option by firms engaged in product recovery management (Thierry et al. 1995). However, maintaining repair facilities introduces managerial control complications not found in traditional manufacturing facilities (Thierry et al. 1995, Chua et al. 1993), such as the quantity and timing of products received for repair, as well as the uncertainty in material requirements imposed by unknown failures (Guide and Srivastava 1997b).

Remanufacturing

Remanufacturing has been considered as the transformation of used units, consisting of components and parts, into units that satisfy exactly the same quality and other standards as new units (Lund 1984). Unlike repair, the remanufacturing transformation process may be performed on failed or working units of a product. Additionally, the process is not limited to isolating and fixing/replacing the failed parts, but involves reworking on potentially all components of the product. In case of remanufacturing, disassembly is complete not partial, as also reassembly, which introduces more complexity in the process. Remanufacturing is a growing subset of recoverable manufacturing systems. This growth has been spurred by economic considerations on the part of manufacturers and consumers, by environmental considerations, by technological considerations and by regulations and laws.

Recent research in remanufacturing has focused on various planning and control areas. Studies have confirmed that the added uncertainty and increased variability in a recoverable manufacturing environment makes the use of traditional planning and control tools ill-advised (Guide et al. 1997a). In a study of capacity planning techniques in this environment, Guide et al. (1997) show that traditional capacity planning techniques tend to perform poorly and techniques modified to account for the environment characteristics perform better. A recent study by Guide and Srivastava (1998) shows that interactions between part type matching and disassembly release rules should be paid close attention to in order to provide improved flow times and customer service. Remanufacturing systems are also subject to varying material yields since not all of the parts disassembled from a unit of a product can be reused or remanufactured. Flapper (1994) discusses the use of discount factors for incomplete material yields, and Guide and Srivastava (1997b) evaluate safety stock to handle this material recovery uncertainty.

Remanufacturing firms also contend with matching demand for remanufactured products with availability of cores. Research by van der Laan et al. (1996) shows that disposal of items must be considered or inventories may grow uncontrollably. Some recent work has focused on joint production and inventory decisions for a mix of remanufactured and new items (van der Laan and Salomon 1997, van der Laan et al. 1996). Almost all the research has so far focused on either repair or remanufacture as a recoverable system. Production planning and control systems capable of coordinating a mix of repair, remanufacture, and new production have not been addressed in the literature. A linear programming model developed by Clegg et al. (1995) investigates some of these relationships but is limited to deterministic inputs.

Characteristics of Recoverable Manufacturing

Recoverable manufacturing systems have several complicating characteristics that distinguish them from traditional manufacturing systems (Guide et al. 1998). Guide et al. (1998) list seven characteristics that complicate the management planning and control of the supply chain functions. These seven characteristics are: (1) the uncertain timing and quantity of returns, (2) the need to balance demands with returns, (3) the need to disassemble the returned products, (4) the uncertainty in materials recovered from returned items, (5) the requirement for a reverse logistics network, (6) the complication of material matching restrictions, and (7) the problem of stochastic routings for materials for repair/remanufacturing operations and highly variable processing times.

Repair Systems

The general structure of the repair facility will be similar to the remanufacturing facility; there are three stages in the facility. At the first stage disassembly is performed, at the second stage the defective parts are brought back to working condition, and at the third stage the product is reassembled from its parts and components. While the general structure appears similar, repair and remanufacturing operations have several differences in their system characteristics, as well as some shared characteristics. It is these sets of shared and dissimilar characteristics which are of interest to the manager of the recoverable manufacturing facility, since if the shared characteristics dominate, then repair and remanufacturing operations could be carried out in the same facility using the same planning and control system.

Characteristics of Repair Systems

The complicating characteristics of recoverable manufacturing identified earlier are assessed here in the repair environment. Characteristic 1, the uncertain timing and quantity of returns, is a reflection of the uncertainty associated with failures. Repair systems have to be able to accommodate this uncertainty in terms of the impact on inventory control, production planning and control, and purchasing. Characteristic 2, the need to balance demands with returns, is not a major concern in the repair system. Most repair activities are initiated on customer request and therefore demand for the repaired product (same unit) comes from the customer who supplied the failed product. This also reduces some of the uncertainty with regard to timing of returns. Characteristic 3, the need to disassemble the product exists in the repair system, however, the disassembly process is not as complicated or extensive, since disassembly is partial and limited to fault isolation and extraction of the failed part(s). The inventory of parts at the disassembly area is limited, the partially disassembled product would be moved to the reassembly area. Characteristic 4, the uncertainty of materials recovered from the failed products, is limited to only the failed items and any other items which are lost (scrapped) in the disassembly process. However, uncertainty still exists as to the parts failed, as well as their failure rates. Characteristic 5, the requirement for a reverse logistic network to handle returns may or may not be needed in a repair system. If the firm engaged in repair operations collects failed products from various available sources, and markets the repaired products then there is a need for a formal reverse logistic system to handle the returns. If the returns come from customers who take back their repaired products then the need for a formal reverse logistics system diminishes. Characteristic 6, the complication of material matching restrictions, would exist for repair systems, but is limited to only the parts that have been disassembled. Characteristic 7, the problem of stochastic routings and highly variable processing times for the parts undergoing repair is applicable in the repair system, since the operations needed to repair a failed part are not known nor is the condition of the part until the part has been evaluated.

Remanufacturing Systems

Remanufacturing systems have the same general structure, there are three stages in the manufacturing system. The first stage is the disassembly shop, the second stage is the remanufacturing shop, and finally the reassembly shop. Products that are to be remanufactured could be in working condition, whereas products inducted into the repair system have some identifiable failures. The remanufacturing system is used to completely disassemble a given product into all its parts and components to the lowest level in the bill of materials at the disassembly stage. All the materials are then processed through the remanufacturing shop, where some of the parts may simply be passed through to the reassembly area as meeting the original specifications of quality and use, and others are remanufactured to the original specifications of quality and use. All components and parts needed to reassemble the product are accumulated at the reassembly stage, and the product is reassembled. In a remanufacturing system, it is not necessary that parts and components be reassembled to the same unit they were disassembled from. The only exception is when part matching requirements are present.

Remanufacturing systems exhibit all of the complicating characteristics of the recoverable manufacturing environment since they constitute the most intensive and complete form of recoverable manufacturing.

Characteristics of Remanufacturing Systems

Remanufacturing systems are typically exposed to a greater degree of uncertainty in the timing and quantity of returns, i.e., characteristic 1, and have to accommodate this uncertainty through the inventory control systems, as well as effective demand management, planning and control. Characteristic 2, the need to balance demands with returns is a major concern in remanufacturing, often, technological advances make returns incompatible with demand. This can lead to a firm having to deal with disposal of excess returns. Characteristic 3, the need to disassemble the product, is complete in remanufacturing as the product is disassembled to its lowest level in the bill of materials. Characteristic 4, the uncertainty of materials recovered is greater in this system. Uncertainty in recovery of materials is not limited to failed parts, those in working condition may also be deemed unfit for remanufacture due to either technological or economic reasons. Characteristic 5, the requirement for a reverse logistics network, is a necessary one in the remanufacturing system. There are many sources of the cores, such as brokers, customers, and OEM manufacturers. To effectively balance returns and demand, and reduce some of the uncertainty in timing and quantity of returns, a reverse logistics network is highly desirable. Characteristic 6, the complication of material matching restrictions is present to a greater degree. Since serial number specific parts have to go back on the same unit they came off from, and common parts are interchangeable, this poses greater demands on the information system needed to track parts, as well as the scheduling and inventory systems. Characteristic 7, the problem of stochastic routings, and highly variable processing times, is more evident in the remanufacturing system, since a large number of different parts are processed through the remanufacturing shop.

Repair versus Remanufacturing

The preceding analysis of the characteristics that complicate the recoverable manufacturing environment as specifically applied to the repair and remanufacture systems indicate that the two systems share some of the characteristics, while on others they differ to varying degrees. In order to compare repair with remanufacturing a framework needs to be developed. Remanufacturing involves a significantly larger degree of planning and control in the manufacturing system than repair. In the case of remanufacturing, during the process itself the identity of the product is lost, since once disassembly is complete there are only parts and components. Product identity is regained at the reassembly stage, unlike repair where at all times product identity is retained. Operations are more extensive in remanufacturing since they cover all parts and not just the failed parts.

The production planning and control (PPC) system for repair systems should be designed to accommodate the complicating characteristics. The repair environment is essentially a make to order environment, and the master production schedule (MPS) should reflect that. The PPC system is designed for fast turn around times, since short delivery times and stated due dates would be the norm. Performance measures in line with these such as minimizing flow times and meeting due dates should be used to evaluate the PPC system. Demand management, and disposal of excess units of cores is not a major design issue. Scheduling and inventory management is limited to the failed parts under repair.

The PPC system for remanufacturing, while structurally similar, is different in many respects. First, the remanufacturing environment can be considered as essentially make to stock. The MPS should account for this, as well as the greater and varied sources of cores, which requires effective supply management. This is critical, given that any imbalance between supply and demand could lead to excessive disposal costs. Demand management is also important, since the remanufactured product is marketed in the same markets as competing new products. Order release of units into the disassembly area, scheduling of parts from disassembly to the remanufacturing shop, and in the reassembly area are important decision areas. Within the remanufacturing shop the PPC system should consider the stochastic routings, highly variable processing times, and by implication, shifting bottlenecks. Inventory management is more important since in the remanufacturing environment, at any point in time there are more parts, both quantity and type, in the system than in a repair environment. Managing finished goods inventory is critical since often the remanufactured good becomes obsolete faster than the competing new product in the market. By implication, cost based performance measures such as inventory, and associated measures such as minimizing flow time should be used to evaluate the PPC system. Due dates may also be an effective measure, especially when the remanufacturing is done in response to customer or OEM returns.

From an environmental focus, repair can be considered as a first option in reusing a failed product rather than discarding it for recycling or landfill. This conserves almost all of the material and value-added content (labor and energy). The marketing activity is focused on the customer since essentially production is driven by customer returns. However, as the product ages, the repair option becomes more expensive over a span of time due to more frequent and different failures. Remanufacturing can then be considered as the second option in reusing a product rather than discarding it. Most of the material and some of the value-added content is conserved. Remanufacturing is more expensive than repair, but less expensive than new products, especially when the environmental cost of disposing the failed product is factored in. While in the short run repair is less expensive, over a longer span of time remanufacturing may become a more economic alternative. The marketing activity in the case of remanufacturing is focused on market segments, not individual customers and the production is driven by the returns obtained from the various sources, not individual customers.

In this section we have examined the repair and remanufacturing systems for their distinguishing features, and for similarities and differences. Of interest to the manager in the recoverable manufacturing environment is whether these distinguishing features and differences warrant separate planning and control systems, or whether the same facility and PPC system can be used to handle both repair and remanufacture. To examine this issue we build a model for comparison.

Model Development

The dynamic environment presented by both repair and remanufacturing activities as reflected by their complicating characteristics precludes the development of analytical models. Therefore we develop a

Factor	Levels
I. Product Structure	1. Simple 2. Intermediate 3. Complex
II. Part Matching	1. All serial number specific 2. All Common 3. A mixture of serial number specific and common parts
III. Priority Dispatch Rule	1. FCFS 2. SPT 3. EDD 4. LBOM 5. HBOM

Table 1: Experimental Design Factors - Repair

Factor	Levels
I. Product Structure	1. Simple 2. Intermediate 3. Complex
II. Part Matching	1. All serial number specific 2. All Common 3. A mixture of serial number specific and common parts

III. Disassembly release mechanism - SNS parts	1. Flush 2. Highest level in BOM first 3. Lowest level in BOM first 4. Greatest expected processing time first
IV. Disassembly release mechanism - Common parts	1. Flush 2. Highest level in BOM first 3. Lowest level in BOM first 4. Greatest expected processing time first
V. Priority Dispatch Rule	1. FCFS 2. SPT 3. EDD 4. LBOM 5. HBOM

Table 2: Experimental Design Factors - Remanufacture

simulation approach to compare the two options. In Tables 1 and 2 we provide the experimental design for the repair and remanufacturing options.

We will present the results of our analysis along with our conclusions. Our preliminary analysis indicates that we expect the two environments to be different requiring the use of separate PPC systems.

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A Case-Based Reasoning Approach for the Optimal Planning of Disassembly Processes

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ABSTRACT

The complexity of planning for disassembly, as well as the time required, increases with the number of components in a product. Furthermore, in dealing with a multiple products situation, it is important to have the capability to create disassembly process plans quickly in order to prevent interruptions in processing. The application of case-based reasoning (CBR) approach in planning for disassembly can go a long way in avoiding interruptions in processing. CBR is a technique that allows a process planner to rapidly retrieve, reuse, revise, and retain the solution to past disassembly problems. Once a planning problem has been solved and stored in the case memory, a planner can retrieve and reuse the product's disassembly process plan any time in the future. The planner can also adapt an original plan for a new product that does not have an existing plan in case memory. Following adaptation and application, the successful plan is retained in the case memory for future use. In this paper, an approach to solve the problem of multi-product/multi-manufacturer disassembly is presented. The focus is on the procedures to initialize a case memory for different product platforms, and to operate a CBR system which can be used to plan disassembly processes.

INTRODUCTION

With today's rapidly developing technologies and product designs, manufacturers are capable of delivering new products to consumers at a dramatic rate. This has, in turn, resulted in shorter life-spans for products because, more often than not, they are discarded even though they are still in excellent working conditions. An overflowing stream of used products scrapped has become an alarming problem for waste management, and is quickly elevating the level of environmental detriments. Countries around the world have observed an explosive growth in the waste stream that is filling up municipal landfills and clogging up incinerators. They have yet to find ways to efficiently manage the problem. As a result, an increasing number of companies in Europe and America are studying the prospect of establishing products reclamation facilities to collect, disassemble, and reclaim components for reuse, remanufacturing and recycling.

Throughout the world, there have been many reclamation facilities established by product manufacturers to disassemble and study their products. Sony, for example, has built the Sony Disassembly Evaluation Workshop in Stuttgart, Germany, to assess the reuse and recycling qualities of electronic products [8]. IBM has also established the Reutilization Center in Endicott, New York, to disassemble and recover reusable components from personal and notebook computers [3].

The attention in this paper, however, is not on the establishment of a single product's or a single company's reclamation facility, but on a facility where a broader spectrum of products can be reclaimed for reuse and recycling. The efficiency gained would also result in a considerably higher revenue. A system of different incoming products from a variety of manufacturers is called a *multi-product/multi-manufacturer environment*. Veerakamolmal and Gupta [10] proposed a reclamation system that integrates collection, distribution, disassembly, and incineration (or landfilling) processes in one domain, called an *Integrated Component Recovery System (ICRS)*. It is particularly desirable to have collaboration among various domains to enjoy the high economy of scale. In order to support the collaboration, a suitable methodology is required to handle the irregularity in the arrival schedules, incoming batch sizes, and large variety of products from a multi-product/multi-manufacturer environment [11]. Moreover, it has to be able to keep up with the rapidly changing product models. Hence, the objective is to design an agile, yet robust system that allows a reclamation facility to operate with profitability and environmentally conscious goals in mind.

To afford such a magnitude of agility, the ICRS needs to be equipped with a computer-aided process planning system to assist in the preparation of the disassembly process. Zeid et al. [13] proposed a framework for applying case-based reasoning (CBR) in disassembly process planning. Employing CBR to solve planning for disassembly in an ICRS's multi-product/multi-manufacturer environment brings several advantages to the system. CBR allows a planner to recall and reuse known good plans that have been successfully used in the past [2]. The planner can also adapt an original plan for a new product that does not have an existing plan in case memory. The basic concepts of CBR include the ability to use old disassembly plans to explain new solutions, to critique new solutions, or to create an equitable solution to a new problem [5]. Three crucial requirements that contribute to a successful implementation of CBR are,

1. Identifying a relevant previous experience,
2. Determining what changes and what stays the same, and
3. Validating, classifying and storing successful case(s) for the future.

The purpose of this paper is to show that, with proper modeling of the system's schema and data abstraction, CBR is the solution to solving the multi-product/multi-manufacturer disassembly process planning problem.

PLANNING FOR NEW CASES BASED ON PRODUCT PLATFORMS

In general, a reclamation process starts with disassembly, retrieval, and restoration—all of which require careful planing [4]. Since every product must first be disassembled, a process planner has to apply different planning strategies for different product platforms to ensure efficiency. Today's manufacturing paradigm is moving towards the product platform concept which stresses on planning and managing of products on the bases of product families—that is, sets of products that share common technologies [7]. This section introduces three strategies to produce a disassembly process plan (DPP) using the CBR technique, based on the concept of product platforms.

1. Platform Interchangeability

Components interchangeability is very common in companies that manufacture assemble-to-order or make-to-order products. This allows a large number of possible configurations in today's products. For example, Toshiba designed a computer notebook (Tecra 8000) that has one thousand, nine hundred and forty-four possible hardware configurations just from interchanging the options (as listed in Table 1).

Although, it may seem very complex due to the number of combinations, one main advantage of utilizing a product platform concept is that the product structure can be standardized. That is, the Tecra 8000 platform is comprised of a standard array of components (viz., motherboard, chipset, memory subsystem, system BIOS, graphic controller and audio/video controller) that make up its kernel structure. Products' structures remain the same even though some components may change. This situation can be easily accommodated in CBR.

Table 1. An example of components interchangability in a Toshiba notebook computer.

Attribute	*Options*
Intel Pentium II Processors [MHz]	233, 266, or 300
TFT Active-Matrix Color Displays [inches]	12.1, 13.3, or 14.1
Hard Drives (HDD) [Gbytes]	4.0, 6.4, or 8.1
Memory [MB]	32, 64, 96, 128, 160, or 256
Modular Bay Options	Floppy diskette drive (FDD), CD-ROM, DVD-ROM, Secondary HDD,
Modem	K56flex with DSVD or Nothing

2. Platform Expandability

Upgrading a product usually involves adding new components from the original equipment manufacturer (OEM) or third-party manufacturers. Adding more components to a product may change its structure and hence the disassembly sequence. This is common in the computer industry where multiple manufacturers can provide components that are compatible with one another. In such cases, we may have to make minor additions to the products' structural layouts before using them. Evidently, with the underlining consistency in the platform, every product's structure across the platform will have a lot of overlapping features. This is also true in mass customization of a product platform. CBR takes advantage of the overlapping features and the set of previously solved problems to develop solutions for the new product structures.

3. Multiple Platforms Integration

Many products are designed by combining two or more platforms, e.g., computer and monitor into a notebook, or a TV and a VCR into a hybrid TV/VCR. Integration of multiple platforms may not require an extensive adjustment to the existing plans (assuming all individual platform plans are already in the case memory). While, in the hybrid TV/VCR case, if the product is highly modularized, a planner may easily combine existing disassembly plans together to create a new one [1], products in multiple platforms integration may require slightly more effort for adaptation. In sum, with a CBR system, the planner does not have to spend as much time to create a DPP as he would have to, if he were to create it from scratch.

CASE MEMORY INITIALIZATION

Initialization of case memory is needed to establish and represent the contents of each case. The organization of the set of cases in case memory provides mechanisms for locating one case or a part of a case in case memory. The cases may be clustered or accessed by common attributes. As case memory becomes very large, the need for an organized structure becomes more important. The procedure to organize the structure of a case memory consists of two principles—generalization and classification.

Generalization

The purpose of generalization is to list a general set of attributes that can precisely describe a product. The attributes are represented in the form of a Disassembly Tree (DT). A DT is used to model a product's structural layout and to automatically generate an optimized DPP. A benefit of the DT representation is that it has a functionality for modeling, storing, and adapting a product's structure for CBR. Furthermore, a single DT can be responsible for generating a whole family of disassembly solutions for a particular product platform. The process of using a DT to generate new solutions may require the *decomposition* and *integration* of two or more DT structures. Often, a plan may be called upon to be a part of a bigger product model. In such scenario, the plan behaves as a partial module among a group of other modules. The process of breaking up the product into modules is called decomposition [6]. An integration procedure is required in order to merge all the partial DPPs for the modules to create a final plan [1]. A DT schema allows a plan to be stored in a general form because the individual component/sub-component relationships allow for a quick integration of modules.

Classification

Case memory needs to include knowledge for distinguishing the classes of products. CBR makes extensive use of the case classification scheme to initialize, append or retrieve the product's data from the case memory. To accommodate the representation for the multi-product/multi-manufacturer environment, we use a *Product Platform Classification* methodology. This classification is based on the fact that the data of products can be hierarchically categorized and divided into classes and subclasses. Just as computers are broken down into sub-categories (e.g. mainframes, workstations, PCs, and notebooks), companies break down their product lines into different platforms. Classifying products hierarchically by their platforms is actually similar to keeping a product catalog and maintaining their corresponding DPPs.

To establish a product platform in a case memory, a *base case*, that will serve as a prototype for future cases, will have to be created. Often, a base case can be used as is, but it also can be adapted to fit a new product profile when necessary. The adapted case is called a *derived case*. The process, called *inheritance*, assigns the base case's attributes and a reference pointer, and prepares for an adaptation process that may assign new values to the existing attributes (such as, a different speed in the computer example) [6].

Initialization Procedure

CBR must first be initialized with case prototypes in order for it to accept new cases to the case memory. The seven essential steps in the initialization process are explained below:

Step 1: List all components together with their precedence relationships and disassembly times (this step requires the use of either an available bill of materials (BOM) or one obtained by means of reverse engineering).

Step 2: Generalize the product structure by annotating each node and formulating a Disassembly Tree (DT).

Step 3: Modularize the DT by clustering subassembly nodes using the ***Modularity Transformation Rule*** (refer to the Appendix section) into *component modules* (*CM*), *subassembly modules* (*SM*), and/or *complex modules* (*PM*). Assign a number to each module in ascending order (starting from zero; assigned to the product module itself).

Step 4: Use the data generated in *Step* 3 to update the DT data.

Step 5: Generate a disassembly process plan (for details, please refer to Veerakamolmal and Gupta [9]), and list the sequence of disassembly. Calculate the total processing time.

Step 6: Classify the products in the case memory by dividing the products into strategic platforms, e.g. computer, monitor, etc. Each platform will store a base (prototype) case of the product's DT and DPP.

Step 7: Store the corresponding case in the case memory. Organize the prepared DT, DPP, and the product specific characteristics for storage. Prepare data representation scheme that is consistent with the classification, e.g., case description, case property, attribute, base case, and operation (Figure 1).

Case Description - Unique name for the case. Case Property (base/derived case) - A base case is the prototype of all the cases in the platform.
Attribute - Corresponding disassembly tree and an array of case characteristics. Base Case - The derived case's parent. For product initialization, the base case remains NULL.
Operation - A DPP that contains the corresponding disassembly sequence to the DT attribute.

Figure 1. A representation of a case.

An Application of the Initialization Procedure

Consider a product composed of five subassembly modules and eight components. The following steps demonstrate the initialization procedure of the case-based system..

Step 1: List all components by their component IDs, predecessor IDs, and disassembly times (columns (A) through (C) in Table 2). For each component in column A, list its successors (column (D)).

Table 2. DT Data in Case Memory.

(A)	(B)	(C)	(D)	(E)
Component ID	Predecessor ID	Disassembly Time	List of Successors	Node Anotation
0201-S0000	-	1	0201-S0001, 0201-S0002	A0
0201-S0001	0201-S0000	3	0201-P0001, 0201-P0002	A1
0201-S0002	0201-S0000	2	0201-S0003, 0201-S0004, 0201-S0005	A2
0201-S0003	0201-S0002	3	0201-P0003, 0201-P0004	A3
0201-S0004	0201-S0002	4	0201-P0005, 0201-P0006	A4
0201-S0005	0201-S0002	2	0201-P0007, 0201-P0008	A5
0201-P0001	0201-S0001	3	-	P1
0201-P0002	0201-S0001	1	-	P2
0201-P0003	0201-S0003	1	-	P3
0201-P0004	0201-S0003	3	-	P4
0201-P0005	0201-S0004	1	-	P5
0201-P0006	0201-S0004	2	-	P6
0201-P0007	0201-S0005	1	-	P7
0201-P0008	0201-S0005	2	-	P8

Step 2: To generalize each component as a node, annotate the root node (the node with no predecessor) as A_0, the subassembly nodes (the nodes with at least one successor) as A_1, A_2, ..., A_5, and component nodes (nodes without any successor) as P_1, P_2, ..., P_8 (column (E) in Table 2). Use the nodes and their precedence relationships to formulate a DT as shown in Figure 2a.

Step 3: The DT in Figure 2a is modularized as follows. The root node (A_0) has two successors, viz., A_1 and A_2. Since both its successors are subassembly nodes, A_0 is a *subassembly module*. Next, since subassembly A_1 is composed of two component nodes (P_1 and P_2), it is a *component module*. Subassembly A_2 has three successors (A_3, A_4 and A_5) which are all subassembly nodes, so it is a *subassembly module*. Finally, subassemblies A_3, A_4, and A_5 are *component modules*. Given that $s[n]$ denotes "module n", A_0 is assigned the number $s[0]$, and the modules stemming from A_1, A_2, ..., A_5 are assigned the numbers $s[1]$, $s[2]$, ..., $s[5]$ respectively (see Figure 2b).

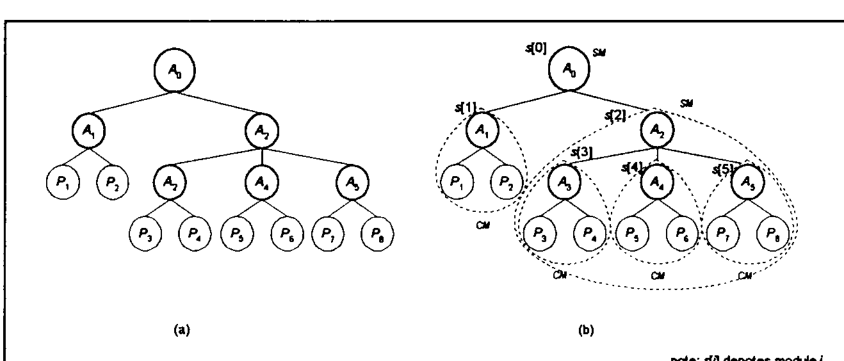

Figure 2. DT generalization and its modularity.

Step 4: Use the information from *Step 3* to add columns (F) and (G) in Table 2 as shown in Table 3.

Table 3. DT Data in Case Memory.

(A) Component ID	(B) Predecessor	...	(E) Node Anotation	(F) Module Type	(G) Module ID
0201-S0000	-	...	A0	SM	s[0]
0201-S0001	0201-S0000	...	A1	CM	s[1]
0201-S0002	0201-S0000	...	A2	SM	s[2]
0201-S0003	0201-S0002	...	A3	CM	s[3]
0201-S0004	0201-S0002	...	A4	CM	s[4]
0201-S0005	0201-S0002	...	A5	CM	s[5]
0201-P0001	0201-S0001	...	P1	-	-
0201-P0002	0201-S0001	...	P2	-	-
0201-P0003	0201-S0003	...	P3	-	-
0201-P0004	0201-S0003	...	P4	-	-
0201-P0005	0201-S0004	...	P5	-	-
0201-P0006	0201-S0004	...	P6	-	-
0201-P0007	0201-S0005	...	P7	-	-
0201-P0008	0201-S0005	...	P8	-	-

***Step 5*:** Generate a disassembly process plan [9]. The product's DPP can be generated as shown in Figure 3. The DPP's sequence is: modules 0 → 1→ 5 → 3 → 4, with a total processing time of 18 units.

Sequence ID	Module ID	Component ID	Desm Time	Rtrv Time	Desm STime	Desm ETime	Rtrv Stime	Rtrv Etime
1	s[0]	0201-S0000	1	0	0	1	1	1
2	s[1]	0201-S0001	3	4	1	4	4	8
3	s[2]	0201-S0002	2	0	4	6	8	8
4	s[5]	0201-S0005	2	3	6	8	8	11
5	s[3]	0201-S0003	3	4	8	11	11	15
6	s[4]	0201-S0004	4	3	11	15	15	18

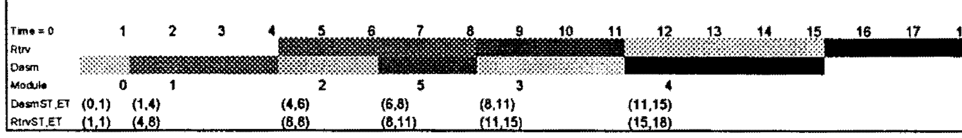

Figure 3. Disassembly Process Plan (DPP).

***Step 6*:** Classify the products into different platforms. Presuming that the CBR system is designed to assist in the reclamation of computer components, the product platforms, for example, can be divided into: mouse, computer, keyboard, and monitor (Figure 4). Later on, when the base platforms have been established, a process planner can further expand the platform as demonstrated in the "Platform Expansion" box.

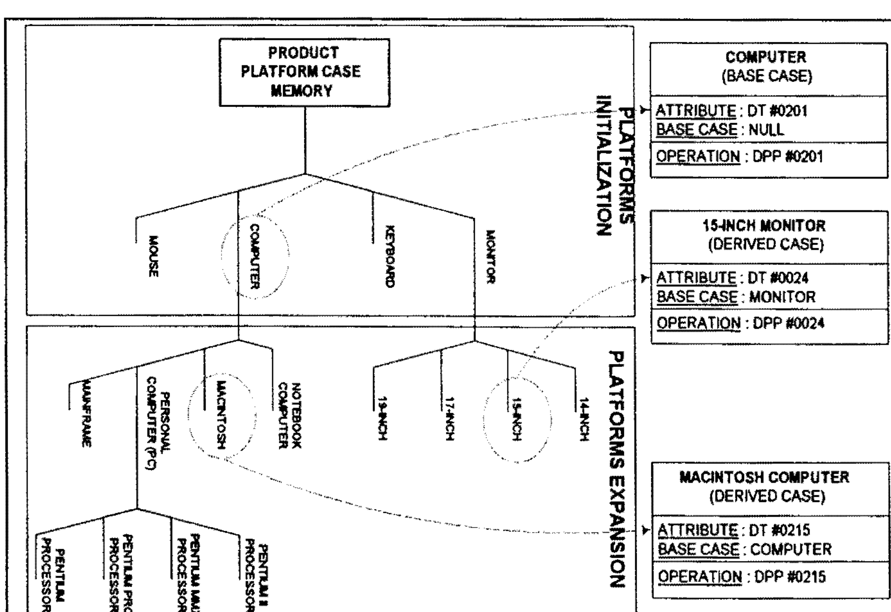

Figure 4. Case Memory.

Step 7: To complete the initialization process, the product's data must be prepared and stored in the case memory. Organize the prepared DT and DPP, and other case specific characteristics for storing in the case memory.

CBR SOLUTION

There are five essential steps in CBR (Figure 5).

- **Mapping**. Recalling a case from case memory is a pattern-matching problem that is based on the specification of a new problem.
- **Retrieval**. The retrieval task in CBR searches case memory for matches between individual cases and the pattern that serves to index the cases. Retrieval can be based on a perfect match, where the pattern is found exactly, or on partial matches.
- **Adaptation**. This function is responsible for applying the case solution from a retrieved problem to the problem at hand. In some problems, a selected case provides a solution to the new problem. In most problem solving, however, the selected case needs to be modified to be appropriate as a solution to the new problem.
- **Revision**. This is the actual running of the adapted plan against the problem. Zeid et al. [13] suggest that a revision process can be modeled as a sequence of transitions from an initial or existing state of DPP, to its final state.
- **Storage**. This is concerned with adding and organizing the readjusted plan to the case memory. Whenever a new plan is introduced to the case memory, a storing procedure is activated.

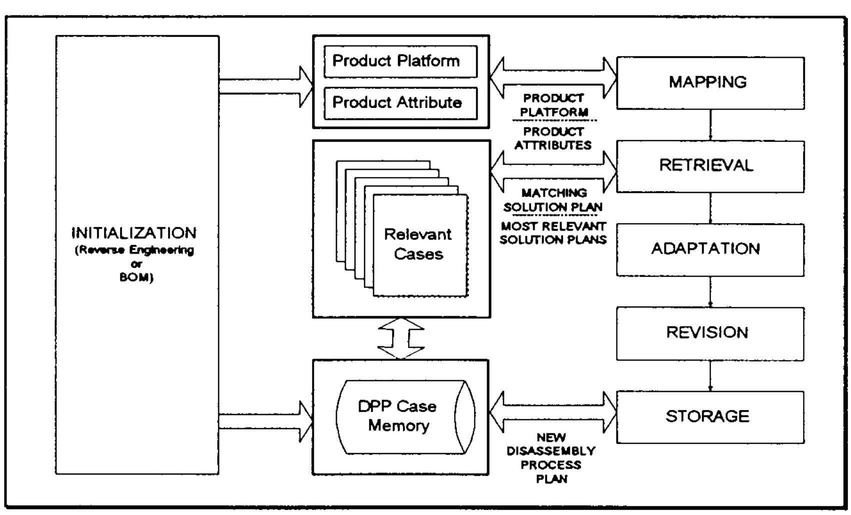

Figure 5. Procedure in CBR.

Solution Procedure

Given that we have an initialized CBR, the steps to map, retrieve, adapt, revise and store the solution to the new case problem are as follows:

Step 1: **Map** the new case specifications (such as product platform, name, or model number) and conduct the *Product Platform* search. If the exact product model is found, retrieve the case from case memory and use the DPP as is, else, search to find similar cases or sub-cases on the same platform.

Step 2: **Retrieve** the most relevant cases by determining how close each case matches the new product specification; and select the most relevant case(s).

Step 3: **Adapt** the retrieved case's DT to current product's DT, determine how close the DT structure matches the new product's specification, and make appropriate adaptation to the DT. Update process attributes of the DT nodes and employ the optimization algorithm to generate a new sequence for DPP.

Step 4: **Revise** the new DPP to make sure that the process has been carried out successfully. If there are any difficulties encountered or remarks to be made, they need to be noted (e.g. a product may contain hazardous components).

Step 5: **Store** the satisfactory solution into the case memory. Update the product platform and the product attribute representation mapping tables.

An Application of the Solution Procedure

This is a simple application of CBR on a product designed with multiple platforms integration. Suppose that product K enters a CBR equipped reclamation station. The product is composed of three electronic modules. Assume that each module exists as one individual product stored in the case memory. The objective in this example is to find an optimal process plan for product K.

Step 1: Map the product description to the case description. Assume that product K has never entered the reclamation facility before. After a preliminarily inspection, a process planner finds that the product's descriptions match the combination of products A, B, and C, which already exist in the case memory.

Step 2: Retrieve the relevant cases. Figure 6 shows the product structure attributes (DT) and operations (DPP) of products A, B, and C.

Integrated Component Recovery System Case Memory (ICRS-CM)

Case Description: A
Case Property: BASE CAS
Attribute: DT #1111

Component ID	Predecessor ID	Disassembly Time	Module ID
1111-S0000	-	3	s[0]
1111-S0001	1111-S0000	2	s[1]
1111-S0002	1111-S0001	3	s[2]
1111-S0003	1111-S0001	2	s[3]
1111-S0004	1111-S0001	4	s[4]
1111-P0001	1111-S0000	2	-
1111-P0002	1111-S0002	1	-
1111-P0003	1111-S0002	3	-
1111-P0004	1111-S0003	1	-
1111-P0005	1111-S0003	2	-
1111-P0006	1111-S0004	1	-
1111-P0007	1111-S0004	3	-

Operation: DPP #1111

Sequence ID	Module ID	Processing Time
1	s[0]	17
2	s[1]	
3	s[3]	
4	s[2]	
5	s[4]	

Case Description: B
Case Property: BASE CASE
Attribute: DT #1112

Component ID	Predecessor ID	Disassembly Time	Module ID
1112S0000	-	2	s[0]
1112S0001	1112S0000	3	s[1]
1112S0002	1112S0000	4	s[2]
1112S0003	1112S0000	2	s[3]
1112P0001	1112S0001	1	-
1112P0002	1112S0001	3	-
1112P0003	1112S0002	1	-
1112P0004	1112S0002	2	-
1112P0005	1112S0003	1	-
1112P0006	1112S0003	2	-

Operation: DPP #1112

Sequence ID	Module ID	Processing Time
1	s[0]	14
2	s[3]	
3	s[1]	
4	s[2]	

Case Description: C
Case Property: BASE CAS
Attribute: DT #1113

Component ID	Predecessor ID	Disassembly Time	Module ID
1113S0000	-	2	s[0]
1113S0001	1113S0000	3	s[1]
1113S0002	1113S0001	3	s[2]
1113P0001	1113S0000	3	-
1113P0002	1113S0000	2	-
1113P0003	1113S0001	1	-
1113P0004	1113S0001	2	-
1113P0005	1113S0002	1	-
1113P0006	1113S0002	1	-

Operation: DPP #1113

Sequence ID	Module ID	Processing Time
1	s[0]	12
2	s[1]	
3	s[2]	

Figure 6. Case Solutions for Products A, B, and C.

For example, product A, which is represented by DT #1111, is composed of four subassembly modules and seven parts. Module -*S*0001 and component -*P*0001 are connected to the *Root* node. Modules -*S*0002, -*S*0003, and -*S*0004 are directly connected to module -*S*0001. Components -*P*0002 and -*P*0003 are connected to module -*S*0002; -*P*0004 and -*P*0005 to -*S*0003; and -*P*0006 and -*P*0007 to -*S*0004 respectively. Product A's DPP is sequenced in the order of modules 0 → 1 → 3 → 2 → 4 (shown at the bottom-most section of Figure 6).

Step 3: Adapt the retrieved DTs to the current product's DT. Using the algorithm presented by Veerakamolmal and Gupta [11], we optimize the process plan for the new product. The algorithm uses the components' modularity and precedent relationships to sequence the steps of disassembly. The optimal disassembly process sequence turns out to be C → A → B. Thus, the algorithm suggests to disassemble C completely, then A and finally B. The total disassembly time is 36 time units [11].

Step 4: Revise the new DPP. Since the process plan has already been optimized, further revision is not required (unless some problems occur at the disassembly line).

Step 5: Store the new case in the case memory. Since product K is a derived case that inherits products A, B, and C's attributes (multiple inheritance), a new platform can be created as a subset of an existing platform (Figure 7). That is, a process planner may decide that product K's general functions are similar to that of product A and assign it as a subset of product A's platform (largely depends on future ease-of-retrieval).

Case Description - K Case Property - DERIVED CASE
Attribute - DT #0216 Base Case - A, B, C
Operation - DT #0216

Figure 7. Case representation of product K.

As demonstrated in this example, we can generalize the three products' structures, with the DT schema, and store them in a modular format. Solving a DPP of the new product can be easily accomplished by integrating the three DTs and, hence, the DPPs.

CONCLUSIONS

This paper addresses the importance of planning for disassembly as a response to recent regulatory trend and increased consumers' environmental awareness. The principle of CBR for disassembly process planning is based on reusing previously successful implementation of DPP to solve new disassembly problems. To work efficiently, a CBR has to be designed with generalization, as well as classification capabilities in order to work in a multi-product/multi-manufacturer disassembly environment. Generalization is a process that incorporates a product's structure into a DT format and its operational sequence (DPP). Classification allows CBR to distinguish between different classes of DTs and DPPs.

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APPENDIX

Disassembly Tree (DT) is a hierarchical representation of the "predecessor-successor" relationships. The DT is made up of a number of modules. Each module can be broken-down until it reaches an "atomic" level composing of individual component units (i.e., root, subassembly, and component nodes). In Figure 8, for instance, A_0 is the root node, A_1 is a subassembly node, and P_1, P_2, P_3 are component nodes.

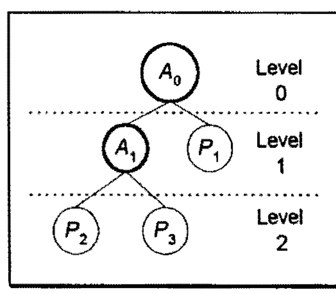

Figure 8. A Graphical Representation of a Product Structure.

The levels within a DT are composed of modular structures which can be divided into a component module, a subassembly module, or a complex module (Figure 9). A *component module* (*CM*) is a module at bottom-most level of the tree that consists only of basic component nodes. On the contrary, a *subassembly module* (*SM*) is a module that has other modules, but no component, as its successors. A *complex module* (*PM*) consists of both component and subassembly modules as its successors.

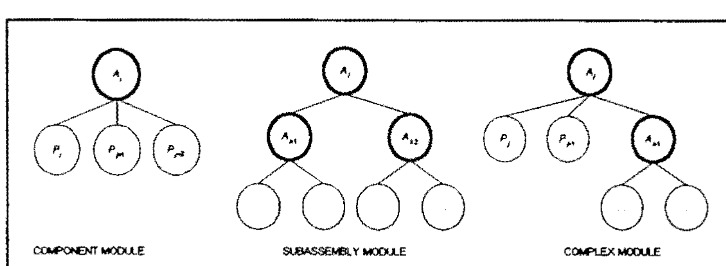

Figure 9. Classes of Modules.

The following ***Modularity Transformation Rule*** can be used to distinguish the types of module:

If <node> a root or a subassembly node
then {
    If <node> has successors in which all are subassembly nodes
    then <node> => *Subassembly Module*

    If <node> has successors in which all are component nodes
    then <node> => *Component Module*

    else <node> => *Complex Module*}

SYSTEMATIC PLANNING OF DISASSEMBLY WITH GROUPING AND SIMULATION

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Keywords: Disassembly, Disassembly Planning, Electrical Scrap, Grouping, Simulation

Abstract

Disassembly of worn-out electrical and electronic devices performed nowadays is costly and hence not attractive. This is mainly caused by the complexity and the large number of variants of the devices that have to been dismantled at the one hand and the lack of comprehensive tools to support systematic planning of disassembly systems at the other hand. This paper introduces a methodology that may support systematic planning disassembly. A few techniques, including grouping of electrical and electronic devices or simulation of disassembly processes and layouts, are outlined. These methods base on the specific characteristics of the devices, their dismantling behavior as well as boundary conditions.

Introduction

Recycling of worn-out electrical and electronic devices („electrical scrap") such as TV-sets, microwave-ovens or fax-machines, is combined with disassembly. But, disassembly performed nowadays is costly and ineffective. Two main reasons can be identified for this inefficiency: the complex boundary conditions given by the appliances, and the lack of qualified tools for systematic planning.

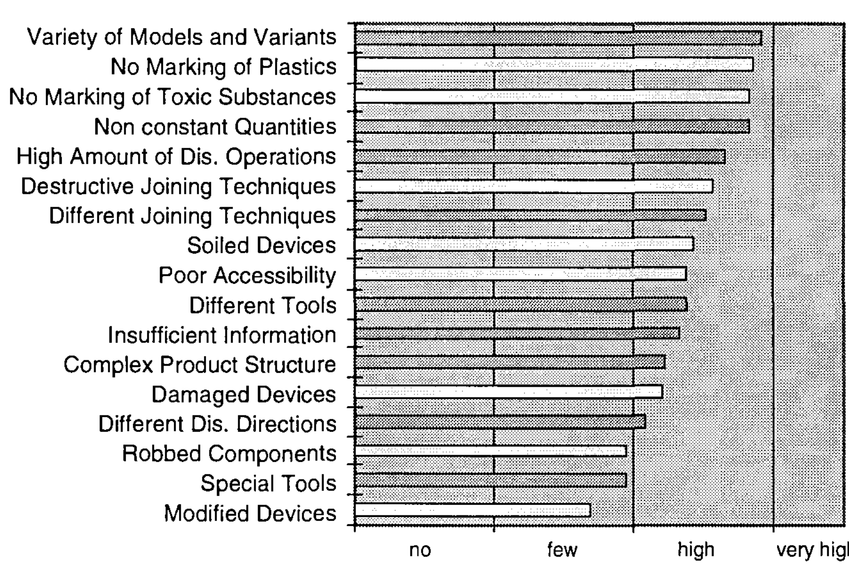


Fig. 1: Problem Fields of Dismantling [Hesselbach 1998]

Fig. 1 shows the results of a survey at 100 disassembly and recycling companies in Germany in the year 1997. Main problems in dismantling electrical scrap are caused by the variety of different models and variants from various producers and production-years. Also the share and the return of different kinds and sorts of devices among the electrical scrap varies and can not be predicted exactly. Other problems refer to the large amount of dismantling operations and the quantity of different joining-techniques that require specific tools for dismantling. Also the complex structure of products makes dismantling more difficult and time-intensive.

For this reasons, disassembly is often performed in a manual manner nowadays. The level of organization is comparatively low. Dismantling operations are performed mainly at single working places. Any kind of linkage of working places with separation of the different dismantling processes is rare. Often the specific equipment at places concerning boxes for fractions or dismantling tools is not planned exactly. By this, material flows are complex and thus, the whole disassembly process is not transparent. Due to the performance of the complete disassembly at one place also the potential of using learning-effects is minimized when the worker has to perform a large variety of disassembly operations.

To make disassembly of electrical scrap more efficient and to increase the share of recycling, the following essential objectives are given:
- to increase the transparency of disassembly processes,
- to structure and to standardize dismantling operations,
- to optimize the use of resources and
- to ease material flows.

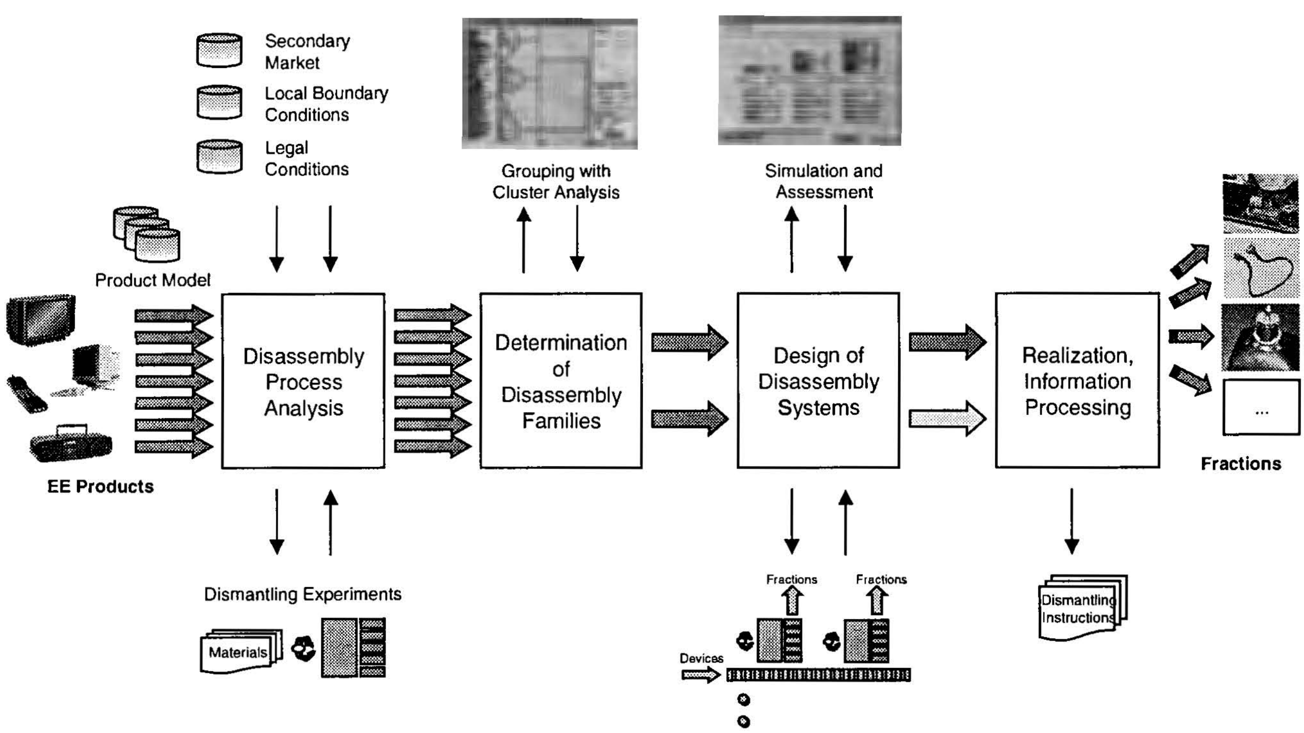


Fig. 2: Methodology of Systematic Disassembly Planning

In order to fulfill these aims, an integrated approach is necessary which supports all stages of planning disassembly systems. Systematic disassembly planning should start with product and process analysis and end with structuring and dimensioning the disassembly system.

Methodology of Systematic Disassembly Planning

Fig. 2 shows the proposed methodology for systematic disassembly planning. This methodology is be subdivided into four phases:

- Disassembly Process Analysis,
- Determination of Disassembly Families with Group Technology,
- Design of Disassembly Systems with Simulation,
- Realization and Dismantling Information Processing.

The disassembly process analysis in the first phase calculates the dismantling criteria of a given spectrum of electrical scrap. This analysis is based on relevant product information that are represented in the product model as well as on data about the boundary conditions, as information about the secondary market (e.g. proceeds of fractions), the local boundary conditions of the disassembly company (e.g. dismantling resources) and the legal conditions (regulation of hazardous materials) [Hesselbach 1996]. The results of this analysis allow an estimation of the dismantling expenditure of the actual spectrum of devices. Fig. 3 presents exemplary the criteria *kind of dismantling tools* and *average tool time*. This results are essential to calculate the capacity utilization of tools and thus, the use of resources.

Aspect	Criterion
Dismantling Process	Disassembly Sequence
	Kind of Dismantling Tools
	Average Tool Time
	Standard Deviation Time
	...
Dismantling Complexity	Amount of Dismantling Operations
	Amount of different Tools
	Quantity of Tool Changes
	...
Material Flow	Amount of different Fractions
	Weight of Fractions
	...

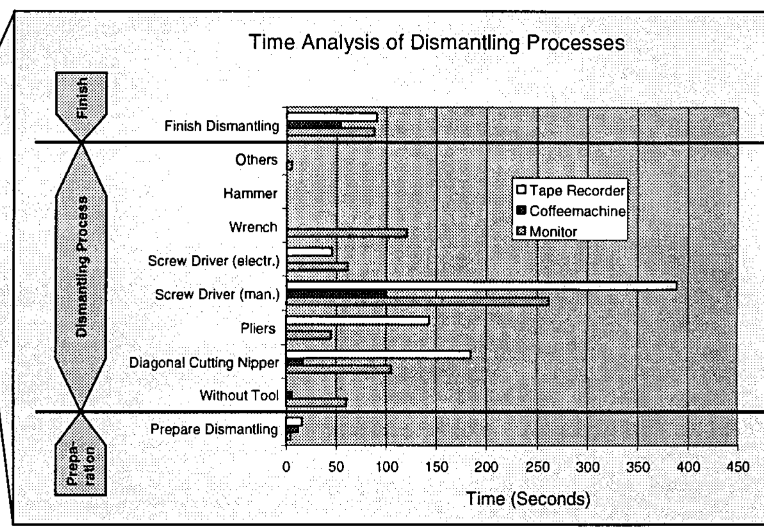


Fig. 3: Dismantling Criteria (Selection)

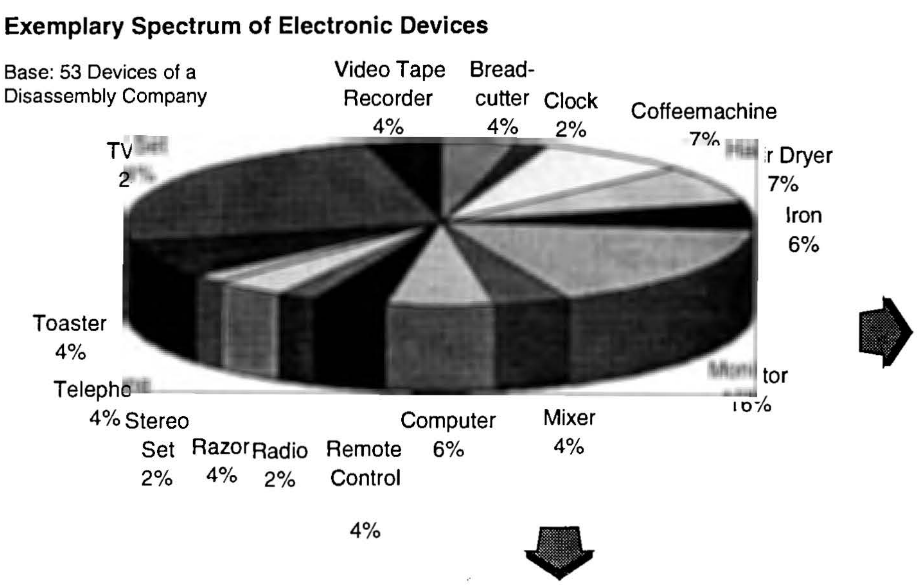
All results of the disassembly process analysis serve as input for the next phase, the definition of disassembly families with group technology. Group technology is an approach to reduce the effects of a heterogeneous spectrum of products by using their common characteristics. Processing families with similar, homogenous products save resources and, finally, costs [Hesselbach 1997; Seliger 1996].

Determination of Disassembly Families

In the introduced methodology of systematic planning, grouping of electrical scrap is done with hierarchical cluster analysis. Cluster analysis allows to take several attributes of the devices into consideration at the same time. In a first stage, for each attribute the distances between all devices have to be calculated using specific distance functions. The Euclidean Distance was turned out to produce usable results. After that, these distance matrices for each criterion are summarized up to one complete distance matrix.

In the following stages, the devices are classified into groups successively such that the distance between two devices of one group is small. After grouping two devices, cluster algorithms calculate the new distances between the combined devices and all other ones. Several algorithms like *Single Linkage* or *Ward* were examined [Miyamoto 1990; Steinhausen, 1977]. The approaches of *Ward, Average Linkage and Weighted Linkage* were identified as suitable for grouping electrical and electronic devices.

The advantage of using hierarchical cluster analysis is that the optimal number of groups do not has be fixed in advance. This number can not be determined before grouping because of the complicate characteristics and the heterogeneity of the electrical scrap. The optimal number of devices can be determined after grouping with the use of a dendrogram.



Results of Classification	
Family 1	Monitor TV- Set
Family 2	Computer Radio Stereo Set Video Tape Recorder
Family 3	Breadcutter Clock Coffeemachine Hair Dryer Iron Mixer Remonte Control Razor Telephone Toaster

Criteria of Classification								
Family	Devices / Group	Average Amount of Components	Average Amount of Fractions	Average Weight of Devices (g)	Average Disassembly Time (s)	Average Tool Time per Tool (s)	Quantity of Tool Changes	...
1	22	20	7.4	15800	446	39	43	...
2	16	18	5.1	3765	213	27	27	...
3	15	13	5.2	1211	166	14	21	...

Fig. 4: Definition of Disassembly Families

In experiments performed at a small-sized disassembly company the actual spectrum of electrical scrap was analyzed during a fixed period of time. The share of devices was comparatively heterogenous. After examination of the dismantling characteristics, the spectrum was analyzed with cluster algorithms to figure out significant disassembly families. The experiments have shown that the given spectrum of devices could be classified into three families to create groups of relatively homogenous objects as given in Fig. 4.

The upper family contains only two kinds of electronic devices: TV-sets and monitors. Regarding the criteria results of classification, the differences of these devices to the other families is obvious. The average disassembly time is normally two times higher than the dismantling time of other ones. Also the average quantity of necessary tool changes and the average process times of the tools are clearly higher. Family three contains small and easy to handle devices (domestic household appliances like coffee machines, irons, ...) that can to be dismantled quickly with standard tools. The dismantling process is relatively different compared with the dismantling process of family one.

Comparing these two families, it becomes obvious that the specific requirements on the disassembly system depend on the characteristics of such a family.

The identification of the optimal layout and dimension of the disassembly system is a difficult task in consideration of the complex boundary conditions and the dynamic character of the dismantling processes. Simulation is a suitable approach to compare different variants of a complicated system and to optimize a system step by step. For these reasons, simulation of dismantling processes is integrated into the third phase of the presented methodology [Hesselbach 1999].

Simulation of Dismantling Processes

Main layout alternatives for disassembly systems are single working places, disassembly lines and disassembly circles. Single working places with a concentration of all dismantling operations at one place are widespread in disassembly companies with a share of 65% [Hesselbach 1998]. Disassembly lines and circles are used only to a small extent. To analyze the material flow in disassembly systems, different dismantling scenarios were simulated and analyzed to figure out the optimal layout and dimension for processing the presented spectrum of devices.

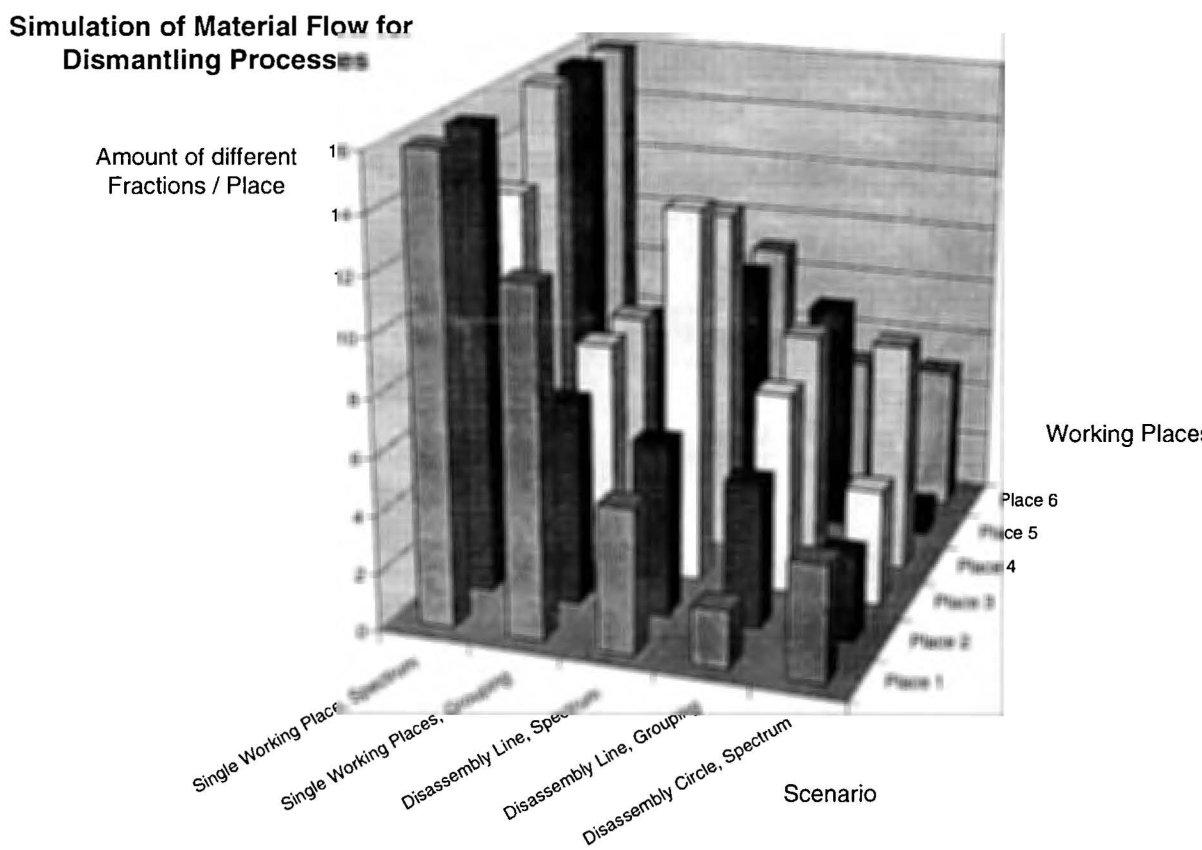


Fig. 5: Simulation of Material Flow in Disassembly Systems

The layout alternatives include single working places, a disassembly line and a disassembly circle with six places each. A scenario describes the specific charge of devices referring to a layout alternative. In the first scenario (*Single Working Place, Spectrum),* all devices of the spectrum can be dismantled at any working place. In this manner, all possible fractions appear at each place. This may complicate the material flow and decrease the transparency of disassembly. In the second scenario, single places were equipped to process only one specific family of devices. The share of fraction per place could be reduced distinct. The next two scenarios describe the dismantling process of a disassembly line for both the complete spectrum and specific families of devices. It is obvious that the share of fractions per place can be reduced very clearly if only a homogenous spectrum of devices will be processed. In this manner, the reduction of the extent of dismantling operations may ease to a clearly arranged material flow.

Next to the material flow mentioned above, other important criteria have to been taken into consideration when designing disassembly systems. To this criteria belong:
- the balance of the system,
- the share of auxiliary process time for dismantling operations or
- the rate of capacity utilization of the resources.

Conclusion and Outlook

On account of the difficulties to describe such disassembly systems with available simulation tools and to allow an user-friendly usage of the presented methodology, the IWF is developing a computer-based disassembly planning tool. This tool consists of modules referring to the four phases of systematic planning. The so-called tool *LaySiD* (**Lay**out **Si**mulation for **D**isassembly) may help to increase the efficiency in recycling of electrical scrap by presenting detailed information about the dismantling expenditure.

Grouping can help to use learning-effects and to ease the effort for logistics by standardization of dismantling processes. Simulation of dismantling processes may make the effects of processing different sorts of electrical scrap transparent. Several information about the dismantling process are calculated automatically to allow an easy comparison of different layout alternatives.

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Organising for Re-use: The Operations Control Issues in Product Remanufacturing

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Abstract

When a durable product reaches the end of its normal life, it is commonly disposed of as landfill or else is scrapped for recovery of its material. In both of these cases the costs associated with collection and operation of a landfill or the costs of shredding, sorting and melting down the reclaimable materials exceed the direct economic benefits of these operations [1]. Remanufacture is the process of bringing a broken complex assembly (called a "core") to "like-new" functional state by replacing and rebuilding its component parts [3]. Because remanufacturing recovers a substantial fraction of the materials and value added to a product in its first manufacture, and because it can do this at low additional cost, the resulting products can be offered to the user at substantial savings. This paper will clearly define the term "remanufacturing" by differentiating it from alternative green production initiatives. It will present the initial findings of a series of industrial case studies which have recently been undertaken in the UK. The focus of these studies has been primarily to investigate current practices in the UK remanufacturing industry. In so doing the study has sought to establish a blueprint of the remanufacturing approach and also to highlight the main operational issues involved in organising an efficient and effective remanufacturing process.

Introduction

Remanufacturing could be the sleeping giant of the U.K. economy, however this environmentally important industrial activity has largely escaped the attentions of the academic research community. Whilst Lund [2] has attempted to quantify the significant contribution made by remanufacturing to the U.S. economy, in the U.K. the industry's scope and its impact on the national economy have yet to be established. As Lund discovered in the U.S., this is probably because such indicators are masked by the number of firms involved and by the many types of products they produce. Early evidence from research currently being undertaken at the University of Plymouth suggests, however, that it may be a more widespread phenomenon in the U.K. economy and may be making a greater contribution than is realised.

A survey of both the U.K. and international literature has shown that most current remanufacturing research focuses upon its environmental relevance and upon its applicability to product design [3, 5]. There has been little sustained academic research devoted to understanding remanufacture *as a business process* nor have any effective tools and techniques been developed which will enable remanufacturing firms to manage and control such complex and uncertain business operations. Even within the remanufacturing industry, there is confusion regarding the meaning of the term "remanufacturing".
This paper will address the above issues by describing the remanufacturing business

process. It will detail the main operational control issues involved in product remanufacturing and it will present a generic model illustrating the activities that comprise a typical remanufacturing process.

The remanufacture domain

Remanufacture is the process of bringing broken assemblies (called "cores") to a "like-new" functional state by rebuilding and replacing their component parts [3]. The practice is particularly applicable to complex electro-mechanical and mechanical products which have cores that, when recovered, will have value added to them which is high relative both to their market value and to their original cost [4]. The process of remanufacture normally involves the removal by the customer of the used product and its return to a specialised facility for disassembly, salvage or reprocessing and replacement of component materials. The product is then reassembled and tested prior to resale or return to the customer [4].

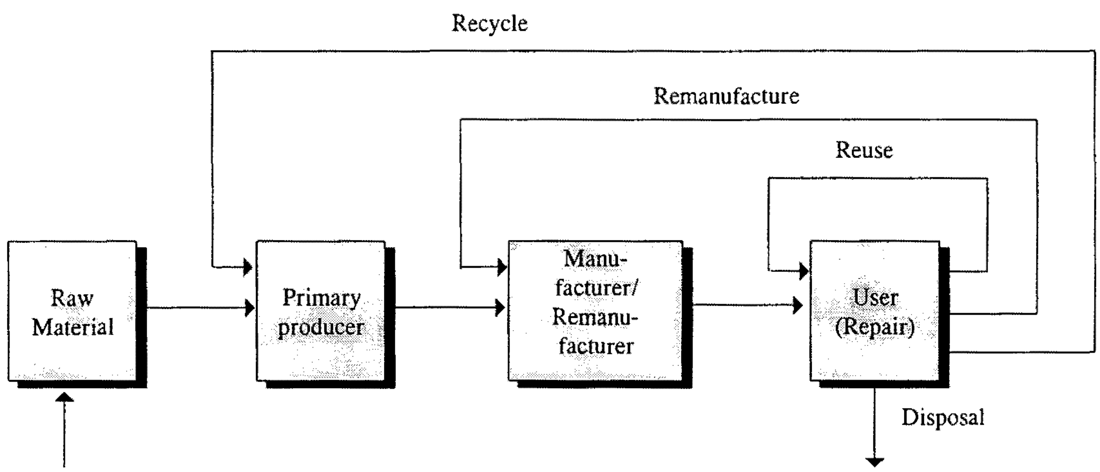


Figure 1. Materials resource system [1]

Within this context, the main problems facing the remanufacturer appear to be associated with high uncertainty and high risk since it is usually impossible to determine in advance the quantity and quality of the incoming products. Remanufacturers also encounter problems related to replacement parts availability, no possibility of adjustment (i.e. tolerances are too tight) and failures which have damaged the interior of the component to the point that replacement of the interior parts would add too much to the cost of the component.

The idea of rebuilding an old machine back to its original specification is not new. What is new, however, is the process whereby an organisation establishes a large-scale operation in order to return to "as new" condition products which it did not originally manufacture. Remanufacture differs from repair in that all components of the item to be remanufactured are completely re-gauged and brought to the original manufacturer's current specifications. The "new" product will thus be at least equivalent in performance and expected lifespan to the original product. Where repair is concerned, the rebuilt product normally retains its identity, and only those parts that have failed or are badly worn are replaced or serviced.

Remanufacture is being driven by environmental concerns (the need to reduce waste during the material extraction and manufacturing processes), legislation (international agreement to reduce the environmental impact of products and manufacturing processes) and economics (remanufacture is often a quality and cost effective option [3]). Figure 1 depicts a hierarchy of five alternatives for a product after its first use in terms of the costs of maintaining or retrieving economic value in the product. The alternatives depicted are: repair, reuse, remanufacture, recycle and disposal. Table 1 defines the various "green" production approaches currently being used in industry. These have been adapted from Amezquita et al, 1997 [3].

Table 1: Process Definitions

Process	Definitions
Remanufacture	Process of bringing an assembly to like-new condition through replacing and rebuilding component parts at least to current specification.
Reuse	Process of using a functional component from a retired assembly.
Repair	Process of bringing damaged components back to a functional condition.
Reconditioning	Process of restoring components to a functional/and or satisfactory state but not above original specification using such methods as resurfacing, repainting, sleeving, etc.
Recycling	Process of taking component material and processing them into the same material or useful degraded material.

From Table 1 it can be seen that remanufacturing is the only process where the worn product is brought back at least to its original specification. Figure 2 depicts a typical remanufacturing process diagram. The importance of quality assurance to successful remanufacture is shown by the dominance of inspection and test procedures in the chart. The remanufacturing process shown can be described as follows:

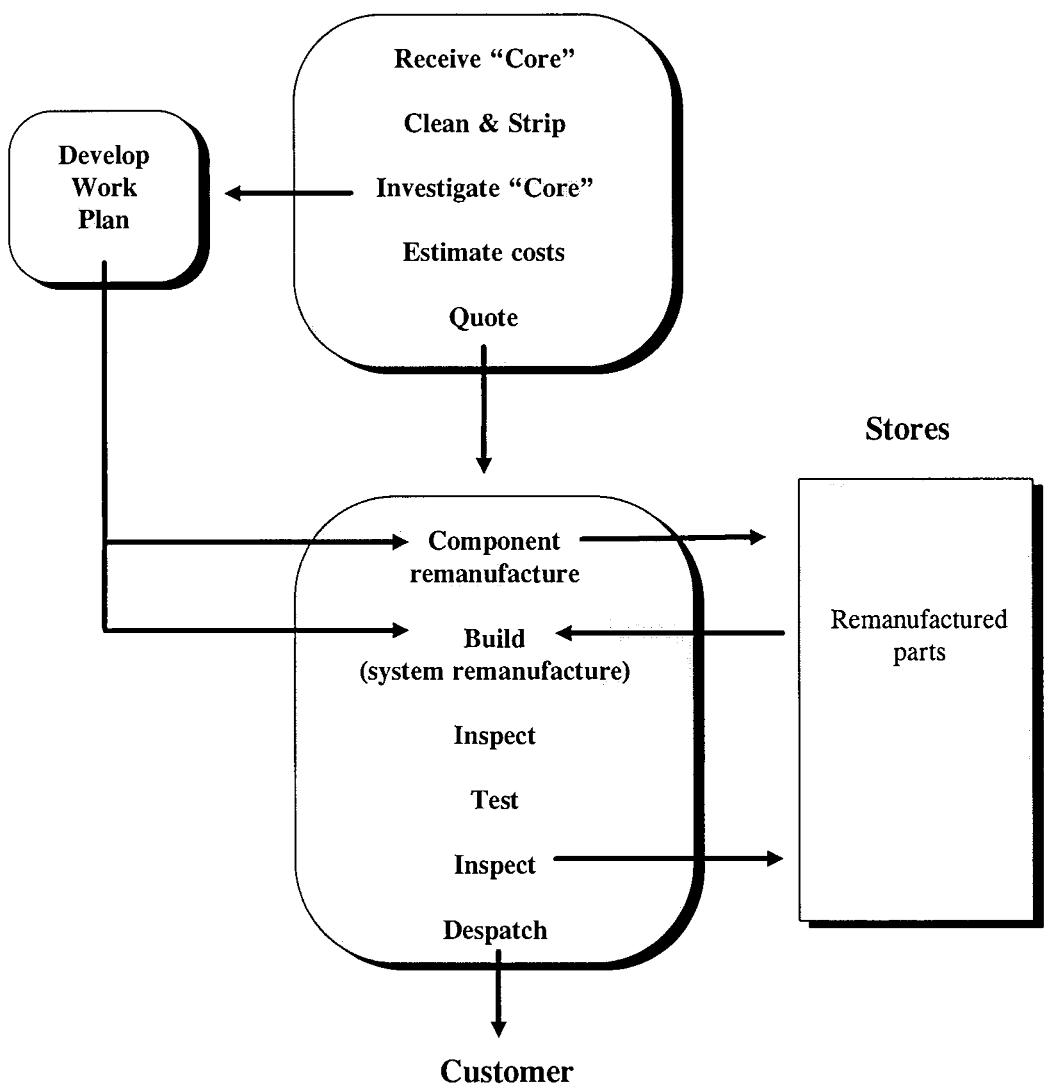
1. *Receive core.* Typically the core undergoes initial cleaning and examination to determine basic information such as its condition, model and year of manufacture [1]. Where the company has access to a sound information system the cores will be tagged for identification and core details will be translated into the company's own nomenclature. This information is entered unto the company database along with customers' stated complaints where such information is available.

2. *Clean and Strip.* The core is then disassembled. With the exception of components which are always discarded (for example, low cost items or items specified in a OEM mandatory replacement list), every component is thoroughly cleaned. During this stage obvious damages and flaws are identified by visual inspection. Parts that survive visual inspection are sorted by part number.

3. *Investigate system and Quote.* All components are evaluated to determine extent of wear and to specify rectification solutions. A parts list is produced detailing the type

and quantity of required new parts. This list will contain parts that cannot be brought up to specification or that are always replaced at any rate. The parts list is given to administration along with the details of the rectification requirement. This information is used to determine an appropriate rectification strategy and product quote. If the quote is accepted then the remanufacture of the core can commence.

Figure 2: Typical Remanufacturing Process Flow



4. *Component remanufacture and put in Stores.* Component remanufacturing (also called component rebuild) consists of the sum total of treatment required to return component parts to current specification. It may involve surface treatment (for example, blasting or rolling in abrasives to restore the surface of discoloured, corroded or painted components) or mechanical and electrical treatment, (for example, building up worn parts by metal spraying, welding and machining to original dimension) [12].

   In the interest of economy, the process chosen for the component remanufacturing program will depend on the type of product and the volume of work involved.

Subcontracting may be used to reduce costs or improve quality. Rebuilt parts which pass the appropriate mechanical and electrical tests are labelled and put into parts inventory in stores. Generally the inventory record does not differentiate between rebuilt parts stock and new purchased parts because these are considered equal in quality [11]. Replacements for items that must be discarded are ordered from suppliers or made by the remanufacturer. These are also put into the inventory stock or else sent to test or build if required immediately.

5. *Build, Test and Despatch* . Once all required components are available in stores assembly kits are prepared using an assortment of rebuilt, purchased and manufactured parts according to the production schedule. These kits are called out to the assembly area as required for subassembly and final assembly. Assembly is followed by whole system testing of the equipment to current specification. If the system passes then it is typically painted and labelled in a way that clearly distinguishes it from a new product [1]. Finally it is given a warranty, which is at least equivalent to that of a similar new product, and is shipped to a customer or else it is put in finished goods stock to await purchase.

   The testing, measurement and quality control methods used are similar to those employed during the original manufacture. The only difference is that remanufacture demands that inspection should be much more rigorous [13]. Even where sampling plans had been adequate during original manufacture, inspection must still be on a 100% basis because in remanufacture all parts are presumed faulty until proven otherwise [1]. In some remanufacturing organisations workers identify their work, for example by colour or stamp, to aid fault tracing and training needs.

Case studies

Although there is an urgent need to develop remanufacturing awareness in all sectors of the modern industry, expertise in the concept is of particular relevance to small and medium sized enterprises. This is because the majority of existing remanufacturers are found within the SME sector. However, because of the profitability of remanufacturing and the desire of original equipment manufacturers (OEMs) to guard their reputations, OEMs are now establishing their own remanufacturing facilities and forming partnerships with existing remanufacturers. Small volume remanufacturers must therefore rise to the challenge posed by these emerging large competitors by enhancing the efficiency of their services. Additionally, environmental laws increasingly require producers to take back products which have rëached the end of their lives. Remanufacturing expertise offers producersm an effective avenue to evade waste limitation penalties whilst, at the same time, maximising their profits.

The research findings presented in this paper have been obtained from a series of case studies which were undertaken by researchers at the University of Plymouth during the initial stages of a remanufacturing research project. The aim of the project is to develop a set of guidelines for decision-making, together with a prototype software-based decision support tool which will enable remanufacturing firms to improve the efficiency and effectiveness of the component assessment stage of the remanufacture process.

Methodologically, the research has followed the cycle proposed by Meridith[6], namely *Description*, *Explanation*, *Testing*. In the initial descriptive stage of the work, the research has investigated the remanufacturing process through literature survey and through observation of remanufacturing firms supported by interviews with key company personnel. Seventeen companies have been visited, of which eleven were deemed to be remanufacturers in as much as the scope of their activities was in line with our definition of "remanufacture".

The dilemma of remanufacturing is how to bring worn out products back to at least an "as new" functional state and in a manner which is cost and time effective. The case studies indicated that this task is complicated by a significant number of operations control issues. The following section details some of these as observed within the qualifying companies.

Operations Control issues in remanufacture

The principal operations control issues highlighted by the case-study work include:

1. *Uncertainty:* Causes of uncertainty include variability in demand volume, core quality, core quantity, product type and availability of technical knowledge. For example, remanufacturers typically accept all orders and all cores offered but, given the high variety of product types, until cores arrive it is impossible to decide whether there are appropriate parts and sometimes skills to fulfil orders. Other causes of uncertainty include problems related to replacement parts availability, no possibility of adjustment (i.e. tolerances are too tight) and failures which have damaged the interior of the component to the point that replacement of the interior parts would add too much to the cost of the component.

   Such uncertainty has significant implications for scheduling, capacity planning and shop floor control. The ability to plan for uncertainty and to make maximum use of capacity is therefore crucial to the remanufacturer [21]. All the companies surveyed indicated that high uncertainty was an inherent aspect of the remanufacturing operation and that the ability to cope with uncertainty was critical to survival. Most companies could cite instances where loss of profit occurred due to unexpected occurrences such as unforecast fluctuations in demand.

   For example Company A, a compressor remanufacturer, had forecast demand and had adhered religiously to a predetermined budget and strategy. Yet it was forced to turn away trade worth in excess of £600,000 during the space of three months in the summer of 1994. The company had been caught unawares by an unprecedented surge in demand that far outreached its capacity and it was unable to secure adequate resource to fulfil available orders within the required time scale.

   As a result of this experience, Company A sought to inoculate itself against uncertainty by establishing an "unexpected events buffer" which included records of seasonal labour and capacity slack that far exceeded normal demand variations. However, it has failed to obtain 100 % immunity [8].

2. *Knowledge acquisition and processing*. Remanufacturing operations require cost and time effective systems that facilitate easy and accurate information accumulation and processing. This is because environmental uncertainty demands the ability to cope with unplanned events (i.e. thinking on one's feet) and this places a premium on efficient and effective decision making. At the same time extreme product variability requires the acquisition and assimilation of vast amounts of data, all of which must be considered by decision makers.

The case study companies all agreed that knowledge acquisition is a major concern in their industry because of the range of knowledge that must be obtained. They also indicated that such knowledge is invariably difficult to obtain. Company G and Company F, both remanufacturers of automotive transmissions, stated that the availability of product history would facilitate their task because the condition of a used machine is governed by its history and working environment rather than by its age or make. However, because customers do not often record the service history of their equipment, they indicated that they are unable to obtain a head start in failure diagnosis [7,9].

For the non-OEM remanufacturer, the knowledge acquisition problem is much more acute because many OEMs are unwilling to release product information. Company C, a railway diesel engine remanufacturer and Company D, a railway rolling stock remanufacturer, indicated that, because OEMs increasingly refuse to divulge technical details, they are often forced to reverse engineer some products. This is costly, time consuming exercise and is not always successful. In addition, they are often obliged to circumvent intellectual property rights problems by working under contract to the OEM [19,21].

3. *Flexibility*. Studies show that flexibility provides an efficient channel for coping with unplanned events [15] and also that the need for flexibility is maximised where uncertainty and variability co-exist [16]. All the companies surveyed expressed a desire to enhance their flexibility so that they can more easily cope with the effects of high variety and uncertainty. The predominant flexibility enhancement approaches mentioned include: subcontracting and the multi-skilling of employees.

Company A stated that seasonal labour and the maintenance of slack on the shop floor were also effective flexibility boosters [8]. Some companies believed that contracts and mergers with subcontractors and suppliers could enhance operational flexibility. In fact Companies A and B, both rebuilders of compressors, stated that the increase in efficiency resulting from their acquisition of some of their subcontractors has greatly increased their operational flexibility [8,14].

"Investigate core". The research has shown that the "investigate core" activity is the key fault analysis stage in the remanufacture process. Here effective and reliable systems are required to gather and evaluate facts. Sound trouble-shooting is required to ensure that valid rectification methods and accurate cost estimates can be ascertained. The case studies show that a crucial element of a remanufacturing business is the ability to effectively diagnose the faults of failed systems, i.e. effective equipment

failure analysis. All the companies surveyed could cite examples where financial losses or drastic profit reduction occurred as a result of inadequate initial analysis. Consider three examples from Company E [20], a quarrying equipment remanufacturer.

Example 1: Dumper Transmission. The unit was assembled and when on test it was found that the 5th gear would not engage. The fault had to be found and rectified. This involved stripping the gearbox completely because the 5th gear was packed first into the casing and hence had to be last out. The fault was found to be a crack in the aluminium housing which should have been identified at the investigate stage. The cost to strip the unit, repair the fault and rebuild the unit was £880. This expense had to be borne by the company because it could not revoke an agreed quote without customer and reputation loss.

Example 2: Jaw Crusher Re-build. The unit was rebuilt, assembled, tested and sent to the customer. After only 3 months in service the mainshaft broke and the unit was returned under warranty. When the unit was stripped, the shaft was found to have been cracked for some time. The shaft had been crack tested at the initial investigation but the crack had been missed. A new shaft was fitted and the unit was assembled, tested and returned to the customer. The cost of poor investigation in this case was £12,000, in addition to the cost of production loss.

Example 3: Cone cruncher. A 13 ton (small) cone cruncher failed at test. The cost to the company of stripping the unit and re-testing was £407 (3 men working for 2 full days). In addition, a faulty gear was found and replaced at a cost of £4000. Total cost to the company of reworking this small cone cruncher was £4407. The profit margin on this job was drastically reduced because the company was unable to alter an agreed quote.

The companies also stated that the" investigate core" activity was often both expensive and time-consuming and that the resource expended on this activity could also reduce their profits. Many companies complained that they were expected to bear the cost of initial inspection and quote even when the potential customer decides to spurn their services in favour of that of their competitors.

Company E, for example stated that it was compelled to introduce a quoting tariff for new customers. It indicated that this was necessary because many of its fault diagnosis procedures (for example ultrasonic testing) are immensely expensive and require significant expertise. Profits could therefore be greatly reduced if free inspection was carried out for large numbers of "non takers" [20].

Company F, a transmissions remanufacturer, stated that although it did not charge any potential customers for inspection and quote, it circumvented time wasters by returning the equipment of "refusers" completely disassembled and without fault report. It indicated that this was not done deliberately to inconvenience the customer but, having already invested resource in diagnosis and quote, it was felt that it would be unreasonable to expend further resource when there was really nothing to be gained [7].

All the companies agreed that it was difficult to decide how much to inspect because over inspection and under inspection both can have adverse financial consequences. Most companies indicated that they would welcome a system that could provide guidance regarding the appropriate level of inspection for products as well as methods of reducing inspection lead time.

Suggestions for further research

The " investigate core" activity (see Figure 2) is one of the most critical activities within a remanufacturing process because it is in this area that decisions are made regarding the condition of equipment and therefore its rectification requirements . Inefficiency in performing this activity can result in disastrous financial repercussions, for example, through inaccurate or untimely quoting as well as use of inappropriate rectification solutions. Latitude in this activity extends quoting lead time which can result in loss of business opportunity.

Despite the great impact of this activity on profitability, the research indicates that few guidelines and tools have been developed to aid its effective execution. It is therefore believed that research needs to be undertaken into this area in order to firstly, understand its requirements and, secondly, to determine methodologies that would aid rapid and accurate equipment evaluation.

Conclusions

This paper has defined the term "remanufacturing" and it has differentiated remanufacturing from alternative green production initiatives. It has represented the remanufacturing process diagramatically and it has described its constituent activities. The relevance of remanufacturing to industry and in particular to the SME community has been highlighted, particularly where remanufacturing expertise offers producers an effective avenue to evade waste limitation penalties while augmenting profits.

Three major remanufacturing drivers have been identified, namely legislature, ecology and economics and the paper has proposed that the key management issues for the remanufacturer are, firstly how to deal with the extreme environmental uncertainty and variability, secondly, how to organise operations such that the considerable knowledge and information required can be gathered and processed accurately and rapidly, without the need of additional resource and, thirdly, the need to ensure accuracy in initial equipment fault diagnosis. The paper contends that initial fault analysis - "the investigate core" activity - is a critical aspect of the remanufacturing process and it supports this assertion through evidence from research.

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Heavy metals in Consumer Electronics Recycling
A multidisciplinary approach

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Abstract

This study describes the heavy metal issues in consumer electronics recycling and a new way of solving these problems by starting a unique cooperation between designers, researchers and recycling experts of the Delft University of Technology (TUD), of the Eindhoven University of Technology (TUE) and electronic manufacturers as well as the recycling industry.
The production, use and discarding of consumer electronics contribute to the increase of heavy metals in the environment. By integral chain management the heavy metals burden for the environment can be minimized. This is only possible when there is a good synchronization and communication between product designers in the beginning and the recycling industry at the end of the product life cycle.

The project concept is that - based on the possibilities of recycling - product design can be modified such that heavy metal problems can be reduced or at least controlled. This can only be achieved if scientists from different disciplinary backgrounds cooperate in a single project. By forming a team of Ph.D.-students from different disciplines (chemical engineers, product designers and industrial engineers) which work together, the heavy metal problem will be tackled by a combination of prevention and end-of-pipe technologies. This will result in a better environmental performance and more economical use of resources.

First experiences of this cooperation have already resulted in a new way of dealing with the separation of the different materials during the end of life phase of consumer electronics. Part of the heavy metal issues can be tackled by focusing the research on the separation and upgrading of the heavy metal containing plastics involved from a perspective of the plastic reuse and therefore not focused solely on the heavy metals separation.

These experiences have shown that multidisciplinary cooperation is an excellent tool in order to foster the goals set by a sustainable development.

1. Introduction

Consumer electronics contribute in the end-of-life phase to the increased dispersion of heavy metals in the environment. These issues have to be tackled by integral chain management. This is possible if there is an optimal interlinkage between product design and recycling industry. It is the role of product design to find the compromise between purchasing, product design, production, functionality and ecological aspects. The present project aims to substantially improve on these issues.

Consumer electronics mainly consist of plastics, metals and glass. Dependent on the goal of handling waste and considering the minimization of the environmental impact for different type of materials, different treatments have to be performed. The present separation technologies used for the processing of consumer electronic waste are focused on maximizing the amount of reclaimable (heavy) metals, like iron (Fe), aluminum (Al) and copper (Cu), but does not specifically take into account control of the other metals like lead (Pb), cadmium (Cd) or zinc (Zn). This results in an unusable rest fraction which contains mostly polymers heavily polluted with heavy metals. Beside this, polymers contain themselves also heavy metals in the form of additives. They have been added to the polymers because of property improvements and processability. The rest fraction still causes the mayor part of the environmental burden of the recycling process of consumer electronics. The reuse of these waste streams will become more and more the key issue in the increasing eco-efficiency of the recycling of consumer electronics. A solution for the problem is also very desirable from a point of view of the optimal product design (saving materials and environment).
The Eindhoven University of Technology (TUE) and the Delft University of Technology (TUD) have decided to combine their expertise in this field in order to develop more efficient solutions for this problem. Therefore not only new separation techniques will have to be developed, but also the logistic possibilities and design limitations have to be taken into account. The reuse of the waste plastic stream would considerable improve the eco-efficiency of the recycling process and in that way open the avenues to reduce heavy metal leakage to the environment and also decreasing the environmental burden via the improved reuse of the plastic waste stream, thus reducing the amount of incineration and landfill. This means that closing the heavy metal cycle can be achieved by removing the greatest bottleneck via improving the reuse of the plastics in consumer electronics. This is the reason why this investigation is focused on the improvement of the recycling of the plastics in consumer electronics. This means not only separation of the plastics but also improving and developing its reuse in preferably new consumer electronics applications.

2. Take back and recycling of discarded consumer electronics

The most important phases in the life cycle of consumer electronics are:

design -> production -> use -> collection -> treatment -> recycling and waste treatment

In general the treatment of consumer electronics in the end-of-life phase is as shown in figure 1. This figure shows schematically that used product are first subjected to a selection of reusable products. These can be redirected to the market. Products, which are no longer reusable, are disassembled for reuse on component levels (e.g. certain chips or power units, which can be reused). Also most of the part with sufficient weight and purity are disassembled for recycling purposes as well as parts, which contain specific, credits. Presently disassembly is taking place manually which makes it very costly. Increasing application of mechanical processing and separation would make end of life treatment more economical, but should not be at the expense of the environmental performance. It is one of the basic aims of the current project to improve substantially the environmental gain/cost ratio of the mechanical processes. When this is no longer possible the products are grinded and the different materials are separated in order to recycle the materials like metals, glass, and plastics. Dependent on the input and the way the process is carried out, there rest waste fractions polluted with heavy metals.

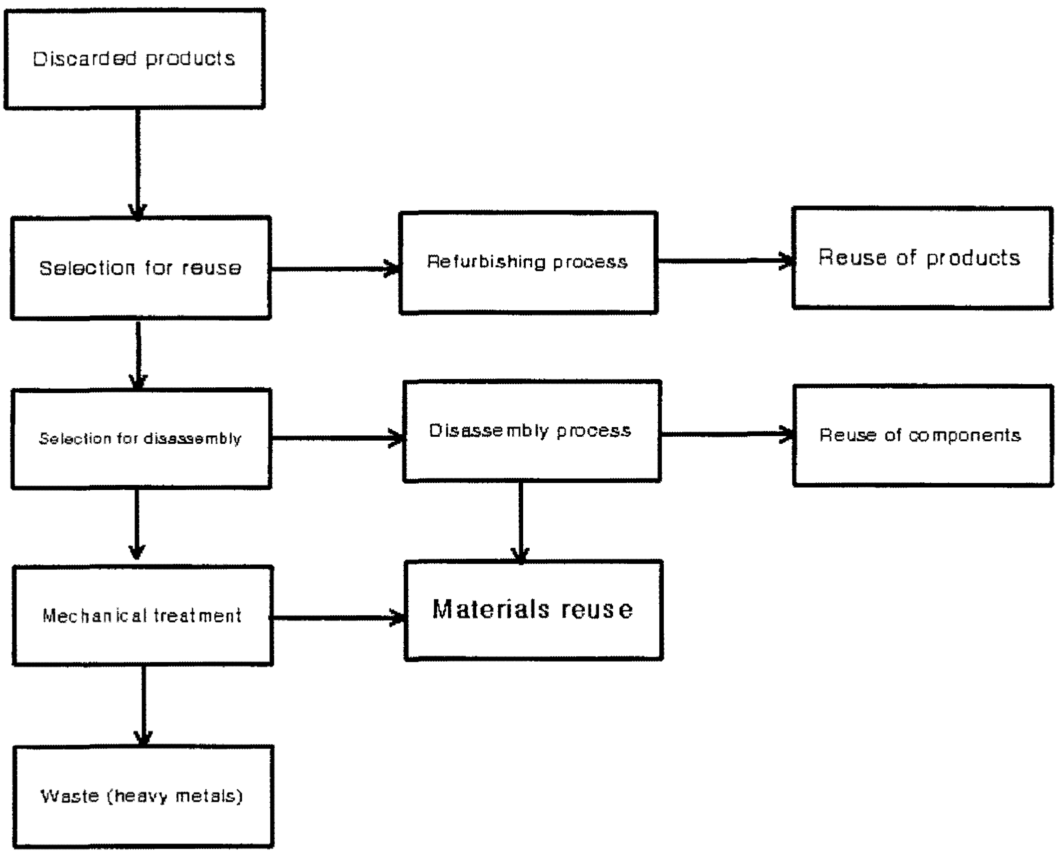

Figure 1. Schematic view of the recycling process of consumer electronics.

In this study the improvements of the recycling process will be measured in terms of eco-efficiency improvement. Th eco-efficiency of take back systems can be defined as the ratio of the environmental gain and the costs expressed in money to obtain this. The environmental gain can be expressed as the ratio of the amount of material actually recycled in unit of weight (kg) and the total weight of material involved. The costs are defined as the costs in money, which have to be made in order to recycle one kg of the material involved. These costs are based on the Dutch take back systems, which are currently operational (price level 1998). The general definition of eco-efficiency of the take back systems can be expressed in a formula as follows:

Eco-efficiency = Environmental gain/costs (money/kg)

This general eco-efficiency definition is worked out in two ways:

1. Eco-efficiency of recycling effectiveness, E(R).

$E(R) = \sum(\text{Weights recycled}*\text{WF}/\text{weights}) / (\text{costs (money/kg)})$

in which M represents materials and WF represents a material fraction

2. Eco-efficiency of heavy metal control, E(HMC)

$$E(HMC) = \sum((\text{Weights HM controlled}*T) / (\text{total weight HM} * T)) / (\text{costs (money/kg)})$$

in which HM represents one heavy metal
T represents the toxicity index, which is a measure of toxicity for a heavy metal based on toxicity data according to Nissen [Nissen, 1997].

Details of the calculation of E(R) and E(HMC) will be published in [Stevels, 1999]. The outcomes of the study will be an answer to the question whether improvements E(R) and E(HMC) will run parallel and if so to what extent. It is interesting to see whether replacement of a toxic material by an alternative less toxic material not only improves the eco-efficiency of heavy metal control (E(HMC)), but also the eco-efficiency of recycling effectiveness (E(R)). This outcome will give further clues how criteria for eco-efficient take back systems will have to be defined; this is in particular relevant in view of pending take back legislation in the EC countries.
Also for assessing designs, calculations of E(R) and E(HMC) for specific products will be of great help. In this way it can be established how far such products are situated from the average E(R) and E(HMC) of streams. This will allow selecting the candidates for product design.

3. The heavy metals issue

The problem of heavy metals plays in three categories

1. Control of potentially environmentally burdening heavy metals
2. Copper fractions, which emanate from the mechanical treatment
3. Mixed plastics which emanate from mechanical treatment

Copper smelters can process copper fractions from the electronic waste recyclers without problems. A number of heavy metals in this fraction like lead, antimony and cadmium can be reclaimed and reused. The plastics present in this copper rich fraction are burned in the copper smelters and their energy content is used. However, not all copper fractions can be recuperated in this way. Unfortunately, partly the copper and also other metals are present in the remaining plastic fraction, which is presently incinerated. Via this fraction part of the copper is lost and together with the other heavy metal contaminants is incorporated in the slag phase. This lowers the reusability and economic value of the incineration slags considerably (low eco-efficiency).
The wish to prevent such environmental problems is translated into new laws and strict legislation resulting e.g. in duty of reclamation and bans on landfill. This is why producers of consumer electronics are being confronted more and more with demands concerning recycling and reuse of their products. These demands must be met within an eco-efficient framework, thus stressing more and more the need of optimal product design. Via the design, producers have direct influence on the use of certain materials and combinations thereof and thus on the reprocessing costs. The wishes and possibilities of users and production units determine the design specifications for a product. Design demands, which account for the end-of-life phase,

must be incorporated as well:

1 secondary material stream properties have to comply with critical material specifications;
2 the technical and economical possibilities of the recycling industry;
3 the technical and economical possibilities of the collection systems and separation of different product streams;
4 functionality requirements of products can limit bulk recycling industry and metal smelters.

The demands of bulk recycling and smelters will be considered as starting points in this study.

4. The role of plastic recycling

Plastic recycling is complicated because of the many different types of plastics involved, which are difficult to separate from each other. Also different additives like flame retardants, plasticizers etc. have been added to the plastics thus resulting in a mixture of different plastics with many different additives (both from organic as from inorganic (heavy metals) sources). The existing physical separation techniques have limited capabilities and even if complete separation is possible the quality of an aged polymer will be less than that of a new virgin one. For less demanding applications reuse can still be very well possible. Because of the decreasing applicability in the reuse of polymers as function of its life cycle the economics become worse and worse; the value of the recycled materials decrease. This limits considerably the recycling of consumer electronics. A technological breakthrough is necessary to improve the recycling efficiency of plastics, both in separation and upgrading of the material as well as in material choice during product design and development. That is why the present project is not only focused on separation and reclaiming, but also on improving the quality of the used plastics via a method of modifying the polymers insuring that their material properties will be maintained and adjusted for applications. Through chemical modification of the plastic waste materials, materials will be produced with improved mechanical and physical properties.

For the determination of the technical and in particular the economical success of the recycling of consumer electronics the volume, composition and availability of streams are essential. Whether such streams are available depends on the type of collection systems and of the economy of scale at the recycler. These data depend on the collectors and the recyclers. Volume and composition of the product streams can be partially influenced. A considerable part of the project is focused on the logistics and process management, which integrates the complexity of the different phases in the life cycle. Optimization criteria are the environmental and the economical aspects.

When the possibilities of the new processing technologies are more clear as well as the volume, composition and availability of the waste streams, it is possible to use these experiences in the design phase to improve the environmental impact of the life cycle and to improve economical bottlenecks in the waste treatment systems.

The results of the project are especially of interest for the producers of consumer electronics, who can anticipate on their responsibility for the end-of-life phase of their products. Recyclers can use the results for optimizing their process and reusing also the fractions, which have been polluted with heavy metals.

5. The role of product design

From an environmental point of view the best way of tackling the heavy metal problem is to prevent that the heavy metals are present in the products. However, this is simpler said than done. Many of these materials have such excellent performance that their substitution and elimination is hardly possible, certainly not in the near future (e.g. copper). Besides this it will also be important to compare the life cycle performance between the heavy metals and the alternative materials.
As consumer electronics consist for the largest part out of plastics, metals and glass, contradictionary processing routes will have to be followed. These depend on the chosen recycling route and on the maximization of the eco-efficiency. This is also valid for the heavy metals, which are always present in certain concentrations in the different material streams. It is the role of product design to minimize ecotoxicity of the products. In order to determine which products are suitable for redesign, ecotoxicity calculations [Nissen, 1997] must be carried out for the products and the material streams. When certain products and material streams have been selected for redesign, it is still very important not to forget the life cycle perspective. This is in general the functionality (which can not always be realized without the use of heavy metals) and the relation functionality/price. A more intensive end-of-pipe treatment can be less expensive than the use of a very expensive alternative. It can be expected that the focus will be directed to the redesign of polymer/ heavy metal material combinations. In order to do this a certain stand of technique has to be taken. Before new design can be made, the following problems have to be addressed:

1. The present separation technologies used by the modern recycling plants are focused on the separation of the optimal mix of (heavy) metals, which can be reused. This results in an unusable rest fraction consisting mainly of plastics contaminated with heavy metals. This fraction still causes an important burden of the environment and further processing will become the economical bottleneck.
2. Plastics contain heavy metals themselves. These have been applied in order to improve certain properties such as flame retardancy (e.g. Sb) and stability (e.g. Pb).
3. The composition of the mix of metals determines the economical value. Some combinations are the cause of high penalties (e.g. copper should not contain Sb, As, Ni, Bi and Al). These combinations should be avoided.

From an environmental and from a designer's point of view the solution for the first two problems should be given priority. The reason for this is that designers should be given as much freedom as possible because they al ready have so many demands which they have to fulfil, in particular the product quality and performance during use. Therefore it is necessary to focus the cooperation between design and recycling on the problems of separation and reuse of the waste fractions, which are causing the highest environmental burden: the polymer fractions contaminated with heavy metals.

6. The role of operations management and logistics of the total recovery chain

Apart from the improvement of processes and the technology innovations for individual activities of the recovery process, as described in the foregoing projects, a further, and probably large, improvement can be obtained by considering the organizational, financial and environmental aspects of the total recovery chain.
The environmental friendly processing of discarded goods is located in the last part of the product chain. Until now, research with respect to optimal collection and processing strategies (in an economic sense or related to the recovery factor) has been directed to each single actor (collector, distributor, processor or smelter). Only the financial result of one single actor is optimized then (e.g. Penev and de Ron, 1996).
However, form a point of view of the environment and of society as a whole, the output of the total recovery chain in relation to the input goods has to be considered, where a multitude of quantities like recovery factor, eco-efficiency and reuse level have to be measured. Particularly it is important to see how the financial result of the actors in the total recovery chain changes compared to a financial optimization of the output of a single actor.

From practice it is known that by considering more actors of the recovery chain, other strategies will be developed than in the case of one particular actor only. This difference can be observed with easy recoverable and marketable materials, like ferro and non-ferro metals (e.g. Al, Cu). It is suspected that a significant different processing strategy will be the result for heavy metals and besides a financial optimization of the complete recovery chain will result in another collection strategy.
In the past research has been carried out concerning the logistic aspects of the recovery of products in their end-of-life phase. For the industrial and transport packaging industry Dubiel (1994) has identified three categories of reusable systems, divided into applications, and three organization structures. However, Dubiel views only costs and does not optimize in any way the financial and environmental aspects for the complete recovery chain.
Jahre (1994) has investigated the existing logistics chains for household waste in Europe. She has developed also a theoretical framework for the collection and processing of electronics products (Jahre and Flygansvaer, 1996). This framework is based on a process for the selection of distribution levels as has been described by Mallen (1970,1996). Mallen uses the following parameters in the logistics chain structure: the number of distribution levels, the number of actors, the type of actor and the number of logistic paths. The number of distribution levels concerns the number of operations that have to be done in order to get the used goods of the last user there, where the final recovery takes place. A consequence of fewer levels can be, for instance, that the transport costs will be high as a result of small volumes. A grouping may result in a reduction of these costs but increases the number of levels.
The number of actors per level concerns the number of collection points, the number of transporters and the number of processing facilities. The more actors per level, the more the selectivity can be.
The type of actor shows the functions that have to be fulfilled: sorting, storing, allocating and fragmenting. For instance, omitting sorting at the end user will increase the customer service as the end user does not have to do so much, but will result in more operations in the chain as the goods (or materials) are not sorted for the recovery process. However, the costs for transport and storage may be lower as the volume will be bigger.
The number of logistic paths regards to the question concerning the number of recovery systems to be installed. For instance, if one manufacturer of photocopiers has installed such a

system, what happens with the apparatus of other manufacturers?
Based upon the theoretical framework of Jahre and Mallen, in this project the logistic structures will be described in a more general form with the help of the four mentioned parameters. Important aspects will be:

- the involvement of each actor within the recovery chain and the influence of the chain structure thereupon;
- the functions of each actor and the value that is added to the chain;
- the number of different possible recovery chains and the reasons for the choice of the applied chains;
- the level of cooperation between the actors within the recovery chain.

The following two main goals will be the starting point of the research in the field of operations management and logistics that will be carried out:

1. the design of systems for operations management and logistics for the recovery chain of consumer electronics based upon optimization of these systems from environmental and financial point of view;

2. the translation of the conditions for these optimal systems for operational management and logistics into requirements for product design.

A model will be developed which describes the complex situation for the end-of-life phase of consumer electronics considering environmental and economical aspects of the complete recovery chain. The economical opportunities of the new developments in recycling as described previously will be determined. The optimization will be carried out by a multiple criteria analysis and different actors within the recovery chain will verify the results.

7. Short outline of the envisioned project

In this project the stand of technologies in the Netherlands will be taken as starting point. New developments during the project time will be incorporated into the project. Via calculations and modeling the product designs will be selected, which have insufficient control over heavy metals. Based thereon-new product designs will be made. Focus is given to the material streams, which are expected to cause a high environmental burden: the polymer fractions contaminated with heavy metals.
Investigations have started focused on a promising new development, which comprises the separation of the heavy metals from the polymer fraction and upgrading of the polymer fraction so that the polymer fraction can be reused. By improving the quality of the waste plastic streams the economical benefits from this stream can benefit the total process and make the recycling of the consumer electronics economically feasible.
By forming a team of Ph.D.-students from different disciplines (chemical engineers, product designers and industrial engineers) which cooperate and do research together, the heavy metal problem is tackled by a combination of prevention and end-of-pipe technologies, which results in a better environmental performance and more economical use of resources.
Refreshingly new is the cooperation of designers with recyclers in the research phase, both focusing on the same problems but from another background. This results in this original way

of looking at the heavy metal problem within consumer electronics. Therefore it is our belief that only by these kinds of cooperation a real step forward can be made in solving these difficult problems in accordance with a sustainable development.

8. Conclusions

1. The production, use and discarding of consumer electronics contribute to the increase of the dispersion of heavy metals in the environment. Integral chain management can minimize the heavy metals burden for the environment in an efficient way. This is only possible when there is a good synchronization and communication between product designers in the beginning and the recycling industry at the end of the product life cycle.

2. In order to reach a considerable improvement for the environmental performance concerning the heavy metals problem, a new project has been started which involves a cooperation between designers, researchers and recycling experts of the Delft University of Technology (TUD), the Eindhoven of Technology (TUE) and electronic manufacturers as well as the recycling industry.

3. The project concept is based on the possibilities of recycling; to modify product design such that heavy metal problems can be reduced and controlled. It is a necessary step for researchers from different disciplinary backgrounds to cooperate in a project which aims at decreasing the heavy metal problems in the secondary materials stream of consumer electronics recycling.

4. First experiences of this cooperation have already resulted in a new way of dealing with the separation of the different materials during the end of life phase of consumer electronics. Part of the heavy metal problem will be tackled by focusing the research on the separation and upgrading of the heavy metal containing plastics involved from a point of view of the plastic reuse and not focused solely on the heavy metals separation.

5. These experiences have shown that multidisciplinary cooperation is an excellent tool in order to foster the goals set by a sustainable development.

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Towards an Operational Definition of Product Stewardship

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An understanding of the definition of product stewardship is developed through a review of 125 papers and books. Based on this work the 93 concepts that were agreed to be indicative of product stewardship, by a panel, are related to management decision making and product stewardship. The importance of between-group differences in interpretation of product stewardship is considered. This work serves as a basis for obtaining a better understanding of and operationalizing product stewardship.

Introduction

Product stewardship is a term frequently used by individuals that are considering the interaction of human products and the natural environment. The term product stewardship can be roughly defined as the responsibilities of the manufacturer for the environmental impacts that are caused by their product. This concept has no widely accepted definition. Consequently, the meaning of this term depends on an individual's weltenschaung or worldview. Such terms are described as being socially constructed, since definitions lack a physical basis they are derived by the agreement of a group of individuals. Hence, the accepted definition of product stewardship can change depending on the individuals under consideration, their location, and the passage of time. To allow for communication about product stewardship, one must first understand the potential scope of its definition and then understand how the term is perceived by different people when they use or consider this term. This paper starts the process of understanding peoples' perception of product stewardship by reviewing the literature and establishing a series of terms that are thought to be relevant to product stewardship. These terms are intended to serve as a starting point for establishing: what product stewardship is, how the meaning of product stewardship changes across specified groups, how the meaning of product stewardship changes with location, and how the interpretation of product stewardship changes over time.

The perception of product stewardship by different groups is important, since it will influence the management team of firms to change their product systems either voluntarily or in response to new regulation. Consequently, an analysis of the different concepts that are in the literature that are deemed to be relevant to product stewardship are identified. A model linking these concepts to the management of products and their lifecycle. This is followed by a discussion of its importance and the development of a series of propositions. Finally, the conclusions are offered.

Method

An extensive literature search identified 125 publications that addressed product stewardship. Each publication was carefully reviewed. Any time a concept that was related to product stewardship was identified it was noted and referenced. This review of previous literature resulted in the identification of 491 terms. These terms were reviewed by two experts. Terms that were duplicated, redundant, irrelevant or obscure were removed. A term was only removed, during the review process, if both experts agreed that the term should be removed. In several cases, terms were left on the list because of disagreement between the experts. After three reviews, the list had been reduced to 226 terms. The list of remaining terms was now given to two other experts to review. The experts were advised to rate each term as either definitely related to product stewardship, maybe related to product stewardship or not related to product stewardship. If a term was described by either of the two judges as being related to product stewardship then the term was retained. Otherwise, the term was discarded. This process left ninety-three terms that describe aspects of product stewardship. The final list was given to another expert to be reviewed for emissions. The list was deemed comprehensive during the final review.

Results

The terms cluster into eight separate categories: five that address the product lifecycle and three that address the management of products. The categories that represent the product lifecycle are: design, suppliers, manufacture, use and end-of-life. The categories that represent the management of products are management goals and values, tactics and strategy, and goals and monitoring. A model is presented in Figure 1 that represents the past and current use of the term product stewardship. The terms associated with each part of the model are stated in Table 1.

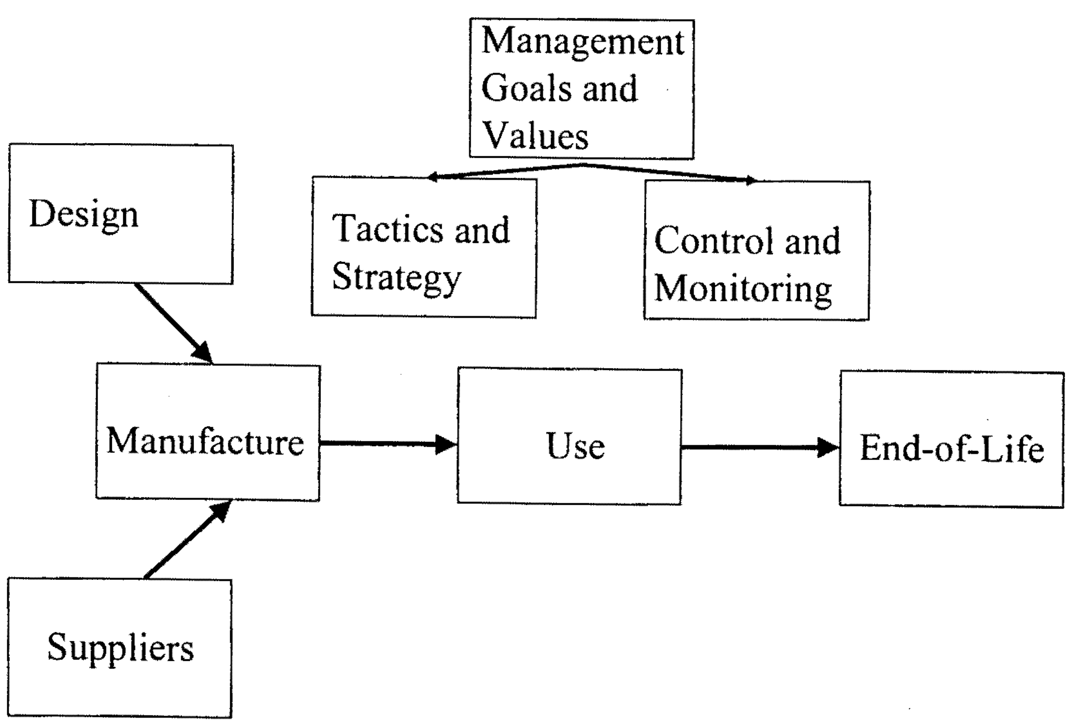

Figure 1: Model to summarize the literature's perception of product stewardship

Category	Term	References
Management of Product		
Management Goals and Values	Closed Material Cycle Corporate Environmentalism Responsible Care Consideration of entire product life-span Environmentally conscious design Understanding the complete impact of a product system during its life Corporate citizenship Cradle-to-grave Green design Green markets Green Image Industrial ecology Green supply chain	3 19 50 108,118,119,120,122,125 107 113,118,124 19 42,121 15,37,70,109 10,86 8 4,20,31,32,36,49,76 11
Tactics and Strategy	Environmental compliance Get ahead of regulation Managing end-of-life streams Recovery strategies Remarketing Elimination of barriers to recyclability Voluntary takeback of product Asset recovery Leasing of product	69 120 18 56 18 107 113 5,18 113,125
Goals and Monitoring	Life cycle assessment Environmental burden of product Release environmental performance updates (on a regular basis) Release of product environmental information to consumers Responsibility for product to manufacturer Waste reduction/minimization plan ISO 14000	56,108,109,111,119,122 111 115 113 113 106,111 80,115
Product Lifecycle		
Design	Design for energy efficiency Design for disassembly Design for maintainability	36 37,51,58,70,107,111,120,124 36

	Design for recycling	36,37,70,107,109,12,4
	Design for environment	5,9,35,36,85,101,105,114,115,116,117,118,120, 124
	Product development lifecycle	83
	Marking type of material on plastic part	107,109,117,124
	Design for disposal	16,110,125
	Design for reassembly	107
	Design for recovery	70
	Packaging reduction	67
Suppliers	Environmentally responsible suppliers	108,115,118,119
	Negotiating with suppliers to change or reduce packaging	108
	Supplier environmental performance	120
	Resource requirements	11,112,122,124,125
Manufacture	Material reduction	81
	Reuse or recycle solid waste	117
	Transform waste into a product	119
	Environmentally integrated production & recycling	88
	Avoidable wastes	81
	Toxic use reduction	119
Use	After sales service	16
	Material life extension	124
	Product life extension	15,89,124
	Monitor how customers use product	121
	Optimize product-environment interaction	49
	Teach customers how to use product	121
	Product durability	15
	Repair	4,28,38,39,40,91,97
	Upgrading	51
End-of-Life	Closed-loop logistics	48
	Deposit refund systems	113
	End-of-life product recovery	110,124
	End-of-life product takeback	5
	Landfill reduction	124
	Material reuse	21,22,81
	Optimized disassembly process	51
	Post-life material retirement	51

	Product reclamation initiative	115
	Reusable distribution items	25
	Resource recovery	62,63,64
	Returnable packaging	59
	Reuse distribution	28
	Reuse of products	28
	Collaborative arrangement for products at end-of-life	120
	Monitor how customers dispose of product	121
	Product packaging waste take-back	106,110,113,125,130
	Recycling from post consumer waste	120
	Teach customers how to dispose of a product	121
	Collection	24
	Dismantling	33,41,75,81
	Eco-logistics	97
	Material recovery	21,22,28,38,39,40
	Materials recycling	70
	Product reuse	81,110,111,117,118, 120,124
	Product recovery	5,21,22,57
	Recycling	18,28,51,72,81,82,91 ,98,106,108,111,117, 118,119,124,125
	Product take-back	28,37,110,111,117, 118, 120,124
	Refill	97
	Remanufacturing	5,14,28,36,38,39,40, 51,62,63,64,70,77,78 ,79,93,94,95,96,97, 106,108,111,117,118 ,119,120,124,125
	Returnable containers	12,59
	Reusable containers	32,52,53
	Reuse of materials	108,111,113,117,118 ,120,124
	Reverse logistics	18,28,33,44,45,46,48 ,56,57,59

Table 1: Concepts associated to product stewardship and their relationship to management environmental strategy and the product lifecycle.

In order to understand how product stewardship is perceived as a function of "type of person", location and time, an individual's perception of the relationship between the ninety-three terms (in Table 1) and product stewardship must be captured.

Discussion

The perception of government regulators, customers, and shareholders eventually effects management goals and values that relate to product stewardship (see figure 2). If regulators, customers, shareholders, and management have similar views towards product stewardship, we expect there to be no change or conflict in current activities. If these groups are in disagreement, we anticipate conflict. If the difference in perception is between management and some other group, we anticipate gradual change in the way that product stewardship is addressed by management, thereby reflecting the attitudes and beliefs of those groups that influence firms' management. If employees have a "greener" view than management, it is anticipated that the firmer will be greener than management policy demands. This is anticipated, since employees will make greener design and manufacturing choices when they are able. Finally, if employees have a "greener" perspective of product stewardship than the management over time the employees' actions will "catch-up" to the managers' perspectives. A series of propositions are offered on the anticipated relationship between perception of the definition of product stewardship and product stewardship activities.

Proposition 1:If shareholders have more inclusive views than management then there will be a gradual broadening of management's interpretation of product stewardship.

Proposition 2:If customers have more inclusive views than management then there will be a gradual broadening of management's interpretation of product stewardship.

Proposition 3:If regulators have more inclusive views than management then there will be a gradual broadening of management's interpretation of product stewardship.

Proposition 4: A gradual broadening of management's interpretation of product stewardship will be fastest if it is driven by either the action or threat of action of regulators.

Proposition 5: If regulators have more inclusive views of product stewardship then there will be an increase in product stewardship regulation in the medium term.

Proposition 6: If location is a major determinant of the inclusiveness of the definition of product stewardship then regulations that have significant effects on international trade will result.

Proposition 7: If industry is a major determinant of the inclusiveness of the definition of product stewardship then industries with conservative definitions of product stewardship will be disadvantaged buy future environmental laws.

Proposition 8: If perception of definition of the inclusiveness of product stewardship varies greatly between the management of different firms within the same industry then environmental regulation can offer certain firms a competitive advantage. Having taken the first step to operationalize product stewardship, it is possible, in the future, to test the previously mentioned propositions.

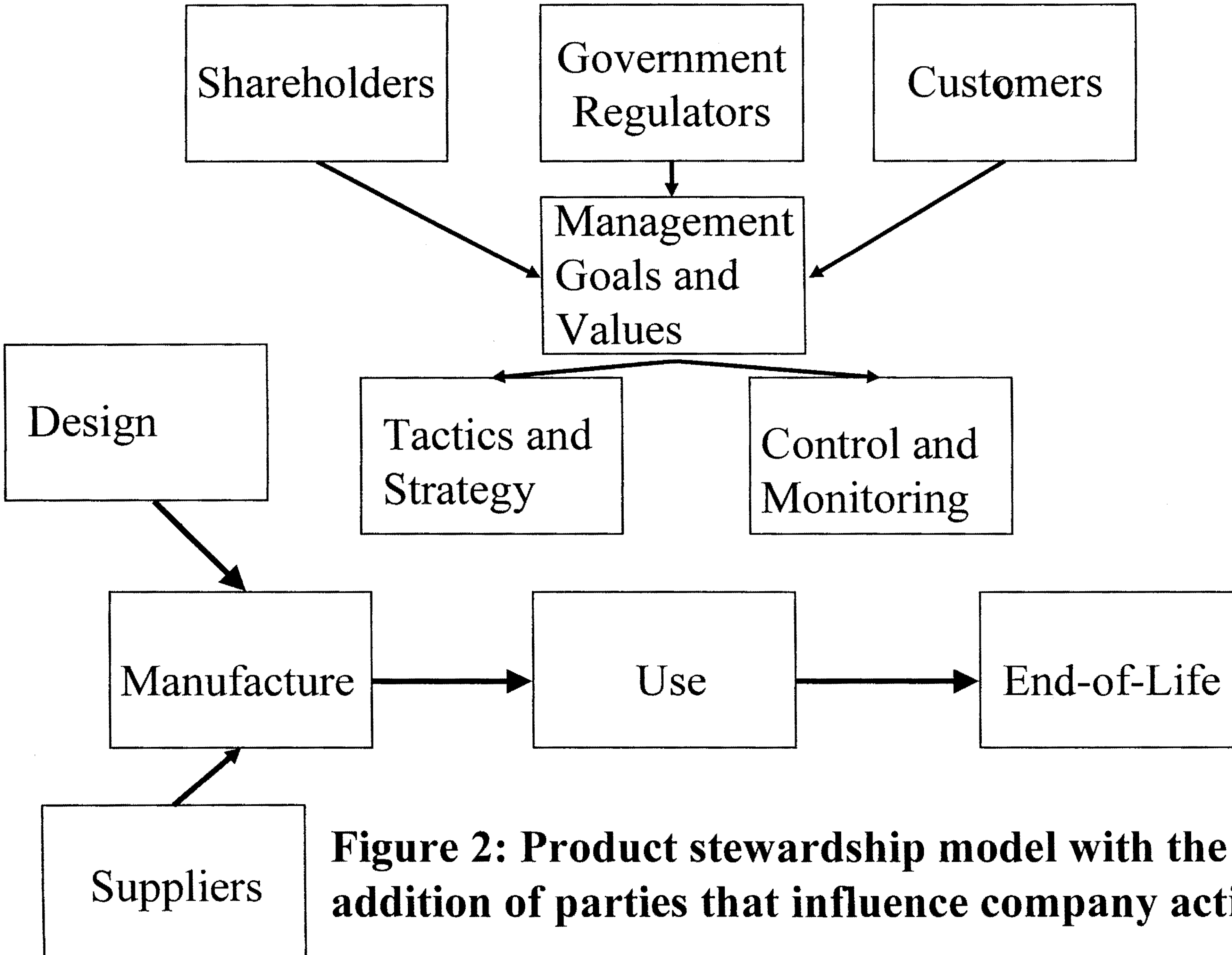

Figure 2: Product stewardship model with the addition of parties that influence company activities

Conclusions

An understanding of differences in product stewardship is useful, since it will indicate which markets are likely to offer advantages to firms or products that have a more inclusive view of product stewardship. It will also indicate which firms, industries, or countries will be disadvantaged by legislation that is based on a broad definition of product stewardship. This is an important question for corporate strategists, since many countries have enacted or are enacting legislation that is based on a broad perspective of product stewardship.

Acknowledgments

My thanks to Bob Ayres, John Ehrenfeld, Dan Guide and Valerie Thomas for their encouragement and assistance on the initial stage of this research program.

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Applying Quality Tools in the Field of Recovery Processes

An initial review of opportunities

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Abstract

Manufacturing companies are showing an increasing interest in the field of environmental issues in general, and recovery processes in particular. A problem many companies face is that literature dedicated to this topic gives them little support in setting up effective and efficient recovery processes. Addressing this problem will require introducing control systems to the field of recovery processes, preferably using experience and knowledge resulting from applying these systems in regular production activities. This paper will focus on the introduction of quality control systems. Firstly, recent developments in the application of quality tools and principles in regular production processes are discussed. Based on this discussion, the possibilities to apply these quality tools and principles in recovery processes are addressed.

Keywords: recovery processes, quality tools, definitions, control, application, opportunities

1. Introduction

In recent years, manufacturing companies are showing an increasing interest in the field of environmental issues. This growing interest is the result of the following market trends and legislational developments [Fiksel, 1993]:

- *Customer consciousness*; customers are getting increasingly concerned about the environmental consequences of the products they use and this concern is starting to play an important role in the purchase decision process.
- *Competitive differentiation*; addressing environmental issues can lead to a competitive advantage for a manufacturing company by creating a 'green image'.
- *Profitability improvement*; embodying environmental issues in product design and manufacturing processes and focusing on recovery processes could lead to significant savings in material, manufacturing and operational costs.
- *Regulatory pressures*; government regulations regarding the environmental impacts of products and production processes are becoming more stringent, especially regarding the disposal and recovery of products at the end of their (first) useful life.

In fact, manufacturing companies are even forced to address environmental issues, especially regarding the disposal and recovery of end-of-life products. According to Thierry et al. [Thierry et al., 1995] this will "...require a fundamental change in doing business. However, there could be large opportunities for companies that succeed in ways of embodying current and future environmental demands in their business policy."

In literature [Giuntini, 1996; Kiel, 1996] one can see the first steps being taken to integrate environmental issues with performance measures from the three traditional areas, i.e. costs, logistics and quality. Especially, the integration of environmental issues and quality has been addressed extensively [Beechner & Koch, 1997; Breeden, Fontaine & Kuryk, 1994; Goel & Singh, 1997], mainly because of correlations and parallelisms between quality management and environmental management [Borri & Boccaletti, 1995]. This has led to the emerging field of Total Quality Environmental Management and moreover, the introduction of standardisation (ISO 14000) regarding environmental management in manufacturing companies [Bergstrom, 1996; Hemenway & Hale, 1996].

A critical analysis of this new field of interest reveals that Total Quality Environmental Management usually refers to "management of environmental quality"; literature seems to be limited to discussions concerning generic business activities and managerial aspects. Although the necessity of integrating quality and environmental issues on a managerial level is not disputed here, it should be mentioned that discussions addressing the integration on a level of operational activities, directed towards specific products or processes, are scarce. However, Thierry et al. [Thierry et al., 1995] show the necessity for manufacturing companies to develop effective operational recovery activities to achieve the needed integration of environmental issues and business activities. Recovery activities, defined here as *all activities regarding the processing of used or discarded goods with the aim to recover products, components and/or materials*, embody specific recovery processes.

Although the importance of these processes to manufacturing companies is clear, the field of recovery is a relatively new and unexplored area to most of them. Examples of companies that could be looked at as an exception to this statement are e.g. Xerox, Océ and Digital. Literature up to this point will give inexperienced companies little support in developing and setting up these processes on an operational level, especially regarding the application of quality tools linked with recovery processes. Oktem [Oktem, 1996] mentions process flowcharting, cause and effect diagrams, experimental design, affinity diagrams and control charting as appropriate tools with regards to quality and environmental aspects, but does not discuss when or how to use them. Penev [Penev, 1996] suggests the use of QFD to achieve recovery friendly product designs, but funded statements about appropriate ways and timing of application are lacking.

Therefore, this paper will address integrating quality and environmental issues on the level of concrete recovery processes, focusing on the recovery of discarded discrete products. The goal of this paper is to give an initial review of the possibilities for applying quality tools and principles in the field of recovery, in order to help inexperienced companies in setting up effective and efficient recovery processes. This issue will be dealt with by addressing existing quality practices, already being applied in traditional production of primary products. This way companies can transfer existing knowledge and experience to the field of recovery processes, which will facilitate the introduction of these new activities [Dambach & Allenby, 1995]. This paper will focus on two specific areas:

- The possibilities for applying (known) quality tools and principles in operational recovery processes. The objective will be to identify the possibilities and gains of applying current quality tools (already being applied by companies in regular production activities) and the need to translate or modify quality tools and principles for application in this particular field.
- The possibilities for applying (known) quality tools and principles to introduce recovery requirements in the design phase of products and processes. The objective will be to identify the possibilities and gains of integrating recovery requirements into traditional design activities and the way quality tools can be used specifically to translate characteristics of recovery processes into product specifications.

Following this introduction, Section 2 will describe the field of recovery in more detail. After this, in Section 3 recent developments regarding quality practices in traditional production activities will be identified. Current quality practices in the area of recovery and the introduction of recovery requirements in the design phase of products and processes are addressed in Section 4. In Section 5 an overview of possibilities to apply quality tools and principles from a recovery viewpoint will be given, leading up to the conclusions and recommendations for further research in Section 6.

2. Describing the field of recovery processes

Recent years have shown an enormous increase in interest in research dedicated to the field of recovery processes. Since this is still a relatively young and unexplored area of interest, one of the difficulties of communicating research findings is the variety of expressions that have been used to describe different recovery activities [Ferrer, 1997]. Therefore, this paper will first give clear and concise definitions of the different recovery practices, before addressing the possibilities of applying quality tools in this field. Nevertheless, the underlying research for this article revealed that a more detailed and elaborate analysis of this particular topic could be valuable. Therefore, a follow-up analysis dedicated to defining and distinguishing between different recovery activities will be conducted and published [Melissen & De Ron, 1998].

Getting back to describing the field of recovery processes, firstly, Figure 1 presents an integrated supply chain, including the recovery of products, components and materials from used or discarded goods, and the development of products and processes in this chain.

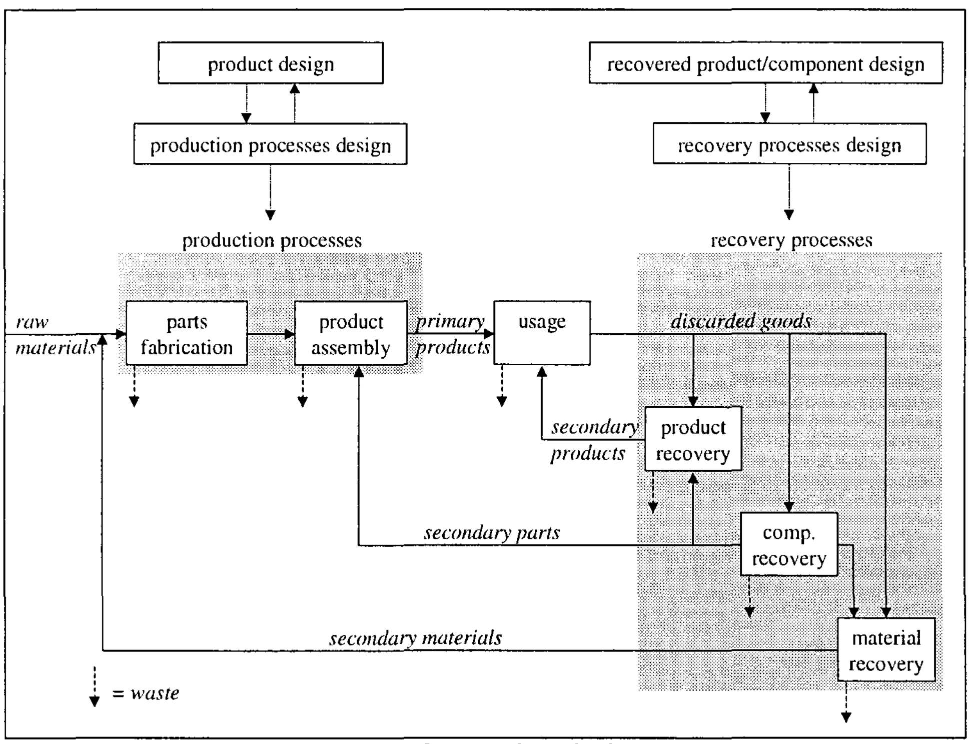

Figure 1: Integrated supply chain

Figure 1 shows that three main ***recovery strategies*** can be identified [partly based on Fleischmann et al., 1997]:

- Product Recovery (PR); the aim of this strategy is to recover reusable products from used or discarded goods,
- Component Recovery (CR); the aim of this strategy is to recover reusable components from used or discarded goods,
- Material Recovery (MR); the aim of this strategy is to recover reusable materials from used or discarded goods.

Actual recovery strategies will usually embody a combination of these main (theoretical) strategies. Both Product Recovery and Component Recovery can be referred to as added value recovery [Fleischmann et al., 1997] or value recovery [Ferrer, 1997], thereby indicating the objective to recover (part of) the value-added during initial production activities.

Specific (combinations of) recovery processes will be aiming at the recovery of products, components or materials with specific characteristics. Therefore, specific ***recovery options*** can be distinguished, based on the designated outcome of the recovery processes (cf. Table 1):

(a) *Repair*; a combination of recovery processes aimed at the recovery of products, with "working order" quality requirements, from used or discarded goods. Specifications are different from those for new products and only refer to returning the product to working order.
(b) *Refurbishing*; a combination of recovery processes aimed at the recovery of products, with specified quality requirements, from used or discarded goods. Specifications are different from those for new products and depend on the situation in which the product will be reused.
(c) *Revision*; a combination of recovery processes aimed at the recovery of products, with "as new" quality requirements, from used or discarded goods. Specifications are similar to those for new products.
(d) *Remanufacturing*; a combination of recovery processes aimed at the recovery of components, with "as new" quality requirements, from used or discarded goods. Specifications are similar to those for new components.
(e) *Reconditioning*; a combination of recovery processes aimed at the recovery of components, with specified quality requirements, from used or discarded goods. Specifications are different from those for new components and depend on the situation in which the components will be reused.
(f) *Cannibalisation*; a combination of recovery processes aimed at the recovery of components, with "working order" quality requirements, from used or discarded goods. Specifications are different from those for new components and only refer to returning the components to working order.
(g) *Recycling*; a combination of recovery processes aimed at the recovery of materials, with specified quality requirements, from used or discarded goods. Specifications depend on the process in which the materials will be reused.

recovery option	**designated output**	**specifications**
repair	products	working order
refurbishing	products	specified (< as new)
reconditioning	products	as new
remanufacturing	components	as new
revision	components	specified (< as new)
cannibalisation	components	working order
recycling	materials	specified (≤ as new)

Table 1: Summary of different recovery options and their designated outcome

Each of the above-mentioned recovery options will comprise of a subset of the following concrete ***recovery processes***:

- incoming inspection and sorting
- disassembly
- cleaning
- testing
- fixing/replacement
- (re)assembly
- shredding
- separation
- upgrading
- miscellaneous (product specific) processes

The actual characteristics of each of these recovery processes depend upon the recovery option they are part of. The subset and sequence of processes related to a specific recovery option will depend upon the characteristics of the incoming goods and output specifications. In general though, the most likely processes for each of the seven main recovery options can be determined. They are indicated in the scheme of activities given in Figure 2.

Before addressing the possibilities of applying and learning from quality tools in these concrete recovery processes (Section 5), it is wise to take a closer look at recent developments in the application of quality tools and principles in the traditional field of production of primary products (production processes). Therefore, Section 3 will give a brief overview of these recent developments as reported in literature.

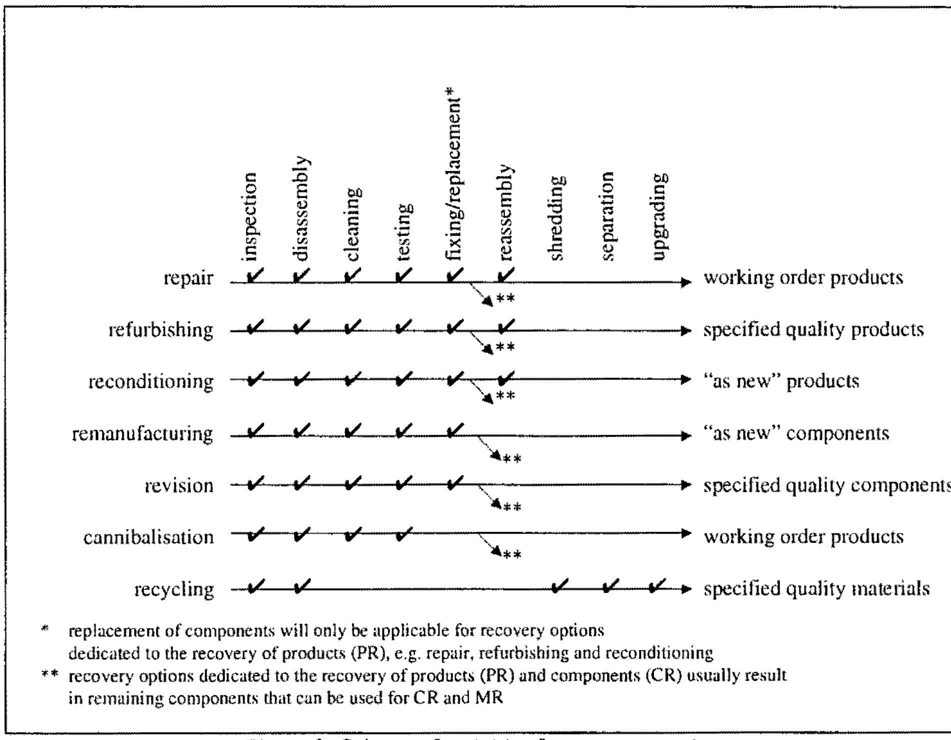

Figure 2: Scheme of activities for recovery options

3. Recent developments of quality tools in production processes

Traditionally, the application of quality tools and principles in production processes was directed towards realising a specified product quality for product users (external quality), mainly focussing on detection of parts and products that do not meet quality specifications. In recent years however, quality activities in production of primary products have moved away from detection-oriented inspections towards more preventive actions, thus reducing costs associated with production activities (internal quality). Key developments in the application of quality tools and principles have been:

- variation thinking instead of tolerance thinking,
- process thinking instead of product thinking,
- prevention through quality by design.

Variation thinking means that the purpose of conducting measurements is not to compare the outcome to tolerances (to separate good and bad products) but to know and control the amount of variation in the output of a process and the distribution in time. In stead of a pass/fail classification, measurement data are used to determine this variation (location and spread). Because of the need to quantify and predict variations, Statistical Process Control tools (SPC), such as Control Charts and Capability Studies [Montgomery, 1997], play an important role in applying variation thinking. The main purpose of a Control Chart is to monitor the stability (predictability) of the mean and spread of the output of a process (on-line), whereas the main purpose of a Capability Study is to asses how well the spread of the process output fits within predetermined tolerances (off-line).

Process thinking stresses the necessity to know cause and effect relationships, i.e. to know which process factors can lead to disturbances in the output of a process. This knowledge is required to control disturbing factors at the root, or even to remove causes of disturbances. Process thinking has lead to a shift from measuring and controlling the process output to measuring and controlling the process itself (e.g. materials, machine condition, operator influences and machine settings). Sometimes Control Charts can be used to control process factors, but it is more likely that other tools are more appropriate [Schippers, 1998]. Some examples of tools that can be used for this purpose are: maintenance of machines and tools [TPM, e.g. Nakajima, 1988], material checks, operator training and instructions, and Poka Yoke or foolproof devices [Shingo, 1986].

Process thinking and variation thinking thus lead to activities to control process variation during production. These activities can be referred to as 'on-line quality control'. Besides tools for monitoring and controlling the process, another group of tools can be applied for so-called 'problem solving' activities, which are used 'of-line'. These problem solving tools [Brassard, M. & Ritter, J., 1994; Montgomery, 1997] are used to analyse problems and to find and remove causes of variation. Some examples of commonly used problem solving tools are: fishbone diagrams, Pareto charts, checksheets and flowcharts. Because of their simplicity, these tools are applicable in most situations by both operators and engineers. Next to that, there also are more complex mathematical tools for problem solving, mostly used by engineers or other specialists. Some examples are: multiple regression analyses and Design of Experiments (DoE; a set of tools to set up and analyse experiments [Box et al, 1978]).

Another 'of-line' improvement tool that is frequently used is the Process Failure Mode and Effect Analyses (Process FMEA) [e.g. Stamatis, 1995; QS 9000, 1994]. It is aimed at finding the weakest points in a process, by calculating a Risk Priority Number (RPN) for possible disturbances, based on experience and judgements of people involved. The RPN is calculated by multiplying three sub-scores: the chance that a certain disturbance (failure mode) will occur, the severity of this disturbance, and the chance that it will be detected and resolved. Disturbances with a high RPN should be analysed and improved. An analyses using the above-mentioned tools can lead to extra (on-line) control activities, but also to alterations in the production process or even the (design of the) produced product.

The insight that some problems can be prevented by paying attention to quality when defining products and processes, has lead to the third key development in quality control: prevention through Quality by Design. One of the most effective ways of variation reduction is addressing this issue as early as in the development phase of products and processes. This way one can identify possible problems before actual production starts, so that control activities can be defined or even better, processes and products can be made robust for sources of variation. Tools to assist designers are partly the same as those for 'problem solving', since improvements can be seen as the redesign of a product or process (e.g. simple problem solving tools, DoE and FMEA).

A set of tools specially developed for product and process design activities (but can also be applied for process improvement), is Quality Function Deployment (QFD [Hauser & Clausing, 1988; Bossert, 1991]). The QFD method consists of four matrices. The QFD 1 matrix is used to translate (i.e. to deploy) customer requirements into (technical) product specifications. QFD 2 is used to translate product specifications into parts specifications. QFD 3 is used to translate the parts specifications into process steps and parameters. In QFD 4 the necessary process control activities are derived from these process steps and parameters. Although these matrices can be seen as coherent subsequent steps, in most cases the application of QFD is limited to using one of the matrices, usually QFD 1.

From the above, it can be concluded that applying quality tools in regular production processes is usually directed towards achieving the following main objectives:

- on-line control of production processes,
- improvement and (re)design of existing processes,
- quality by design.

4. Current quality practices in the field of recovery processes

Getting back to the field of recovery processes, given the demands a certain recovery strategy or option places on the quality of discarded goods, one should be able to control the quality of products during their complete life cycle. Current quality-directed activities in this relatively new field show a striking resemblance to traditional application of 'detection-oriented' quality tools in the field of production of primary products (before the above-mentioned recent developments). Quality-directed activities in recovery processes are currently largely limited to testing and inspection to specifications, to separate 'good' from 'bad' products. In a number of instances quality is not even measured, but only estimated as input for cost calculations.

Testing and inspection will certainly remain important in the field of recovery, because the input determines for a large part the appropriateness of certain recovery options and processes. However, taking a closer look at current practices reveals, it is certainly safe to say not all possibilities for applying quality tools and principles are fully exploited yet. Especially variation thinking and process thinking, as described in Section 3, have not been transferred to this new field up till now.

In literature dedicated to recovery processes, discussions concerning Quality by Design activities are usually limited to references to Design for Environment (DfE) activities. The importance of this range of activities is stressed extensively [e.g. Dambach and Allenby, 1995; Fiksel, 1993]. Actual DfE activities, as described in literature, are often focusing on translating the outcomes of Life Cycle Analyses into product requirements [e.g. Cramer, 1996] and introducing and applying general design rules in the design phase of products. Some examples of such design rules are Design for Disassembly and Design for Recycling [e.g. Warnecke & Düll, 1996], which are comparable with Design for Manufacturing (DfM) rules. Usually, these design rules are directed towards limiting materials, energy consumption and pollution in production and use, and use general checklists and guidelines, e.g. for choosing joint and connector types, in the product development phase.

Generally speaking, no attention is given to detailed characteristics of specific recovery processes (e.g. based on the recovery option they belong to) and suitability of specific product features in reference to these processes. Transferring Quality by Design activities, as discussed in Section 3, to the area of recovery processes would imply introducing such recovery requirements into the design phase of products, based on an analysis of the specific features and characteristics of products and recovery processes. These activities could be referred to as Design for Recovery (DfR). The next section will specifically address these DfR activities.

5. Transferring recent quality developments to recovery processes

This section will address the possibilities for applying quality tools and principles in the area of recovery processes, based on experiences and knowledge derived from application in traditional production activities and taking into account the characteristics of recovery processes. The following three subsections will give an analysis of possibilities linked with recovery processes to achieve the three main areas affiliated with the application of quality tools and principles:

- on-line control of recovery processes,
- improvement and (re)design of recovery processes,
- Design for Recovery activities.

5.1 On-line control of recovery processes

Looking at the differences between the areas of traditional production of primary products, and recovery of products, parts and materials from used or discarded goods, the most important difference refers to the incoming material flow. This will be an important factor to address, when applying quality tools and principles, especially regarding the first few processes of each recovery option. As was indicated in Section 3, process thinking stresses the importance of knowing cause and effect relations for (possible) process disturbances. With regards to recovery processes, the main disturbing factor will be the varying and unpredictable quality of incoming used and discarded goods.

In traditional production environments controlling the quality of incoming goods is mainly achieved by controlling previous processes (e.g. materials and parts production). Applying process thinking for recovery processes in a similar way would imply looking at the use-phase and first production, since the characteristics of used and discarded goods can be seen as the output of these processes. This would mean a change from current quality practices in the area of recovery, since these are mainly focusing on inspection and testing of incoming goods (also see Section 4). Next to that, variation thinking would imply that the primary purpose of conducting measurements regarding the incoming goods is not to compare to tolerances (to separate 'good' from 'bad' products, parts or materials), but to know and control the level of variation in the output of previous processes and the distribution in time. This knowledge will also make it possible to anticipate on variation patterns.

At this moment though, very little knowledge and suitable data are available in literature with regards to actual variation in characteristics of incoming goods and the distribution in time. Next to that, the possibilities to reduce and control this variation to a state of statistical stability have not been addressed in literature and practice, certainly not on an operational level. Therefore, this is an important subject for further research. Examples of tools that could be applied to analyse and control variation are: Capability Studies, multi-vari charts, multiple regression analysis and Control Charts.

Although the quality of incoming goods should be controlled by previous processes, sometimes it may not be possible to ensure a homogeneous flow of incoming goods to control the variation in the process output. In these situations, one can aim at creating a recovery process that is robust for these differences, try to control the variation in quality levels of incoming goods by mixing different batches, or anticipate on these differences by changing the process settings. Examples of recovery processes that could clearly benefit from mixing batches or anticipating on variation patterns, thereby controlling the process output, are separation and upgrading of materials. The process settings can be controlled using instructions and guidelines, which can be generated by Design of Experiments (also see subsection 5.2).

Controlling the variation in characteristics of (the flow of) incoming goods will be very important, but generally speaking it will not be sufficient to control a recovery process. Additional control activities should address the other dominant process factors. Based on the dominant process factors, recovery processes can be divided into processes that are largely depending on human factors, such as inspection, fixing, disassembly and reassembly, and processes that are largely automated/mechanised or use chemical processes, such as shredding, separation and upgrading.

For the human factor dominated processes, controlling the process will largely depend on factors such as level of concentration and craftsmanship. To control this type of process factors, quality tools, such as foolproof tools or Poka Yoke [Shingo, 1986], can play an important role. Two examples of the way these quality tools can be used in recovery processes are:

- A tray with numbered pictures of the parts that need to be recovered during a disassembly process. The operator is required to disassemble the incoming goods according to the sequence indicated on the tray and put the disassembled parts on the tray. This could ensure

the disassembly process to be executed in the optimal order and prevents forgetting to disassemble specific parts. This same tray could be used again for the reassembly process.
- Using spanners with a build-in mechanism to ensure the right torque force being applied during the reassembly process.

For automated and mechanised processes the state of the machine plays an important role and can be controlled by maintenance of machines and critical parts [e.g. Nakajima, 1988]. Next to that, the settings of the machines and processes can be controlled by using instructions and guidelines, e.g. regarding the concentration of cleaning fluids used during the cleaning process or temperature settings for chemical processes used in separation. Optimal settings can be generated by Design of Experiments (subsection 5.2). For some recovery processes, such as assembly and reassembly, it is to be expected that, through Design for Recovery activities and developments regarding recovery technologies, automation and mechanisation will become increasingly important. This would shift attention from controlling human factors to controlling machine settings and maintenance activities.

Concerning output measurements, recent developments in traditional production activities (also see Section 3) show that 100 % checks or detection-oriented sampling should not be the main means of controlling recovery processes. The primary goal of control activities using product measurements should be monitoring the stability of the recovery processes themselves, e.g. using Control Charts. Using product measurements to control the processes can be difficult when they concern assembled products that require complex functional testing or products that are produced in low volumes. However, specific tools for these situations are available [Wheeler, 1991].

Since the stability of the outcome of recovery processes largely depends upon the incoming materials, inhomogeneity of these incoming materials will often lead to inhomogeneity and thus unstable variations in the output, which makes application of statistical tools such as Control Charts very difficult. In cases where it is very unlikely to find a stable variation in the outcome, a sample of single measurements of a product does not give information about the underlying process and no predictions can be derived for subsequent products. In processes such as shredding or upgrading, however, the output is more likely to be stable. For such processes, stability and predictability of the quality of the outcome can be monitored by taking samples during recovery operations (using Control Charts).

5.2 Improvement and (re)design of recovery processes

Looking at problem solving tools, it can be assumed that most of these tools will be applicable in the field of recovery processes. Because of their simple nature, problem-solving tools like Pareto Diagrams and Fishbone Diagrams can be useful and appropriate tools for application in all recovery processes, without the need to adapt them. Other improvement and (re)design tools, such as Design of Experiments, FMEA and QFD will certainly be useful tools for application in various recovery processes, but the specific way to use them will not always be obvious and could require adaptation for specific recovery processes.

Design of Experiments can be used to determine the optimal settings for recovery processes, e.g. to determine temperature settings for separation processes or cutting time and speed for shredding processes. Next to that, Design for Experiments could assist in determining optimal material mixes, e.g. for upgrading processes, as indicated in the previous subsection.

Analysing incoming goods is an important step towards improvement and (re)design of recovery processes. To predict the suitability of incoming goods for specific recovery strategies, options and processes, tools such as multiple regression analysis and multi-vari charts could be useful. For linking characteristics of incoming goods or primary products to recoverability and suitability for specific recovery processes Paired Comparisons [Bhote, 1991] could be used.

A Recovery Process FMEA could be used to analyse weaknesses of specific recovery processes, e.g. a Disassembly Process FMEA. This tool would enable analysing possible problems resulting from weaknesses in the disassembly procedure, such as operators using too much force to disconnect joints, thus damaging reusable parts. The proposed improvement following from such an analysis could be to introduce a drill that will slip at a predetermined maximum force, thereby protecting recoverable products and components. It is also possible to use a Process FMEA that is specifically focused on possible problems through incoming materials. This type of Process FMEA could be referred to as a 'use oriented Recovery Process FMEA', to some extent resembling the UMEA suggested by [Penev, 1996]. It could be used to analyse the need to change recovery processes, to cope with differences between used or discarded goods and primary (new) products resulting from the use phase.

QFD matrices could play an important role in translating second hand market requirements to specific recovered product, component or material specifications, consequently resulting in improvement and (re)design of specific recovery processes. An example of applying QFD could be to use QFD1 to translate customer demands concerning upgraded materials to technical specifications of these materials. Such an analysis could even result in adding specific material fractions to the process to ensure specifications demanded by customers are fulfilled.

5.3 Design for Recovery activities

With regards to quality by design, the application of quality tools dedicated to this subject in the area of recovery processes will mainly refer to Design for Recovery activities. As discussed in Section 4, in literature several general Design for Environment guidelines, referring to suitability of product designs for recovery processes, can be found. These guidelines are usually directed towards a specific group of products [e.g. Penev, 1996]. Some examples of such guidelines are given in Table 2:

Design for ...	**General guidelines to ensure suitability**
incoming inspection and sorting	coding and labelling
disassembly	reversible connectors instead of welding/gluing
cleaning	use non-corroding materials
repair/fixing/replacement	replaceable modules
reassembly	Design for Assembly rules
shredding and separation	use mono-materials, less types of materials
upgrading	use non- or slow-degrading materials

Table 2: Examples of general recovery guidelines for product design phase

These general guidelines or checklists are not very specific. Therefore, DfR for actual processes belonging to a particular recovery option for a particular product, should be more detailed and specific. This requires the application of additional tools to generate such specific process-related product requirements and technical specifications ensued from these requirements.

A tool that can be used to translate requirements of specific recovery processes into product characteristics is a reverse QFD 3 matrix. A reverse QFD 3 matrix could be used to derive more specific requirements from actual characteristics of a recovery process. An example would be a separation process, which uses the specific gravity of materials to separate them. A reverse QFD 3 could then be a very useful tool to assist designers in translating the separation process characteristics to specifications for e.g. the materials and shapes to be used in the designed product.

Standard QFD matrices can also be used to introduce recovery requirements into the design phase of primary products. When translating functional specifications to technical specifications of a product, using a QFD 1 matrix, these requirements can be part of the functional specifications. These requirements can be integrated in the product definition process (QFD 1 & 2) and in defining production methods (QFD 3). A recovery process oriented product FMEA can be used to evaluate the suitability of a designed primary product for a specific recovery option or process, thus evaluating specific product features that could lead to disturbances in the recovery process.

This can be done for both the new product (as delivered to the customers) and the product after use by these customers (as delivered to the recovery processes). Next to that, a Recovery Process oriented Product-Use FMEA could assist in analysing what could happen (go wrong) in the use phase of a product, so that the used or discarded product is less suitable for a specific recovery option or process. The outcome of these analyses could be to change certain product features during the design phase, e.g. to make the product more robust for misuse, or to append a specific instruction for users to prevent misuse.

6. Conclusions and recommendations for further research

Based on the underlying analysis of this paper, the following can be concluded:

- The field of recovery processes is a relatively new and unexplored area of interest to most companies and researchers, which can be illustrated by the variety of expressions that are used to describe different recovery activities.
- Generally speaking, current quality practices in the field of recovery processes can be characterised as mainly detection oriented (some exceptions to this statement have been mentioned earlier).
- The field of recovery processes (and companies involved in these activities) could benefit from application of quality tools and principles aimed at achieving on-line control, improvement and (re)design, and quality by design. This could contribute to the further development of the field.
- This paper shows how quality tools and principles, directed towards achieving the three objectives mentioned above, can be applied in the field of recovery processes, which could assist companies in setting up effective and efficient recovery processes on an operational level.
- Quality tools and principles can be applied in recovery processes, in three different ways:
  - analogous to application in traditional production activities, e.g. 'problem solving' tools,
  - in an adapted form, e.g. a Use oriented Disassembly Process FMEA,
  - to integrate recovery aspects and others simultaneously, e.g. introducing recovery requirements in the design phase of products through application of QFD1.

The field of recovery processes could benefit from further research directed towards:

- prediction and determination of variation patters in characteristics of used or discarded goods,
- further development of quality tools and principles adaptations for the field of recovery processes,
- defining and distinguishing between different recovery activities [an analysis dedicated to this subject will be published by Melissen & De Ron, 1998],

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CARPET RECYCLING: THE VALUE OF COOPERATION AND A ROBUST APPROACH TO DETERMINING THE REVERSE PRODUCTION SYSTEM DESIGN

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Abstract

It is estimated that complete carpet recycling would avoid an estimated U.S. annual landfill cost of $65M and recover lost material value of $300M [1]. Designing an adequate reverse production system is critical to the economic viability of recovering this lost value. In this paper, we develop a robust mixed integer-programming model to support decision making in reverse production system design. A robust model seeks solution close to the mathematically optimal solutions for a set of alternative scenarios identified by a decision-maker

Large startup costs and competing technologies for the material and chemical recycling may lead to situations where inter-company cooperation would be mutually beneficial for all parties involved. In this paper, we apply the model to a representative U.S. carpet recycling industrial case study involving two different companies. The value of cooperation is explored, and a robust solution is found for two major sources of uncertainty, volumes of carpet collected and price of recycled material.

1.0 Introduction

Large-scale recycling networks are expensive and their design and operation are based on uncertain information. Setting up a reverse production system (RPS) in the U.S. to handle the roughly 4 billion pounds [5] of carpeting disposed of annually is a massive undertaking, especially due to the relative lack of existing infrastructure. Gathering required information about used carpet characteristics and amounts is expensive, difficult and time-consuming with little previous history to draw upon. To model the uncertainty that this lack of information creates, we assume that there will be "experts" who have established scenarios that represent different possible outcomes for infrastructure alternatives. These scenarios may represent different assumptions about how a market will respond to a price or how many local recyclers will be prepared to partner with a company. We believe that establishing these scenarios is more realistic than finding probability distributions for uncertain parameters and hence, we present a robust programming approach for the design of RPS infrastructure.

Flapper [7, 8] gives a systematic overview of the logistic aspects of reuse. Currently, most of the research in reverse production systems tends to be product or system specific due to the various features and complexities needed to handle the different recycling and reuse scenarios. Research on recycling and resource recovery

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for specific materials such as paper, plastics and sand include [2, 11, 16]. Building and iron production waste recycling, resource allocation, and planning are presented in [19]. Similar to the approach presented in this paper, Spengler, *et al.* [19] define a location/allocation model to determine the number, size, and location of reclamation facilities and demanufacturing plants. Our model extends this to include multiperiod and robust aspects.

Published works in robust optimization cover many of the basic formulations of optimization problems, but are currently limited in scope and complexity. Mulvey [15] makes a case for the application of robust optimization as superior to stochastic optimization when dealing with single or infrequent decisions high in uncertainty. Current robust models have addressed problems that include multi-period layout planning, scheduling, international sourcing and the knapsack problem from [6, 9, 12,20]. Gutierrez [10], develops a robust approach for uncapacitated network design and proposes a solution using a Benders' decomposition approach [3].

2.0 Reverse Production System Model

A verbal description of the deterministic mixed integer-programming model for reverse production systems, (RPS), as given in Realff [17] can be stated as.

Maximize: *Net Profit* (Revenues – Operating and Fixed Costs)

Subject to: ***Flow balances between sites***
(based on material consumed and produced by the tasks located at those sites).

Upper and lower bounds
on storage, transportation and processing of material at sites.

Logical constraints on sites,
such as the need to open a site before allowing tasks to be located there.

This model provides the mathematical basis for in the following synergy study and is extended for our robust study.

2.1 Robust Reverse Production System Model

A robust modeling approach differs from a stochastic approach in that, in the former, probabilities are not associated with the uncertainties. Instead, all scenarios deemed potentially realizable are enumerated, and a solution is sought which is suitably 'close' to the optimal solution for each scenario. This overall solution may or may not be mathematically optimal for any of the potential scenarios.

Kouvelis [13] defines 'close' in several different ways. In this paper we will use the measure of robust deviation which is defined by Kouvelis as:

> *The performance measure (appropriate for the single scenario decision) is applied for evaluating the decision across all scenarios, and then the worst case performance is recorded as the robustness indicator of the decision.*

Thus we will subtract the optimal solution for each scenario from the robust solution and determine how 'close' it is by the maximum deviation for any scenario. The 'optimal' robust solution will be the one with the minimum maximum deviation.

The RPS model from Realff [17] is extended to develop the robust formulation. After the scenarios are determined, the model is used to obtain the optimal solution for each scenario. Then, a multi-period formulation of the model is used to get the robust solution. The only parameters which vary between periods are those which are determined to change in the scenarios. The multi-period model is used to obtain the robust deviation solution as defined by Kouvelis [13].

The most significant change in the RPS model from [17] is the alteration of the objective function. Define Ω as the set of all specified scenarios, then the optimal solution value for a scenario $\omega \in \Omega$ is $O_\omega{}^*$ as found by the original RPS model. R_ω is the value of the objective function for the robust configuration under scenario ω. The robust model can be stated as:

Minimize: δ

Subject to:

$$\delta \geq \{O_\omega{}^* - R_\omega\} \qquad \forall \omega \in \Omega$$

R_ω = ***Net Profit for scenario ω***
(Revenues – Operating and Fixed Costs)

Flow balances between sites for each scenario ω
(based on material consumed and produced by the tasks located at those sites for each scenario).

Upper and lower bounds for each scenario ω
on storage, transportation and processing of material at sites, this is constant over all scenarios except for upper bound on the volumes of materials collected.

Logical constraints on sites across all scenarios,
such as the need to open a site before allowing tasks to be located there, this is constant across all scenarios.

The model was solved with a commercial mixed integer programming solver AIMMS [4] on a 200 Mz Pentium Pro Windows NT system. The model contained at most 327,318 constraints, 311,136 continuous variables, 3,774 integer variables and 1,812,660 non-zeros (robust formulation). The solution times ranged from half an hour to nine hours. In section 3, the basic model will be used in the synergy study, while the robust version of the model will be used in the robust study.

3.0 Model Application to Strategic Infrastructure Design

To illustrate the use of the model presented in this paper, we have developed two case studies. The case studies involve two hypothetical U.S. companies, A and B.

Company A has developed a process for the depolymerization of nylon 6 to Caprolactam (depolymerization A, or DepolyA), and has a used carpet collection infrastructure partially in place. Company B has developed a different process of depolymerization of either nylon 6 or nylon 6,6 to hexamethylene diamine, or HMD, (depolymerization B or DepolyB) and has a different used carpet collection infrastructure partially in place. Company A is willing to build processing sites at Houston, TX, Birmingham, AL or Port Elizabeth NJ. Company B is willing to build processing sites at Bakersfield, CA, Chattanooga, TN or Kingston, ON. The potential processing and collection sites can be seen in Figure 1.

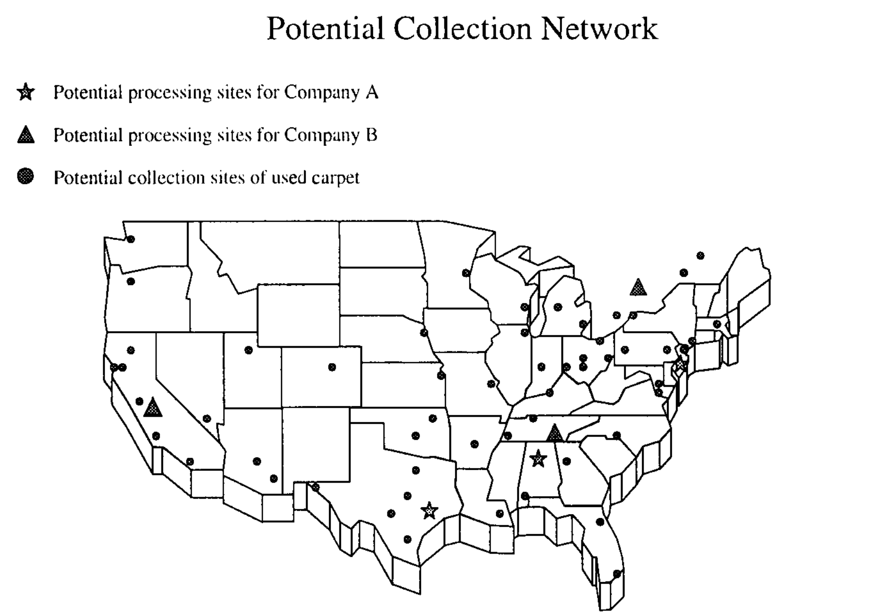

Figure 1. Geographical Distribution of Carpet Collection and Reprocessing Network

In all scenarios, the collecting company charges an amount to collect the used carpet. This is not strictly necessary, since in most scenarios, positive revenues were generated when a small fee is paid for collecting. But it was decided that charging for collection of carpet was more realistic, either through taxes, incentives, or a charge to retail establishments.

Sorting of used carpet is considered to be done by hand, but with some relatively inexpensive equipment. Thus carpet costs $0.01 a pound to sort, but the overhead is relatively inexpensive at the processing sites, and greater volumes can be done. Sorting is allowed at each of the collection sites, but a workspace and storage facility must be used, and so $50,000 annually is added to the overhead cost of on site sorting.

We are not aware of any depolymerization technique for either polyester or polypropylene carpeting, so carpet of this type is only allowed to be landfilled, or ground into shoddy for resale. Shoddy can be used for furniture stuffing and the stream of dirt, calcium carbonate, and latex can be used as a soil enhancer. Shoddy is sold at a modest price at a processing site, while the soil enhancer is given to a local nursery or garden shop. Other waste from the processes and unwanted carpet after sorting is disposed of at a local landfill, with a corresponding tipping fee.

The cost of processing facility is assumed to include the ability to depolymerize up to the capacity at no additional charge. Each site is limited to one depolymerization facility and Company B can also include grinding machinery at its sites. It is also assumed that either type of depolymerization process can triple its capacity by doubling the equipment cost. This is done to incorporate a notion of 'economy of scale' for the processing capability. Table 1 provides additional data used in the analysis.

Table 1. Prices used in scenarios.

Description	Value
Selling Price of Caprolactam from [18]	$0.93 per pound
Selling Price of HMD (Hexamethylene diamene)	$0.80 per pound in Synergy Case study
Selling Price of HMD (Hexamethylene diamene)	$0.70, $0.90 and $1.10 as low, medium, and high in Robust Case Study
Selling Price of Soil Enhancer	0
Selling Price of Shoddy per pound	$0.20 per pound
Dumping of Carpet from [14]	-$0.025 per pound
Charge for collection in Scenarios	$0.02 per pound
Cost to sort used carpet	$0.01 per pound
Setup cost to sort at a processing site with 60M capacity	$1,714 per annum*
Setup cost to sort at a non-processing site w/ 60M capacity	$51,714 per annum
Cost to set up for Grinding 60M pound capacity	$1,534,000 per annum
Cost of Grinding	$0.01 per pound
Setup cost Depolymerization for 100M lb capacity	$7,570,000 per annum
Setup cost Depolymerization for 200M lb capacity	$11,430,000 per annum
Cost to set up Depolymerization for 400,000,000 pound capacity, both types	$17,320,000 per annum
Cost of shipment	$0.06 per ton per mile
Cost for opening processing site	$1,000,000 per annum
Total amount of used carpet allowed to be collected by each company in the Synergy Case Study	Approximately 250,000,000 lbs.
Price charged to Company A by Company B for Nyon 6	$0.29 per pound
Price charged to Company B by Company A for Nyon 6	$0.15 per pound
Total amount of used carpet allowed to be collected in each of the robust scenarios	Low(L) – 267,268,417 lbs. Medium(M) – 494,236,525 lbs. High(H) – 698,767,776 lbs.
Used Carpet make-up	Nylon 6,6 - 43% Nylon 6 - 28.5% Polypropylene - 18% Polyester - 10.5%

*Annualized costs are based on taking the total capital costs and depreciating them over seven years to generate an annualized equivalent cost.

3.1 Synergy Case Study

In the first case study, we will use the model to determine the impact of cooperation between the two companies by sharing collection resources. Scenario 1A is the case of Company A using only its existing infrastructure without interaction from Company B. Scenario 1B is Company B using only its existing infrastructure without interaction from Company A. Scenario 2AB is from the perspective of Company A selling sorted carpet to Company B, while Scenario 2BA is the reverse case. Scenario 3 has Company A selling Nylon 6,6 to Company B and Company B selling Nylon 6 to

Company A. Scenario 4 is from the overall perspective, in which the total net revenue is maximized regardless of company and a processing site was required for both companies.

As can be seen from Table 2, the greater the cooperation, the more profitable it is for both companies. However, Company A has to pay a substantial premium to Company B to get its Nylon 6 since, due to the greater volumes Company B can use, it can employ better economies of scale. For scenarios 2AB and 3, we used the marginal price to determine the selling price; $0.29 is just above the marginal, which explains the small increase in net revenue for company B between scenarios 1B and 2AB. The price of Nylon 6,6 to Company B is substantially above the marginal. However, since it is currently being disposed of by Company A, it would be doubtful that it would be sold just above the marginal.

It must be stressed that the costs in the synergy case studies do not reflect actual costs, but instead illustrate ways in which our model can distinguish when and how cooperation can be mutually beneficial.

Table 2. Net revenue of optimal solutions.

Scenario	Company A	Company B	A and B combined
1A	$11,715,200	-	-
1B	-	$36,368,513	-
1A + 1B	-	-	$48,083,713
2AB	$14,241,617	$36,530,190	$50,771,807
2BA	$27,880,141	$46,956,086	$74,836,228
3	$23,744,731	$45,215,839	$68,960,570
4	$25,711,605	$56,311,095	$82,022,700

3.2 Robust Case Study

In the robust case study, we determine nine scenarios based on three different levels of two parameters, collection volume and the price of HMD. All other parameters are held constant. We will consider scenarios where the collection volumes grow in both volume and geographic diversity at a low, medium and high level. We accomplish this by increasing the number of cities included in successive levels as well as increasing the amount of used carpet that can be collected from each of the cities. The maximum amount of used carpet that any city can provide is based both on the size of the metropolitan region and how easy it is believed to be able to collect used carpet from that city. Our second parameter of concern, the price of HMD, is varied at $.70, $.90, and $1.10 per pound. The price of caprolactam was not varied since a ten-year review by [18] showed a steady rise in the price of caprolactam which can easily be explained by inflation with one brief exception. Thus we believe that the price of caprolactam is sufficiently stable. Three alternative settings for collection volume, and three for the price of HMD, result in 3x3 or nine alternative scenarios to be investigated. The optimal configurations for each of the nine scenarios and the robust solution can be found in Table 3.

Table 4 gives the differences between the revenue generated by the optimal configuration for each scenario and the revenue generated for this scenario by the robust solution configuration. The robust configuration is not identical to any of the optimal configurations for the alternative scenarios, but it is closest to the Medium volume, Low HMD price scenario. The robust solution is within $14,543,000 and 70%

of the optimal for all scenarios. Within the Medium and High volume scenarios, the robust solution is within 10% of the optimal. The revenue generated by the optimal solution for each scenario can be found in Table 5. In Table 5, the worst case configuration is considered to be the configuration taken from the nine scenarios which gives the lowest revenue amount. As can be seen, the value of perfect information is high, since the values are 40% to 70% of the optimal net revenue for each scenario.

Table 3. Optimal values for the robust scenarios, ω.

Collection	**L**	**L**	**L**	**M**	**M**	**M**	**H**	**H**	**H**	**Robust Solution**
HMD Price	**L**	**M**	**H**	**L**	**M**	**H**	**L**	**M**	**H**	
Sorting										
Atlanta								•	•	
Bakersfield								•	•	
Birmingham				•	•		•			•
Chattanooga	•	•	•	•	•	•	•	•	•	•
Dallas				•	•	•				
Denver				•	•	•	•	•	•	
Detroit				•	•	•				•
El Paso							•			
Las Vegas							•			
Los Angeles	•	•	•	•	•	•	•	•	•	•
New York				•	•	•		•	•	
Oakland	•	•	•	•	•	•	•			•
Phoenix				•	•	•	•	•	•	•
Portland	•	•	•	•	•	•	•	•	•	•
Riverside	•	•	•	•	•	•	•			•
Sacramento				•	•	•	•			
San Antonio				•	•	•				
San Diego	•	•	•				•			•
San Francisco	•	•	•	•	•	•	•			•
Seattle	•	•	•	•	•	•	•	•	•	•
Processes										
Chattanooga Depoly B 200*	•	•	•							
Chattanooga Depoly B 400				•	•	•	•	•	•	•
Chattanooga Grinding 60	•	•	•	•	•	•				•
Chattanooga Grinding 120							•	•	•	
Bakersfield Depoly B 200								•	•	
Birmingham Depoly A 100				•						•
Birmingham Depoly A 200							•			

* The number after a process indicates the process capacity in millions of pounds annually

There is a strong preference for DepolyB in the model, even when the revenue for selling HMD is less than caprolactam. This is due to the volumes involved, and the fact that DepolyB can process both Nylon 6 and Nylon 6,6. This means that in the optimal solutions DepolyB processes 250% of the material that DepolyA gets from the same amount of used carpeting. We have found that volume is a strong driver in carpet recycling, and a process that can handle a greater percentage of the used carpet returns will enjoy a natural advantage, provided its capital and operating costs are not prohibitive.

Table 4. Optimal values for individual scenarios and for robust solution configuration.

Collection Volume	HMD Price	Optimal Net Revenue	Robust Configuration Net Revenue	Optimal – Robust Net Revenue	% of Opt.	Solving Time (Sec)
Low	Low	$32,588,300	$25,406,200	$7,182,100	78.0	2402
Low	Medium	$48,298,700	$34,814,000	$13,484,700	72.1	1939
Low	High	$64,015,900	$49,480,700	$14,535,200	77.3	1971
Medium	Low	$69,012,400	$66,872,900	$2,139,500	96.9	9315
Medium	Medium	$95,353,700	$87,934,000	$7,419,700	92.2	2049
Medium	High	$124,414,800	$115,539,000	$8,875,800	92.9	2085
High	Low	$108,797,600	$99,971,800	$8,825,800	91.9	2840
High	Medium	$137,427,200	$131,972,000	$5,455,200	96.0	2675
High	High	$178,515,000	$163,972,000	$14,543,000	91.9	1697

Table 5. Worst case comparisons.

Collection Volume	HMD Price	Optimal Net Revenue	Worst Case Configuration Net Revenue	Optimal –Worst Net Revenue	% of Opt.
Low	Low	$32,588,300	$15,580,700	$17,007,600	47.8
Low	Medium	$48,298,700	$29,211,000	$19,087,700	60.5
Low	High	$64,015,900	$43,879,800	$20,136,100	68.5
Medium	Low	$69,012,400	$37,918,800	$31,093,600	54.9
Medium	Medium	$95,353,700	$53,918,800	$41,434,900	56.5
Medium	High	$124,414,800	$69,918,800	$54,496,000	56.2
High	Low	$108,797,600	$38,938,300	$69,859,300	35.8
High	Medium	$137,427,200	$54,938,300	$82,488,900	40.0
High	High	$178,515,000	$70,938,300	$107,576,700	39.7

The greater profitability of caprolactam drives the creation of DepolyA at the low HMD price levels, but even here, there is a preference for the DepolyB process. Both of these are taken into account in the robust solution as shown in Table 4.

4.0 Conclusions and Extensions

In this paper we develop insights into the value of cooperation through the application of the RPS model. We then extend the model into a robust form, and use it to find a robust solution that performs well over a set of scenarios. The robust solution is particularly suitable for the design of RPS since these systems are traditionally expensive, difficult to change, and there is not enough quality information to formulate a stochastic programming-based approach.

Our next step is to extend these results to the modeling and solving of more extensive versions of the problem and to different product types with similar RPS features. For the use of the model to be practical, the solution approach needs to be improved so that larger models can be solved in reasonable amounts of time. We believe a traditional decomposition approach may be effective for this. The potential for companies to collaborate in the design and operation of reverse production systems is high. Models like ours can be used to represent and highlight these synergies and shed light on the efficient design of the industrial ecologies of the future.

5.0 Acknowledgements

This research has been partially supported by the Consortium for Competitiveness in Apparel, Carpet, Apparel and Textile Industries (CCACTI) of the State of Georgia. The authors are grateful for the generous interaction and guidance provided from many industry experts, especially those from Mark Ryan of DuPont and Mike Costello of Allied Signal. We value the input from Georgia Tech Ph.D. student Selin Cerav. It should not be assumed that the results in the paper's case studies can be used to judge the economics of current carpet recycling efforts. Although the data is representative of general trends and qualitative differences, none of the numbers or networks described can be interpreted as the operational reality of any existing company or system.

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Activities of Japanese Industry for Product Recycling

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Abstract
The amount of waste in Japan has increased tremendously during the last years. Thus, it has become one of the most important environmental problems. As there is a strong trend for tightening legislation, Japanese producers are increasingly obliged to take disassembly and recycling of their products into account. Since local and cultural barriers still exist, this paper gives an overview of the general situation, regulations and policies, as well as ongoing activities and trends in Japanese industry. In addition, approaches to disassembly and recycling of automobiles, household appliances, copy machines, single use cameras, IT-equipment and vending machines are summarized and discussed.

1 General Situation

The combination of highly advanced industries geared towards mass production and a social system that encourages mass consumption has led to massive generation of waste in Japan /1, 2/. General waste and industrial waste have increased every year and reducing its volume is presently one of the most important environmental problems /3/. General waste refers to trash disposed of by households and offices, whereas industrial waste arises from industrial activities, such as production processes. Currently, about 50 million tons of general waste are disposed of annually /3/. As for industrial waste the total volume amounts to about 400 million tons /4/. The traditional approach of waste treatment in Japan, starting with its collection by local governments and subsequent incineration or burial in landfills, can no longer be handled this way. On one hand, incineration is a major source of dioxin. On the other hand, general waste landfills will be filled up in about 9 years on average nation-wide and about 5 years in the metropolitan areas /1/. Moreover, current sites for disposal of industrial waste are expected to be filled up in two to three years in real terms /1/ and the construction of new sites creates serious social problems. In addition to the shortage of landfill sites, the extraordinarily high price of land makes dumping extremely expensive /3/. Therefore, it has become urgent to reduce and recycle waste (Figure 1).

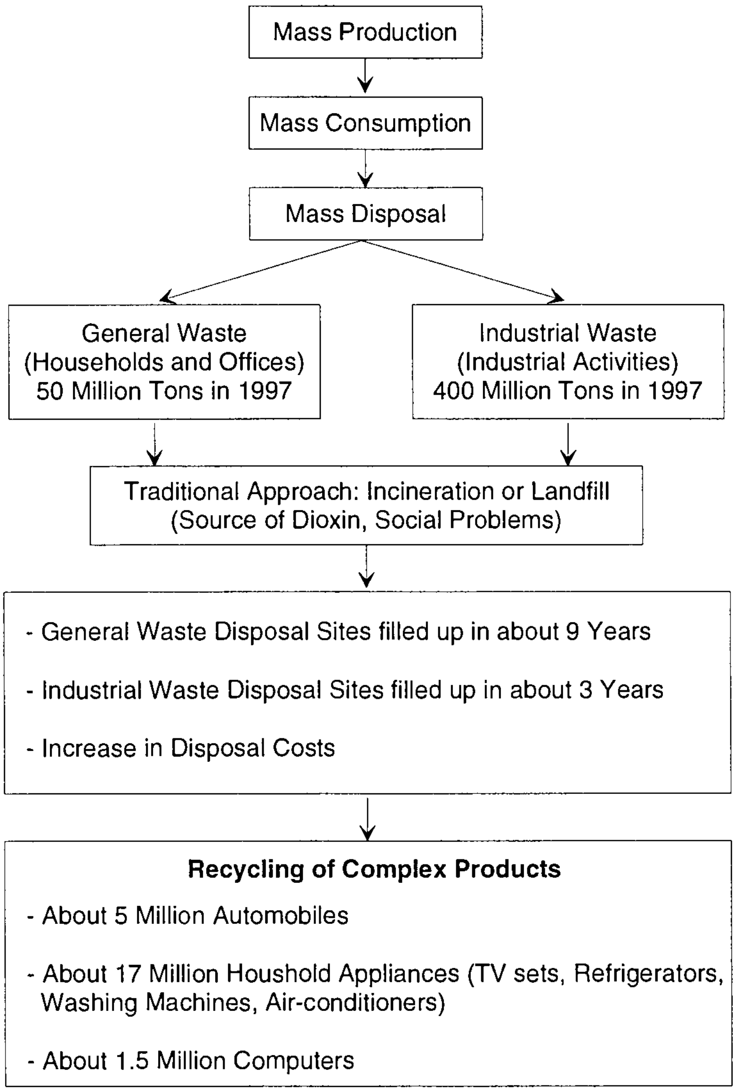

Figure 1: Waste Management in Japan

In 1993 the cumulative number of registered automobiles reached 63 million units /5/. Their estimated lifetime is about 8 - 10 years /6, 7/ with an average usage of 100,000 km /5/. The number of automobiles scrapped annually reached about 5 million in 1996 and is expected to top 6.5 million in the year 2000 /7/. In 1993 a total of 190 shredders were in operation /5/. The leftover material mix produced by shredding products is called shredder dust. The amount of shredder dust originating from automobiles totals more than 1.2 million tons per year /5/. The cost of disposing this dust is increasing rapidly. The rate in the Tokyo area in 1992 was 15,000 Yen per ton. However, at this time burial of shredder dust in controlled disposal sites was not required. In 1993 about 5,000 recycler existed in Japan with an average manpower of 1 - 3 people, capable of processing 2.3 automobiles per day /6/. Some of them are connected by computer networks to enhance their business. An example is Nippon Good Parts Group /6/.

In 1996 the estimated number of discarded TV sets, refrigerators, washing machines and air-conditioners amounted to 17.42 million units with a total weight of 650,000 tons /1, 8/. These items account for about 80 % of all electric home appliances discarded annually /1/. The average lifetime is 9.7 years for TV sets, 10.2 years for refrigerators, 9.0 years for washing machines and 10.2 years for air-conditioners /9/. Moreover, in 1997 about 1.5 million PCs had to be disposed of /10/.

In addition, it can be stated that a second hand market for consumer goods, excluding automobiles, exists only on a small scale in Japan. This is due to two main reasons. On one hand, consumers are very critical and worried about problems that might occur with second hand products and prices remain relatively high. On the other hand, producers are concerned about product liability and their image in case problems arise. Also, the society is very innovation friendly, thus leading to frequent replacement and disposal of consumer goods. Producers take advantage of this tendency by releasing new product models at a fast pace. Limited space can also be a contributing factor to this pattern of early replacement.

2 Regulations and Policies

In October 1991, Japan enacted the "Law for Promotion of Utilization of Recyclable Resources" (Recycling Law) drafted by the Ministry of International Trade and Industry (MITI). The objective is to reduce the amount of waste and promote recycling by designing products for ease of recycling. Producers of washing machines, TV sets, air-conditioners, refrigerators, automobiles and products containing nickel cadmium batteries, such as personal computers and portable phones (type 1 products) are required by the law to develop a system for evaluating the environmental impact of their products in both manufacturing and disposal /11/. Moreover, the materials used in product components must be documented in order to facilitate disassembly and recycling after disposal.

Additionally, in July 1992 an amendment to the "Law on Waste Disposal and Public Cleanliness" (Waste Disposal Law) by the Ministry of Health and Welfare was enacted. It allows municipalities to request disposal assistance from producers of products designated by the ministry as "difficult to dispose of properly" /12/. Included are large TV sets and refrigerators since their design has been judged as inadequate to the recycling law. In this way producers are forced to consider a proper recycling of their products.

In November 1993, the "Basic Environment Law" was enacted. It concerns waste management and recycling and forms the basis for the Japanese policy regarding fundamental environmental issues. In September 1994 the Waste Disposal Law was revised stating that shredder dust has to be buried in controlled disposal sites. In April 1997 the "Container and Packaging Recycling Law" went into effect and in June 1998 the "Energy Saving Law" was revised. In addition, in January 1998 the Japanese automobile manufacturers published a voluntary declaration stating their objectives for automobile recycling. The main points are that in 2002 new automobiles will be designed so that 90 % (weight) can be recycled; the use of lead (excluding batteries) will be reduced to 50 % by 2000 and to 33 % by 2005. Furthermore, in 2002, 85 % and in 2015, 95 % (weight) of discarded automobiles will be recycled.

Moreover, in June 1998 the "Electric Appliance Recycling Law" released by MITI and the Ministry of Health and Welfare was enacted. It aims at the recycling of washing machines, TV sets, air-conditioners and refrigerators and states that by the year 2001 producers of those home appliances are required to collect their products and recycle them. Furthermore, the intention of the government is that the consumers pay between 2,000 and 8,000 Yen for product disposal. Additionally, the manufacturers have to announce the recycling costs of their products. So far, the law does not cover computers, monitors and other IT-equipment (information technology), but there are already plans to include them in the near future.

The creation of an ecology-friendly society is one objective in MITI's overall program to redefine and reform the economic system of Japan. To do so, MITI has taken a long-term view in their efforts. By 2010 it is expected that the Japanese waste and recycling market will grow from its present size of approximately 15 trillion Yen ($ 112 billion) to 37 trillion Yen.

Related employment is projected to expand from a current level of 640,000 to about 1.4 million /1/. With the creation of jobs and the growth of a new industry in mind, MITI actively promotes R&D in the private sector through low-interest loans and tax incentives.

In conclusion, there is a strong trend for tightening the legal conditions. Producers are increasingly obliged to assist in the recycling of their products. This development is similar to the policy in Germany. The general consensus in Japan is that to tackle environmental problems, industry, administration and the general public have to act together to achieve breakthroughs. With this objective in mind, the Waste Management Division of the Ministry of Health and Welfare, the Environment Division of the Ministry of Agriculture, the Environmental Agency of the Ministry of Interior and the Environmental Division of MITI might soon form a separate Ministry of Environment.

3 Current Activities in Industry

A survey was conducted in order to get an overview of activities of Japanese producers regarding disassembly and recycling. The survey was carried out with 15 of the most advanced Japanese companies regarding environmental considerations. They are leading companies in their business areas and market their products worldwide. The information was gathered by way of personal interviews with open-ended questions. Therefore, the statements of the interviewees exhibit a wide range in their level of abstraction. In addition, the information was not limited to one specific field. Since most of the companies are active in a broad business area, the experts who provided the information represented a variety of branches and divisions. Furthermore, the background of the more than 50 interviewed experts influences the picture (Figure 2). Also, some information had to be treated confidentially and can, therefore, not be included in this paper. Due to the aforementioned reasons the statements are neither assigned to single companies nor weighted. Rather they are grouped into categories and subsequently ranked within them. Using this procedure the intention is to provide an overview and show trends.

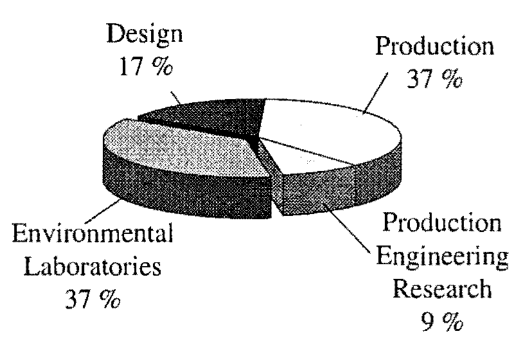

Figure 2: Background of the interviewed experts

All of the 15 companies have already declared environmental strategies. Current priorities are mainly given to material utilization. Only four companies ranked re-use of components first. They are active in the camera, copy machine and computer business. Producers mostly prefer material and thermal recycling because the major criteria in the Japanese market are cost and product liability. When asked about the economic attractiveness, or the potential profitability, of recycling 7 out of 15 companies, almost 50 %, stated recycling might become a business in the future (Figure 3). However, it should be noted that the majority of optimistic replies were given by experts from either corporate environmental laboratories, or production departments of companies already running a profitable recovery business.

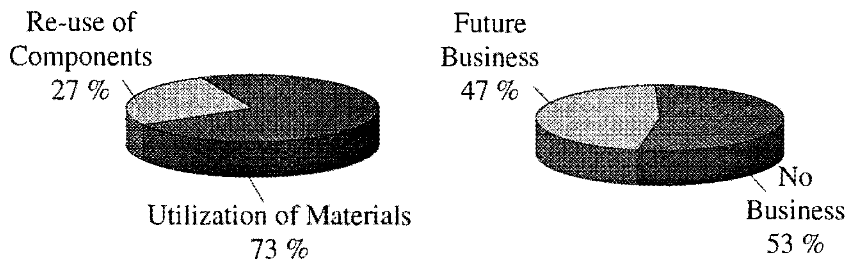

Figure 3: Priorities and attractiveness of recycling

A summary of implemented and ongoing activities regarding product disassembly and recycling is listed in Table 1. They are categorized into design and recycling related issues. The single statements of the experts were summarized and subsequently ranked according to how often they were mentioned.

Category	Actions taken or in progress
Design	• design guidelines for ease of (automated) disassembly, recycling, identification, material selection (checklist based) • LCA software development and/or application • development of CAD or spreadsheet calculation software-based disassembly evaluation methods • reduction of number and types of components and joining elements • standardization of plastics • material coding • reduction of hazardous materials (e.g. lead, cadmium) • development of environmentally friendly materials (e.g. lead free solder) • unification of plastic grades • concepts and prototypes for environmentally friendly products • modular design • replacement of plastics by metal (e.g. aluminum housing)
Recycling	• recycling of copy machines, single use cameras, IT-equipment, bumper, remanufacturing of vending machines • experimental recycling of automobiles, TV sets, refrigerators, air-conditioners, washing machines • CFC removal and recycling • development of recycling systems for printed circuit boards • experimental recycling of plastics • development of plastic identification equipment • development of shredder dust recycling technology • issuing of recycling manuals for automobiles • development of an airbag activation system • remanufacturing of automobile components (e.g. starter, dynamo, diesel injection pump, digital meter, car navigation system)

Table 1: Activities regarding disassembly and recycling

At the design stage the main focus is on issues supporting material utilization. Special attention is paid to plastics, hazardous materials and the development of new materials. However, efforts are also being made to consider the disassembly of future products, and thus, support potential re-use of components. At the recycling stage emphasis is also given to material recovery. Nevertheless, for some products, disassembly and recycling processes and systems are already established or under investigation. Surprisingly, the remanufacturing of automobile components, as is presently done by German producers, is carried out on a small scale only. The Japanese automobile manufacturers are worried about problems that might occur and product liability. Therefore, there is a conservative attitude about entering this market. Nevertheless, some independent recyclers remanufacture automobile components.

In the following sections selected recovery approaches will be introduced and discussed. Presently, companies jointly carry out extensive basic R&D activities for disassembly and recycling. This typical Japanese approach aims to combine existing technologies, save costs, and gather know-how. Based on the results, the individual companies continue their investigations independently. Two examples are the joint activities of automobile manufacturers and producers of household appliances.

Efforts to recycle discarded automobiles are carried out under the leadership of JAMA (Japan Automobile Manufacturers Association). JAMA is a non-profit association comprised of the 13 Japanese manufacturers of passenger cars, trucks, buses, and motorcycles. The investigations are especially focused on reducing the volume of shredder dust, development of recycling technologies and vehicles that are easier to recycle. A project titled "Development and Practical Testing of Technology for the Treatment of out-of-use Automobiles" was initiated at the end of 1996 and is to be completed in 1999 /13/. Hereby, it is aimed at reducing the shredder dust from 25 to 15 %. This is to be accomplished by the development of equipment and technologies for disassembly and treatment of components specified by the Ministry of Health and Welfare, as well as components whose recycling is considered practical, such as glass, tires and bumpers. However, a remanufacturing of major components like engines or gearboxes is not intended.

Current activities regarding disassembly and recycling of household appliances are organized by the Association for Electric Home Appliances (AEHA). Products focused on are TV sets, refrigerators, washing machines and air-conditioners. An experimental demonstration plant with a capacity of about 150,000 units per year was set up. This equals the amount of appliances discarded in a Japanese city of 1 million inhabitants /8/. Its operation started in April 1998. The investment costs are approximately 3 billion Yen (excluding land) with operational costs at 60,000 Yen per ton (three shifts). About 40 - 45 workers are needed for its operation. Its aim is twofold: 1) To develop and realize technologies for labor-saving, safe and efficient material recycling processes. 2) To develop and establish an integrated system covering everything from the collection to the recovery of valuable materials and their detoxification /8/. The plant was jointly developed by Mitsubishi Electric Corp., Hitachi Ltd., Mitsubishi Materials Corp., Matsushita Electric Industrial Co., Ltd. and Sony Corp. However, the objective of the demonstration plant is to compile fundamental data and gain experience in mass recovery of materials for utilization. Re-use of components is not a consideration.

Nevertheless, not all activities regarding disassembly and recycling are carried out jointly. Individual producers like Nissan, Fuji Xerox, Fuji Photo Film, Fujitsu and Fuji Electric are either already running a successful recovery business or do their own practical investigations on a bigger scale. The following section provides a more detailed insight in the recycling activities of the above mentioned companies.

In October 1997 Nissan set up a prototypical automobile recycling facility, including a sales shop, with the primary purpose of obtaining market information. Currently, 45 different components are offered as "Green Parts". Taking the variety of car models into account 3,000 different components are available. The current sales volume is approximately 4 million Yen per month. Nissan contracted an insurance company to provide liability coverage for any incidents caused by the recycled components. Most of the customers are either people with low incomes or owners of older model cars. Components for newer models are rarely ordered since demand for them usually stems from automobile accidents. In such cases, the cost of repair or replacement, carried out by a professional mechanic or garage, is covered by insurance. The general automobile recycling procedure is similar to the one used in Germany. Components disassembled for re-use are subsequently cleaned, wrapped, labeled and stored in a warehouse. Engines considered for re-use must have less than 80,000 km of use, and are tested to insure they function properly. No remanufacturing of components takes place. The process that was developed aims at small-scale recycling based on the structure of the Japanese market. The process is partly mechanized. Some data is given in Table 2. It should be pointed out that the current operation costs of the facility (without investment costs) are covered by the proceeds.

Site area	8660 m^2
Overall capacity	300 cars per month, in the future 600
Manpower in operation	5 workers, 2 administrators
Average proceeds from last car owner	3,000 Yen
Average proceeds for Al and St per car	2,000 Yen (depending on separation quality)
Average proceeds for re-used components per car	15,000 - 20,000 Yen
Price of components in relation to new ones	35 - 50 %
Average costs for CFC per car	3,000 Yen
Equipment costs	130 million Yen

Table 2: Selected data of Nissans automobile recycling facility

In 1995 Fuji Xerox established a system to recover components and materials from collected copy machines. Currently, 28 different machines are recycled. A product database was established by systematically collecting field data from each machine. Using this data, the company can estimate the remaining lifetime of components and identify which ones are suitable for re-use prior to recycling. Collected machines are classified by usage, which is based on the number of copies made. The disassembly and cleaning processes are carried out in a line. The machines are transported using AGV`s that are also used in the production line. For the most part, simple tools such as electric screwdrivers and cutting pliers are used for disassembly. However, water jet cutting is also applied. To assure an appearance comparable to new products, very advanced technologies are used for cleaning. CO_2-dry-ice blasting is utilized for large units like the frame, while small components are cleaned using ultrasonic waves. These processes are highly automated. Components that pass subsequent quality inspections are used in the production of new machines. Fuji Xerox makes no distinction between machines which contain components. All of them have the same price, service and performance. Although the average lifetime of a machine is 3 - 4 years, they come with a 5-year warranty. The facility currently processes about 100 units per day, however it has an installed capacity of 300 units per day. Therefore, more volume is required to reach a high utilization of the partly very advanced equipment. Currently, about 300 people are involved in copy machine recycling. The aim for the next two years is to achieve a balance between operating expenditures and proceeds; a return on investment in equipment is not a consideration. The systematic collection of product data provides Fuji Xerox with a distinct advantage in their recycling efforts. Neither Xerox USA nor Xerox Europe have comparable systems. One reason for this is that more than 95 % of the machines in Japan have maintenance contracts compared with 30 - 40 % in the USA and Europe. Another difference is the cleaning procedure. Whereas in Europe water and solvents are used, CO_2-dry-ice blasting is applied in the USA and Japan.

In 1986 Fuji Photo Film introduced single-use cameras into the market. A manual recycling system for its "QuickSnap" cameras was established in 1990. In 1992 the first single-use cameras designed for re-use of components were released and an automatic recycling system set up. At present there are 16 different types of cameras available. Nine of them are recycled using an automated line. The remaining 7 types are disassembled on a manual line using semi-automatic machines and simple tools. The cameras are designed for automated disassembly fitted with joints that snap together. Currently, 90 % of the components are re-used, 8 % of the remaining material is re-utilized for cameras and 2 % is utilized for other purposes. The average time between the date of sale and the recycling of a camera is about 3 - 4 months. About 85 % of the cameras are recycled within one year. The recycling process consists of three steps: separation, disassembly and inspection, and plastic recycling. Components passing the quality inspection are transported to a storage area by AGV`s and subsequently used in the automated camera production line. On average components can be re-used 5 times. Table 3 shows some technical data of the system. According to Fuji Photo Film the relation to the investment in the production and the recycling system is about 50 %: 50 %. The system is profitable.

Overall capacity	4 million cameras per month
Product types	16
Manpower in operation	20 - 25 in three shifts
Manual line capacity	1.5 million per month (7 product types)
Automated line capacity	2.5 million per month (9 product types)
Utilization	about 70 %
Equipment costs	some 10 billion Yen

Table 3: Selected data of Fuji Photo Film "QuickSnap" camera recycling system

Fujitsu established 13 centers for the collection of personal and mainframe computers, terminals and other Fujitsu IT-equipment. A collection service is also offered to IT-equipment leasing companies. Five recycling centers were established where the focus is on material recovery, primarily from business IT-equipment. The capacity of all 5 centers is about 16,000 tons per year. The following data refers to the main center located in Kanagawa Prefecture. The disassembly is done manually using simple tools, such as pneumatic screwdrivers, pliers and pincers. Disassembled components are sorted according to their material. Material fractions include cables, ABS covers and boards. Fujitsu's Engineering Center is 'on call' to supply information in case a material is not readily identifiable. Only a few components are disassembled for re-use. These include cables used to connect mainframe computers with peripherals, like printers, external hard discs, and large hard disc drives. Re-usable components are stored and used for maintenance of older models. Some printed circuit boards are shipped to the USA where gold is recovered and chips are disassembled for re-use in toys, etc. Table 4 provides some technical data. The company is profitable based on full cost calculation (including land, building, etc.). However, this is partially accomplished by outsourcing the recycling of labor intensive products, like printers, to subcontractors who pay lower salaries. Fujitsu also utilizes part time workers. Right now about 30 % of all recycling is done by Fujitsu itself.

Site area	1,918 m^2
Floor area	623 m^2
Products	IT-equipment, e.g. personal computers, workstations, mainframe computers
Overall capacity	5,000 tons/year, expanded to 7,000 tons/year end of 1998
Manpower in operation	16 workers, 4 administrators
Equipment costs	about 15 million Yen (excluding building and 2 rented fork lift trucks, but including 12 million Yen for a shredder)
Revenue	250 million Yen in 1997
Profits	+10 % of revenue

Table 4: Selected data of Fujitsu's computer recycling facility

Fuji Electric remanufactures a limited number of its vending machines. This is performed as a service to major customers, like Coca-Cola. The machines continue to be the customers' property. Two similar plants for vending machine remanufacturing exist. Here, the remanufacturing process used by the subsidiary, Fuji Electric V&C Altec, Co., Ltd., will be described in greater detail. In general, vending machines have an average lifetime of 4 - 5 years, which correspondents to approximately 100,000 sales procedures. A new machine costs about 350,000 Yen. The fee charged for remanufacturing ranges from 10,000 - 100,000 Yen depending on the condition of the machine. The machines turned in by customers are from 2 to 7 years old, with an average age of 5 years. They exhibit a wide range of usage influences including dirt, corrosion, deformation, cracks and holes. The overall procedure consists of classification, disassembly, cleaning, painting, re-assembly, adjustment and final testing. Disassembly and re-assembly are carried out using simple tools, like screwdrivers, grinders, pliers and tools to beat out dents. Electric/electronic components, such as power supply and control units, are checked and repaired if needed. The recycling ratio is about 99 % of the number of components. In most cases interior components are not seriously damaged. Most often exterior parts, like outer panels, display or fluorescent lights are replaced. Fuji Electric supplies any spare parts that are needed. The degree of automation is low. After being remanufactured, the machines can be used for another two years. Table 5 gives some technical data. Since remanufacturing is offered as a customer service, geared towards supporting product sales, the profits are marginal.

Overall capacity	150 vending machines per month
Manpower in operation	about 25
Proceeds	10,000 - 100,000 Yen per vending machine
Equipment costs	15 - 20 million Yen (excluding the building)
Lead time	about 2 weeks

Table 5: Selected data of Fuji Electric's vending machine remanufacturing system

4 Summary

The massive amount of waste that has been generated over the past years, and which continues to increase, is one of the most important environmental problems in Japan. As legislation becomes more stringent, product disassembly and recycling is of rising importance to Japanese industry. To provide an overview of the current situation and show trends, more than 50 experts from 15 of the most advanced Japanese companies regarding environmental considerations, were interviewed. Main findings indicate that material utilization and thermal recycling are presently the preferred options rather than re-use of products and components. Nevertheless, almost half of the companies are optimistic and believe that recycling might be an upcoming business. Current activities, at both the design and recycling stages, mainly focus on supporting material utilization. However, efforts are also made to facilitate the disassembly of future products. Some companies are already running a successful recovery business. Existing systems range from highly automated to manual ones using simple standard disassembly tools. Currently, the recovery system for single-use cameras is profitable. The remanufacturing of vending machines and recycling of IT-equipment are also showing modest profits. A balance between operational costs and proceeds has been achieved for automobiles (excluding the investment) and will soon be reached with copy machines.

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Acknowledgements

The authors are pleased to express their sincere gratitude to the participating experts from Denso Corp., Fuji Electric Corp., Fuji Photo Film Corp., Ltd., Fujitsu Ltd., Fuji Xerox Corp., Ltd., Hitachi Ltd., Matsushita Electric Industrial Corp., Ltd., Mazda Motor Corp., NEC Corp., Nissan Motor Corp., Ricoh Company Ltd., Sharp Corp., Sony Corp., Toshiba Corp. and Toyota Motor Corp. The authors also would like to thank Prof. F. Kimura for his collaboration during the organization of the survey.

Second International Working Seminar on Re-Use

Eindhoven, March $1^{st} - 3^{th}$, 1999

Re-Use of assembly systems
-
A great ecomomical potential for recycling

wbk

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Abstract

In addition to the consumer goods, capital goods also offer a great potential for ecological and economic optimization. In view of this fact the Project WIMONDI, started in September 1998, focusses to create a marketable Re-Use of of modules and components of assembly systems by using technically and organizationally continuous concepts.

The objective of the project is to increase the usability and prolong the lifespan of the assembly systems through the organized rebuilding of assembly facilities as well as the refurbishment and re-use of their components. Therefore, it is necessary to develop organizational and methodical strategies to realize a workable Re-Use concept.

WIMONDI is being conducted with tight cooperation between Industry and the University to initiate the conception of new distribution and user models between the supplier and user of assembly facilities.

Motivation and target setting of the WIMONDI project

The tendency of customer requests towards individually tailored products is leading rapidly to an escalation in the variability and at the same time to a decrease in the production figures of the manufacturer. On the other hand, the market cycles by means the time between two product generations are becoming increasingly smaller. For example, the time between two product generations in the area of consumer products and electronic devices such as those in the field of telecommunication have reached a very low level. Life cycles of under 3 years have become more and more reality.

Recently, many facility suppliers have begun to develop product-neutral, standardized assembly modules to meet the resultant compliancies of the assembly /N.N.-95/. These enable an easier set-up of the assembly facilities to adapt technically to the required part numbers, variations and safeguards. On the other hand, the modules guarantee an increased suitability for the re-use of the components of the facility. The economic potential of Re-Use becomes clear when the time between two product generations of the products and the lifespan of the production facility are compared. Lifespans of capital goods in assemblies of up to and over 20 years are not uncommon (compare Fig. 1).

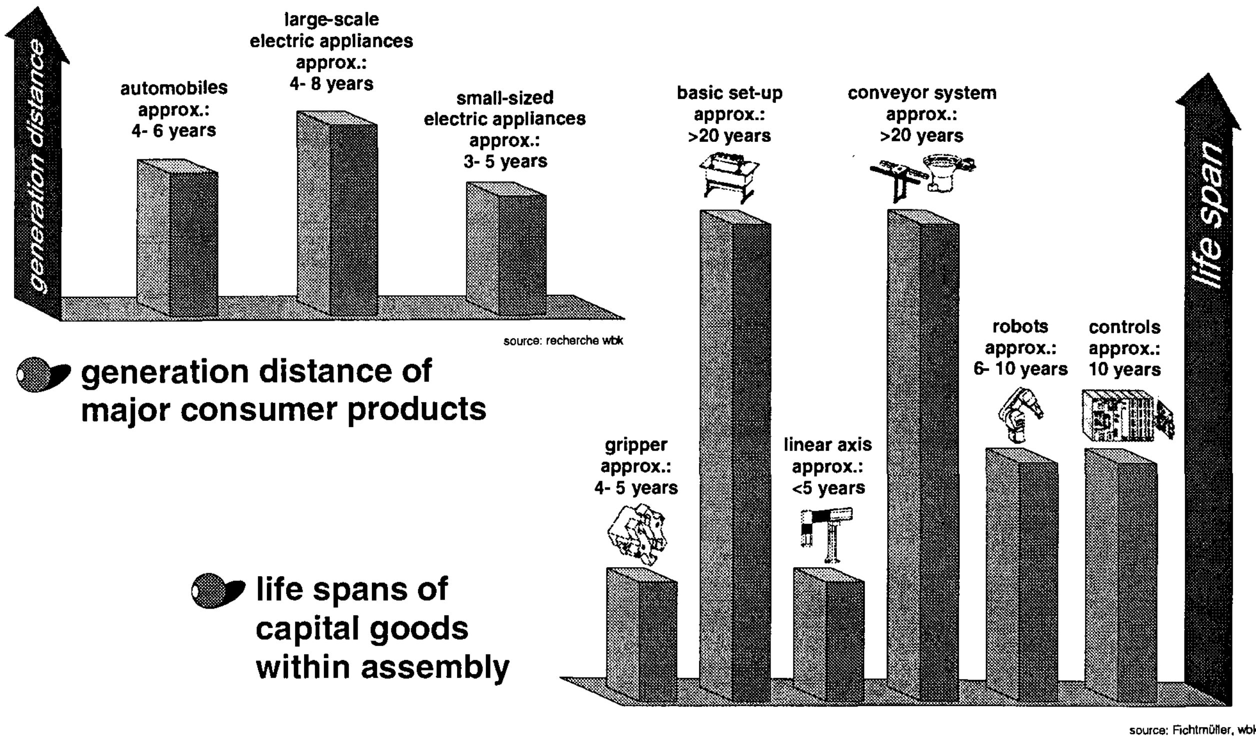

Fig. 1: Comparision of products and assemblies

In view of the afore mentioned market changes, the main point of the ecological consideration of the re-use ideology in Germany is still in the range af consumer products. The Re-Use of machines and production systems has only increased in importance in a few areas of the capital goods market although the value compositions of the machines and of the systems have a high potential.

A positive example of this can be seen in the market for used machine in the machine tool industry which is growing and today in Germany, has a turnover of 5% (approx. 600 Million DM per year) of the market of new machine tools /KAP-96/.

Research shows, in comparision to the machine tool industry, the renewed set-up of used assembly facilities is narrowly realized although there is a turnover of 6 billion DM/a for new assembly systems in the assembly industry /VDMA-97/. The same studies show a possible degree of re-utilization of up to 70% and therefore present a great economical potential /FIC-96/.

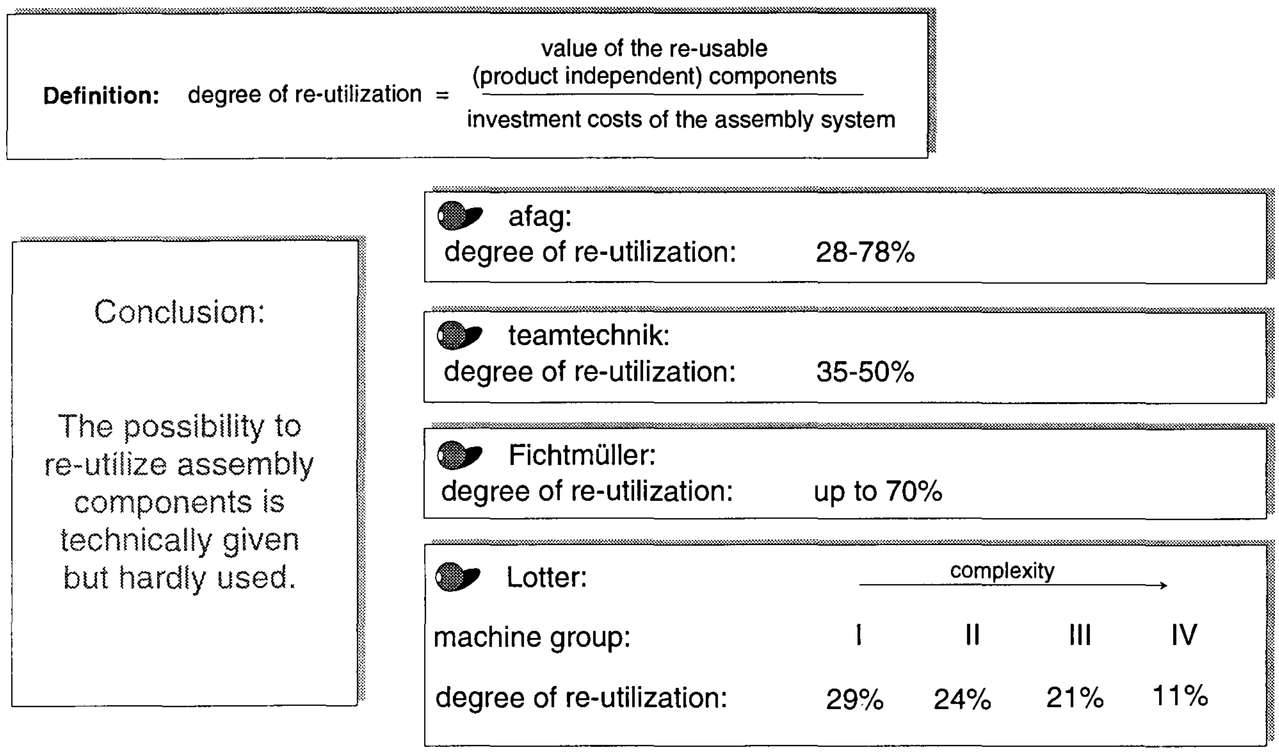

Fig. 2: Potential degree of re-utilization of assembly facilities

The WIMONDI Project

Stemming from this present situation, the objective of the WIMONDI Project is to establish a new production oriented service in the area of assembly facility industry through the Re-use of facility components. This enables several advantages:

- The effective use of capital goods through the well organized re-utilization and with that the preservation of material and raw material resources
- The creation of new jobs at the manufacturing level by the facility supplier through the initiation of the new business field dealing with disassembly and refurbishment of the re-usable module, sub-assemblies and components as well as the implementation of maintenance, service and repair.
- The introduction of alternative methods of distribution and user models in the field of assembly industry.
- The focussing on the main functions of the business partners by out-sourcing.

To realize these above advantages, the assembly producer must have methodical support to guarantee an optimal re-use. For the development of the methods, the basis criteria for a high re-usable index of used modules and components of assembly facilities is shown in Fig. 3. As well as the technical criteria such as the possibility of destruction free disassembly and the cleaning feasibility, economical and organizational criteria must also be factored in. Only a sufficient procurement market of used components and a sufficient selling market for used products guarantee an economically successful refurbishment and re-use concept.

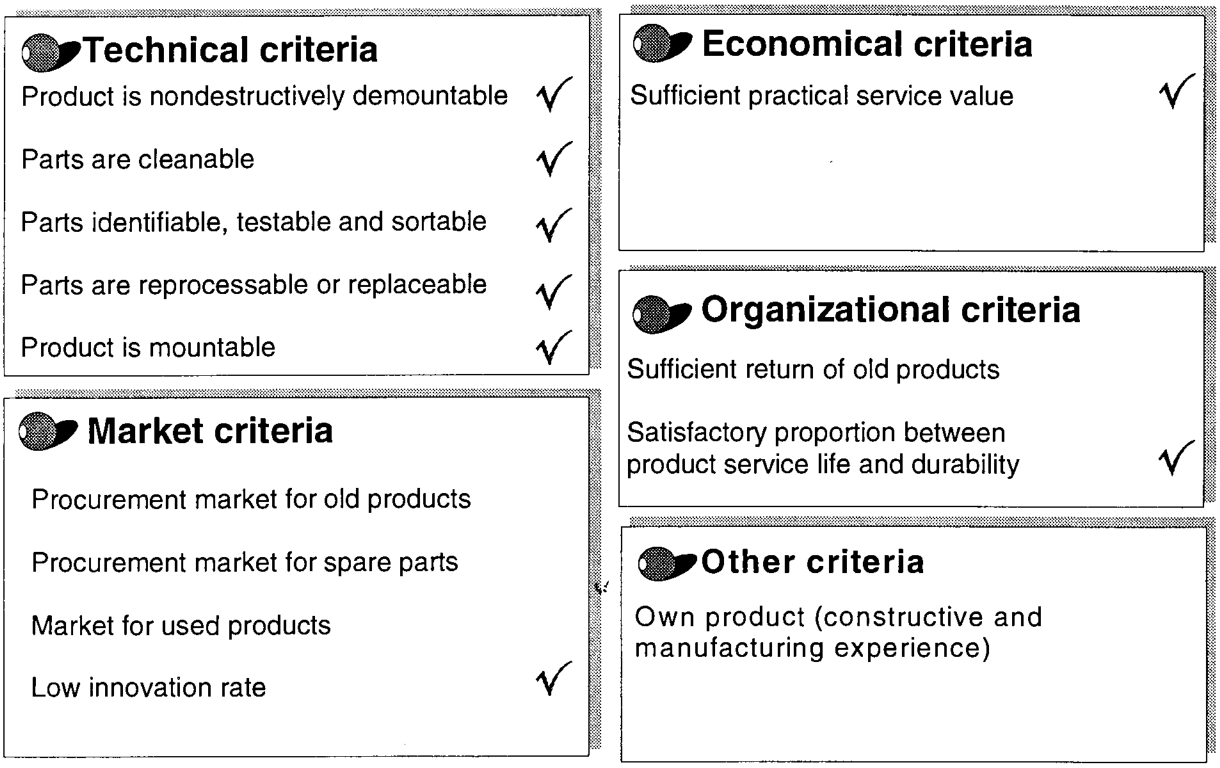

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Fig. 3. Criteria for the Re-use of Products

Basic technical conditions for new distribution and user models for re-use concepts

The technical criteria are fulfilled by an increasingly striding standardization in the form of modular assembly systems. In this respect, the facility supplier called Teamtechnik, located near Stuttgart, introduced one of the most advanced systems into the market last year (compare Figure. 4). Teamtechnik not only attempted to standardize the so-called fundamental units like basic carrier units and supporting units but also to standardize process modules for example screwing machine modules. The standardized mechanical and electrical interfaces enable a simple and fast set-up as well a low-cost disassembly of a facility .

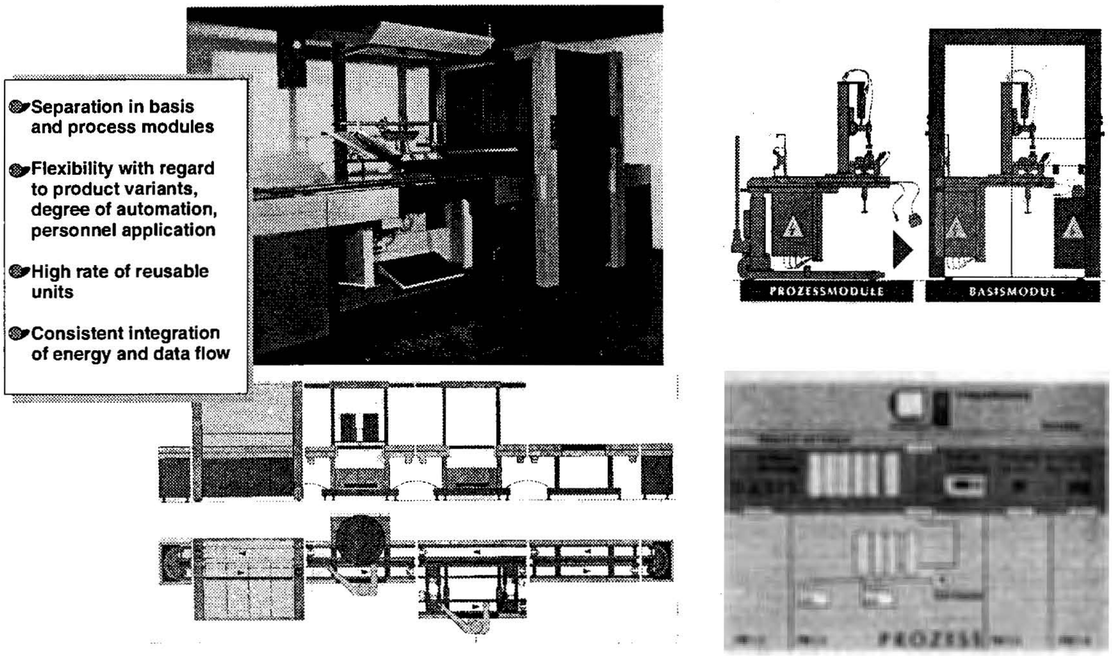

Fig. 4: Module systems for assemblies

In general the re-use concept can be executed by independent companies. But an advanced procurement market of used components and a market for used products can be assured through the employment of new distribution and user models. An example of this is the leasing concept (compare Fig. 5).

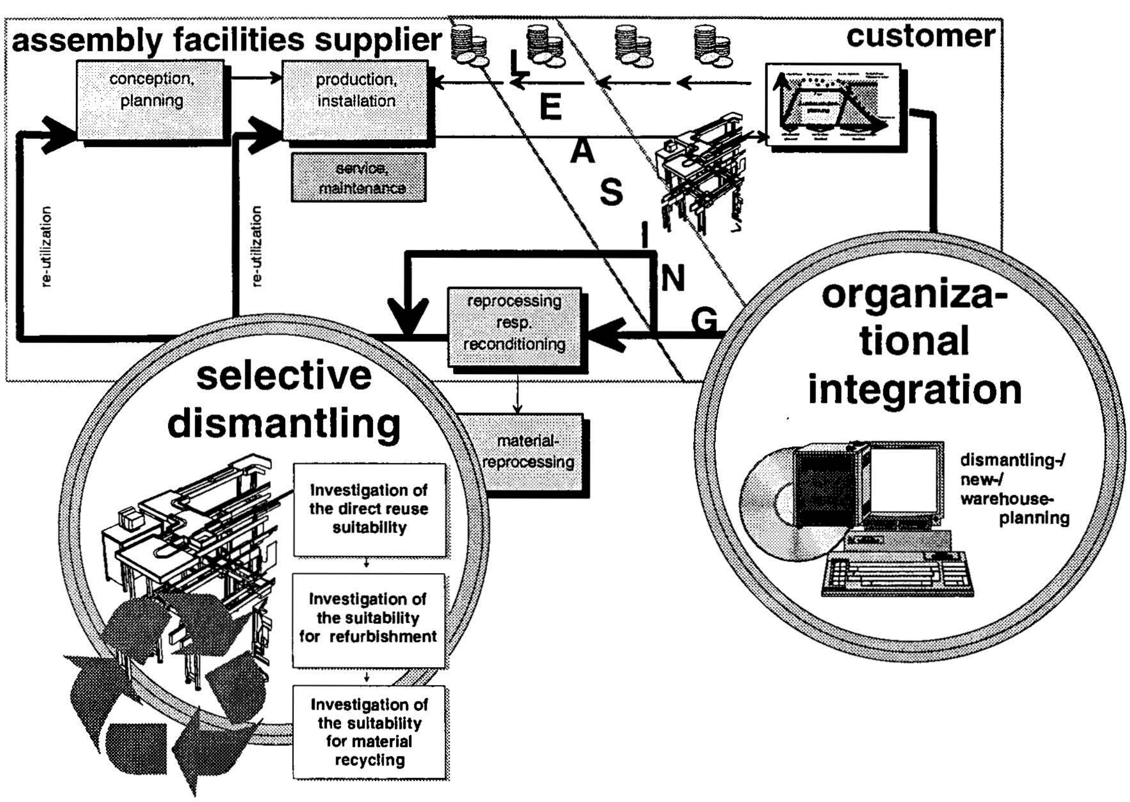

Fig. 5: Distribution and user concept

The leasing concept visualizes a new operation field of the facility manufacturers which up to now only encompassed the planning and construction of facilities, through the organized rebuilding by disassembly and refurbishment such as the reinstallation of used assemblies. As well as the advantage of having an improved market situation it is an essential advantage to reinforce the connection between the customer and the leasor. This enables the leasee is to realize a low-cost facility with used components for products with a higher risk in the market with respect to their approximated production figures.

For a successful establishment of the leasing concept, it is important for the leasor to be able to reliably determine the leasing-rate. The leasing rate is calculated from the capital cost, operating costs for repairing and maintaining the system meanwhile operation, the costs for dismounting and the depreciated value.

Within the WIMONDI project a method will be developed to enable the calculation of the operating costs during the planning stage on the basis of the activity based costing. The method simulates the relevant operations during the running time of the facilities in the form of processes and dictated costs. With that, the certainty of the determination of the leasing rate can be raised whereby a basis for the realization of the leasing model is given.

Methods of Economical Assessment of the Re-Use Application

The organized re-building of components differentiates the various recycling strategies according to the type and the condition of the parts. These strategies are:

- direct re-use,
- re-use after refurbishment and
- material recycling.

To estimate the most economical method of recycling, methods will be developed which will help to predict the costs and profits that occur due to the re-structuring.

In view of the fact that during the re-building and re-using of facilities, various activities and thereby expenditures incur which decrease the profits of the re-used components, these activities have to be considered in the calculation methods. These activities are affected by the dismantling, testing, cleaning, preparing, storing and re-assembly of the components.

Basically, the expenditures are calculated according to the personnel costs and the time needed for the process. To estimate the needed operation times, the procedures of time studies from the usage of manual assemblies can be used /HAR-97/. The following fundamental procedures are possible (compare Fig. 6):

- Estimation and Comparison Techniques on the basis of similar modules and components
- Time recording according to the REFA-Method
- Analytical Time Estimation with the procedures „Systeme vorbestimmter Zeiten“ (SvZ)

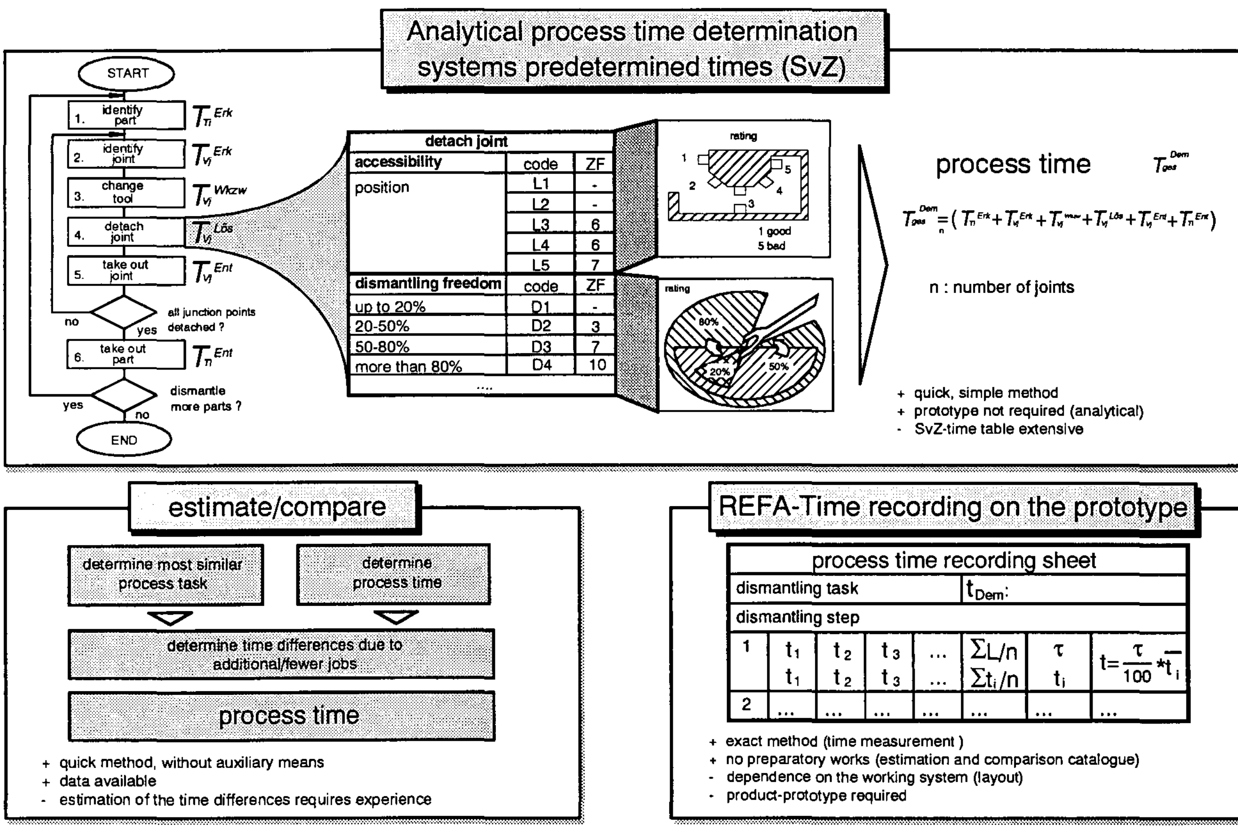

Fig. 6. Methods of Time Studies

An essential indicator of the Estimation and Comparison Technique is the necessity of the construction of a comparison catalogue which through a classification system can enable the identification of similar processes of the actual re-building project. The determination of the comparison values is usually a costly procedure.

In the case of already established assembly components which are often used, like in the case of the afore mentioned basic modules and standardized process modules, the necessary operation costs can be recorded with REFA-method. The recorded efforts can be assigned to the components and stored in a database. Not only the direct re-use of modules should be estimated but also the efforts of refurbishment and repair caused by the exchange process of relevant wear and tear parts within the module should be examined.

The Analytical Time Estimation necessitates a nonrecurring effort in the construction of the SvZ-Timetables /FEU-93 /. This technique is universal and applicable to non-standard components in an assembly system.

For the estimation of optimal recycling strategies, the expenditures that occur during the rebuilding process, must be compared with the profits of the direct re-use, the re-use after repair and refurbishment as well as the material recycling. While the evaluation of the alternative material recycling is based on the knowledge of the material composition and the available recycling processes, the depreciated value of the assembly components for the alternative direct re-use must be estimated. For this, business methods are available for example value depreciation methods such as the Renewal Theory and different theories in the field of maintenance (Compare Fig. 7). The applicable theory depend on the type of component.

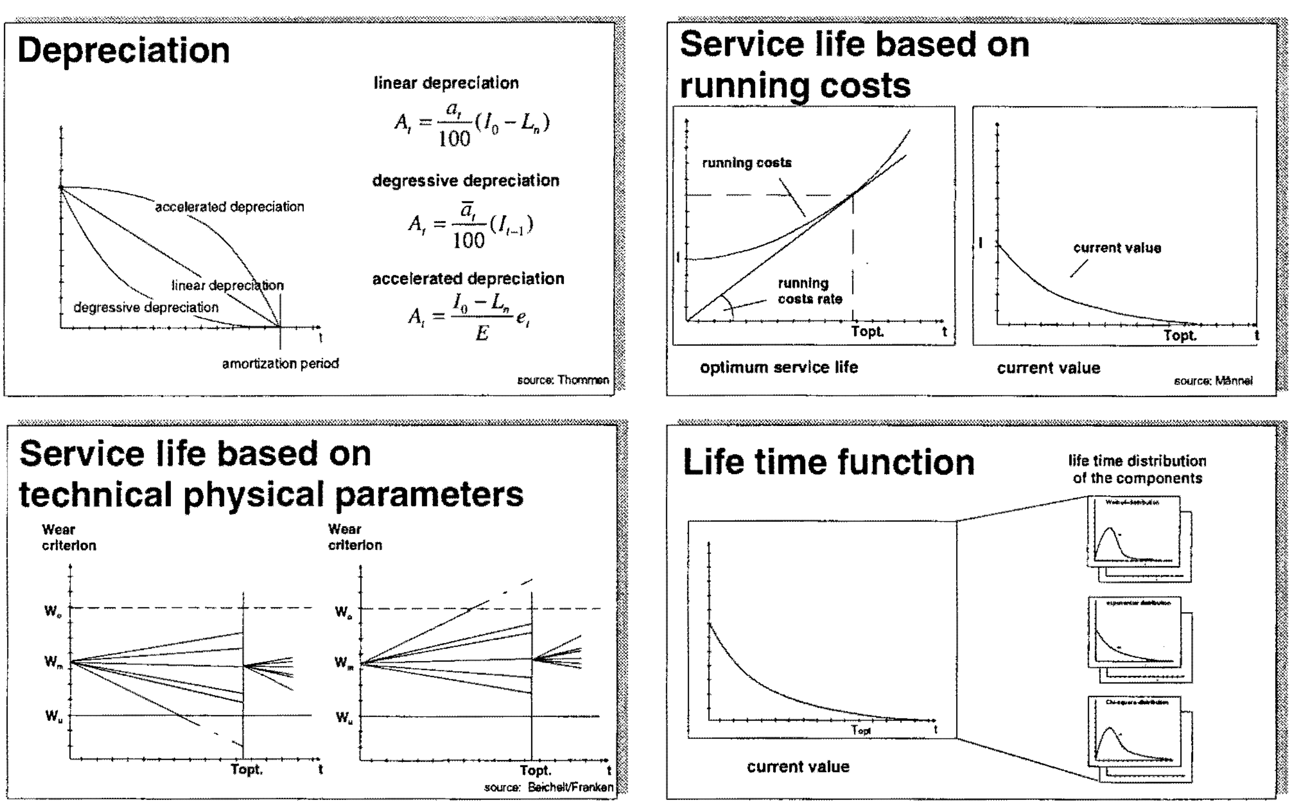

Fig. 7: Methods of estimation of the depreciation value.

Especially, with respect to the investigation of the refurbishment and re-use, mathematical models on the basis of specific component lifespans are suitable. Through the use of failure analysis, the examination of the ability to repair or exchange parts which wear before others is possible. The lifespan models are verified and detailed through the feedback of data from the maintenance and repair of the system during plants operation.

Generally, a continuous information model has to be reached which uses data in a purposeful manner from different groups. In addition to the above-mentioned information of the system operations, parts lists and CAD data from the construction and order dates from marketing are needed for the calculation of the sales volumes as basic information to be integrated into the overall concept.

Conclusion

On account of the large amount of methods and data to be handled, a software tool will be developed within the WIMONDI project. This instrument should contain all functionalities for the costs and profit assessment of the reuse and material recycling.

The system will enable the evaluation of modules, components and material mixtures as well as their combinations with regards to dismantling and material recycling. It will contain numerous databases of disassembly, cleaning and testing times, recycling process and customer groups for most modules and materials.

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To plastic waste collection for better material recovery.

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SUMMARY

Polymer consume in industrial countries is about 10% by weight (or 28% by volume) from all collected waste, which comes in through the municipal collection systems (MCS), and contains different polymer types. For the injection of such mixed plastic's waste in recycling or reprocessing of new goods, special sorting methods, or chemical compatibilisers are necessary to receive final material (recyclate) with similar service properties as the „raw" polymers. By recycling over degradation instead of the sorting of the waste, fractionation of degradation products can be done to receive reusable products for repeated synthesis or environmental inert emissions. To decrease the recycling and recovery costs of polymers the whole recycling cyclus should be optimized, starting with collection. All the industrial separation methods are expensive, in comparison with separation through consumer. In different countries diverse collection systems are proposed. These systems for plastic containing waste, are shedulded and their deficiencies and advantages are discussed. Instead of multi-container collection, environmental engineering, based on an instrument of material environmental selection criteria during product design is developed. In the early stage of design of new construction, properties concerning usage and processing are taken parallel into the consideration with environmental impacts. In this way misleading directions of development can be recognized and corrected before the production starts.

1. Introduction

Polymer consume in industrial countries is about 10% by weight (or about 28% by volume) from all collected waste, which comes in through the municipal collection systems (MCS), and contains mainly (~90%) six different polymers: polyolefines (HDPE, LDPE and PP), polyvinilchloride (PVC), polyethylene terephtalate (PET), and polystyrene (PS) [1,2]. The residual fraction of other polymers includes acrylonitrile-butadiene-styrene copolymer (ABS), acrylics, nylon, polycarbonate, some other thermoplastics and thermosets (Tab.1). Industrially developing countries will reach this amount in a short time. For the injection of such plastics mixture in reproduction of new goods special performance methods are needed, to receive continuously final material (recyclate) with stabile properties. For the chemical or energetical recovery presortation is necessary to become re-synthesable depolymerisation products and/or environmental friendly endproducts. For plastic waste recycling optimal solutions should be found. A number of scientists are looking for such solutions, but they usually try to solute it particularly, carrying out researches only on one of the steps of the recycling chain. For the solution should be searched complexly, starting with the design over collection till recycling or material recovery.

Table 1. Plastics in munitipal waste and their particular lifetime

Polymer	Total in weight %	Under 3 months*	Till 2 years*	2 - 10 years*	Over 10 years*
HDPE	24	40	26	21	13
LDPE	22	56	24	15	5
PP	16	30	32	29	9
PVC	14	17	39	19	25
PS	10	23	37	29	11
ABS	6	2	18	69	11
PET	5	77	14	9	0
PU	3	4	12	68	16
Other	1	11	14	50	25

* in % from each polymer type content in waste

In previously Easteuropean-block countries, and not only there, the plastic waste stream is growing yearly with the import of the goods and increasing of the usage of plastics in packaging. According to the historical background, no seriously concept of this waste management exists there. All the domestic waste till now lunches in one trash container and is deponied in the landfillings. The aim of this study was to analyze and to compare the experience of the industrial countries in the plastic waste management.

If strongly defined, reuse is the input of the produced article after its first use in the same application as before. The examples from polymer goods are: reuse of PET drink bottles, fuel cans in cars, fountain-pens after refilling and some other. But such examples are seldom. Therefore under reuse of polymers oft is mentioned the reuse of the recovered material in the performance of the new goods. A number of polymer scientists and industrial researchers under reuse are mentioning every usage of polymer waste, not looking on application field: real reuse, material recovery or also energetical recycling. In this presentation under reuse is to understand real reuse and material recovery.

2. Economy of recycling

Contemporary recycling is an industrial branch, and, as every other, it must follow the market forces. It means, that frequently economical factors determine the development directions of recycling. However there are different arts of funding in various states. Recycling factory should have positive economical balance (rentability), to be competitive with the chemical industry and to give profit for the factory owners.

The recycling costs **K** can be calculated mathematically by following empirical equation:

$$\mathbf{K = P + (S - B) - C_C - C_T - C_S - C_P},$$

where $\mathbf{C_C}$, $\mathbf{C_T}$, $\mathbf{C_S}$, $\mathbf{C_P}$ are costs for collection, transport, sorting, and performance; **B** the price of waste, **P** is the price of sold products and **S** - subsities from the state, if such exists. The final value of **K** should be $\mathbf{K} > 0$. It can be reached by decreasing of the costs or increasing of the product price through the quality of the recycled material. In dependence of the recycling methods different endproducts are coming into the market. By energy recovery or feedstock recycling there is not a great difference in quality between raw material and the endproduct of the recycling. Products from the material recovery are launching as granulates on the same market as direct synthesized plastics, and in this case the price can be determinated. It must be mentioned, that the price of recycled polymers should be lower as for the virgin material, because there is a great scepsis about quality of recovered plastics among performers and users. The individual costs can change, but the most variable value is the sorting costs of the waste.

Not all the costs can be covered through selling of the recycled materials. In the states, in which the governments have recognized the ecological danger of the plastic waste, different subsidution methods are existing to support the recyclers. It can be achieved with the including of the recycling costs in the price, direct funding, increasing of the deponie costs, or with legislative acts. Usually there is a combination of all the points, mentioned above.

3. Collection variants

3.1. Munitipal collection systems

There are differences between waste collection methods in various states. That is a result of different case studies [2] and, after explaining advertising, acceptance level of consumers. Also inside of one country there can be differences from commune to commune. On the lowest step of the waste management „stairs" are such countries, where all the waste is collected together. There the sorting costs are high and/or therefore all the waste is launching in the landfilling deponies. The plastic waste amount in the deponies there grows continuously. The long degradation time and mixture with other waste makes the sorting and recycling of this waste practically impossible. In this case the waste management can effective help only for the newly collected trash.

Historically the first separate collection was grounded on the „bring" system [2]. There the end-user has to bring recycable materials to the collection stations without any refunding. This system has not reached a great acceptance by consumers, because they had to cover collection and, particular, transport costs themselve.

Currently in environmental self-confident countries there are different multicontainer „hold" collection systems [3-5]. In the first stage the consumer can collect the packaging waste directly after shopping in special containers in the shop. By the delivery of the goods to consumer, the supplier takes the packaging with him. The deposit system for bottles and, in some states, for metal drink cans, is wide established. On the other side numerous containers for the waste collection are presented. The number of the waste containers is varying from 4 to 9. Additionally there are special waste collection parks („bring" system) for the great size garbage, for example furniture and hosehold electric equipment. The main problem of these

countries is the explaining work among the citizens and a great number of the containers.
The main attention in this paper will be devoted to the plastic waste collection, what does not means that the collection of other waste is organized in the best way. In the well-known German system all plastic containing waste comes together with metal cans in one „yellow container". After that expensive sorting methods, not excluding manual sorting, are used. The better variant seems to be established in Ötztal region, Austria [5]. There only the plastic waste comes into 3 different containers: bottles, multicomponent drink packs and pure plastics from packaging are collected separately from other waste. But also this variant is not the best one, because for packaging mostly 6 polymers: HDPE, PP, LDPE, PS, PVC and PET are used. If these materials does not contain fillers and other additives, that change material properties, used for sorting, the separation seems to be a soluble problem. But if these additives change the properties, the separation is nearly impossible. This problem might be solved using more containers - for each polymer type one. The consumer can not identify the polymer art because the identifying signs are not used by all the products, and nobody has an analytical ecquipment at home. The number of containers increases collection and transport costs, but reduces the waste separation costs. The waste sortiment, what comes together in one container should be optimized and adapted to the sorting posibilities.

3.2. Collection and separation in household

The consumer in household uses his free time for the separately waste collection. The sortiment of polymer types, comming together in household is wide and the volume of each fraction is relative small. The researches of the plastic waste content in household are showing that it contains over 10 polymer types [1,2]. The most content of this waste are used packaging materials. Not looking on diferent signs (barcodes) for a number of packages, decribing the used polymer type, missing collection logistics of the MCS does not allows the effective sortation in household. As a result comglimed plastic waste lunches in collection container and creates problems by sorting. Often this waste contains different impurities such as adhered food rests or grease, causing aditionall pretreatment problems. The way to decrease sorting costs and not to irritate the consumer in household, might be the use of a definite, minimal, polymer type for the various packaging. In this case the consumer should not search for the identification sign on the package, but can sortate waste according to the good, which was packed. For example, yoghurt cans can be made only from PP, meet can be packed only in LDPE and butter only in HDPE. This solution is acceptable for the consumer and recycler, but not for the polymer producing industry. Another possibility is to color each plastic type in one legislative determinated color: for example HDPE in blue and PP yellow and so on. Then the consumer can collect the plastic waste according to the color in the container with the same color. Against this method could be plastic good designers. For mechanical sorting use of special, different for each polymer type, additive can be reasonable. Such additive allows the identification of the polymer type with the spectroscopic methods. As a result mixed plastic waste should be possible to separate mechanically on automatic production lines. The future solution lies everywhere between the presented variants.

3.3. Collection and separation by industrial consumer

There are practically no problems for the direct material recovery from the performance waste and residues in the same performance plant. Every industrial postperformance waste can be collected seperatly and injected in the same product performance line without pretreatment. For postconsumer plastic waste reuse seperation of polymer types is necessary.

All the industrial separation methods are more expensive, in comparison with separation through consumer. The consumer uses his time, or has a special collecting employee, for the separately waste collection. The waste performer needs only to collect waste fractions from the containers. In different countries varying collection systems are proposed and they have reached some acceptance level of the consumers. As mentioned above, one way to reduce the sorting costs is the way to increase the number of containers in which different plastic waste fractions are collected seperatly. From the point of view of recyclers the optimal variant should be then, when every polymer type comes in separate container. But, for example, 20 polymers and copolymers needs also 20 containers. To such number of containers nobody's acceptance can be received.

One of the best places, in which different polymer waste can be started to collect seperatly is in agriculture. There the plastic waste appears seasonally and in eash season only limited polymer types are used, mostly only PE and PP. In the early spring, when new plants are planted out, the pots and boxes, used for sprounting can be collected. After cleaning and desinfection they can be sorted, broken extracted for recovey and whole kept in depositories for reuse in next years. After the greenhouses are dismanteled, films can be collected type pure and recycled without sorting. Also fertilizer sacks, which are made mainly from PE, can be after separate collection recycled without problems.

As the next example the good suplier companies can be taken. These companies receive from producers articles in industrial package in large ammounts. These articles are often packed in plastic containing materials. The packaging materials contents cardbord, paper, PE, PP and PS. In the first step the industrial packaging can be separatly collected directly in the suplier company during dividing the cargos to the shops. After that another part of packaging material, what was necessary for the transport, can be taken back and added as pure polymer types to previously collected waste. This waste is collected to lots, appropriate for the transport and send to the recycling factories.

Table 2. Polymers in hospital waste

Polymer	Article examples	Waste yearly, t
HDPE	Syringes	5,5
PP	Syringes	2,3
LDPE	Bottles, packaging	21
PS	Injection cateters	0,7
PU	Tubes	0,8
PA	Dyalyse units	0,1
PVC	Tubes	2,7
PC	Oxigenators	0,1
Latex	Gloves	10

As another example for the possibilities of separate postconsumer plasic waste collection, with larger spectrum of plastyc types, the hospitals can be considered. In a full service hospital with 1300 beds about 43 tons of plastic containing material are used. Usage of the number of high-performance and commodial plastics in medicine is limited by biological compatibility and chemical resistance, and single use medical equipment volume is growing yearly (Tab.2). The main used polymers are HDPE, LDPE, PP, PU, PA, plasticized PVC, PS, PC and latex [6]. Mostly no fillers or reinforcements are used, because the medical equipment parts usually should be transparent. In this case only 10 collection containers are necessary: for each plastic one and one aditional for the residual polymers, for example, for the drugs packaging, what contains together with numerous plastics also aluminium cover film. From each polymer type limited medical instrument parts are produced, for example, surgeon glowes from latex or, in the last time, PU; tubes mostly from PVC or PU and syringes from PP or PEI. No special knowledges in polymer analitics are necessary to collect glowes seperatly from tubes or syringes and as result practicaly pure plastic type fractions can be collected. In every hospital sharp equipment parts as needles, scalpel blades and other are eliminated in special recycling containers. The main problem there is the sterlisation of used materials. It must be done after collection in the hospital to avoid infection danger already during the transport of the waste to recycling factory. The articles, which was in the contact with blood are prohibited to inject in the material recovery. They can be used only for energy recovery.

The best example for just ideal reuse of recycled plastics, on my opinion, is developed in some small and middle capacity companies of the sport clothing industry [7]. These companies are collecting the clothes, made full from polyesther. After the melt recovery of the polyesther they are producing buttons and zippers from the recyclate. These products are used in the production of the new clothes. The limiting factor for this reuse are not mechanical properties of the recyclate. For the recycling are used polyether fractions with diferent color. The mixing of these fractions during recovery alows to become the recyclate only in limited, most dark colors, because the bleaching process is very expensive

4. Environmental engineering (design)

Instead of multi-container collection, environmental engineering for commglimend polymer waste minimization as the new method is oncoming. This method is based on an instrument of material environmental selection criteria during material design. Starting the design of new construction, properties, concerning usage and processing are taken parallel into the consideration with environmental impacts [8]. If the construction contains a number of plastic parts, one, optimal polymer or composite material, can be chosen out. After usage the separation and demontage is not necessary. The main problem is that the unified databases for all polymer materials are not developed enough.

The steps of such design are : initial estimation, semi-quantitative screening, quantitative screening and final decision. By initial estimation the identification views only the process of production, usage and disposal. After that additional acquirements are added in step by step screening. Finally the optimal materials an technologies can be selected. After this theoretical research a minimum of experimental tests should be done for the final decision. The main advantages of this method are shorter design times financial savings and complex recyclable articles.

Conclusions and outlook

Despite on various polymer waste management systems all over the world, the optimal one is not found. The opinions of polymer producers, recycling industry and consumer oft are different.

To solve this problem principially new plastic waste management systems should be developed to satisfy all the sides. Parallel new, more effective and simple, plastic identification methods and sorting techniques should be developed.

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Draft Paper for the Second International Working-Seminar on Re-Use

Planning and Control in Disassembly: The Key to an Increased Profitability

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Abstract: Disassembly for both recycling and remanufacturing has contend with a high degree of uncertainty: The process cannot be determined in advance as the nature and the state of the incoming products are unknown. Processing times and failure likelihood can only be estimated on the basis of previous operations. The market for disassembled materials and parts is dynamic and unstable. Planning and control of disassembly is therefore a complex task. This leads to the need for flexible and profitable disassembly systems. This paper presents the architecture of a flexible disassembly cell and a methodology for planning and control of its operations. The following reports on experience with a prototypical implementation.

Keywords: disassembly, disassembly-cell, scheduling, process planning

Introduction

Disassembly is an important part of remanufacturing as well as the start of every recycling process. Much research has been done in the former field. In Germany, due to strict environmental legislation and governmental pressure towards recycling, much effort has been made in the recycling of products. Both remanufacturing and recycling include the disassembly of a discarded product so methods developed in one field can be applied to the other.

Research on disassembly has been widely dominated by technological questions such as automation (Reinhart et al., 1995) and the design for disassembly (Seliger et al., 1993). To cope with the growing volumes of electrical products and to be able to provide high process flexibility, hybrid disassembly cells have been established in both research and industry (Scholz-Reiter et al., 1998). However very little work is reported on the accompanying organizational issues such as planning and control. Yet there is a remarkable potential for cost reduction and increasing efficiency, as disassembly involves a high degree of manual work with resulting high labor costs. The presented approach attempts to fill this gap.

1. General conditions for planning and control in disassembly

1.1 The economic push and pull to recycling

In recent years, a rapid development towards encouraging companies to tackle recycling could be observed. Reasons for recycling are due to push and also to pull mechanisms.

The *quantity of discarded products* is increasing every year. In 1994, there were 1.5 million tons of discarded electrical products and 2.4 million tons of discarded cars in Germany alone (NN, 1996). This is due to several reasons. First a decreasing product life is caused by increased innovation, making products that are only few years old already obsolete. Some products are even designed not to last longer than a few years. Additionally, the drop in the price of electrical products has led to an increasing use of electronics in almost every sector of daily life.

One reason pushing companies to recycle is that in small, highly populated countries such as Germany or the Netherlands, the *landfill capacity* is continually declining and becoming more expensive. It is predicted that 75% of all available dumps in Germany will be filled by 2000 and that the remaining dumps will be filled by 2015 (NN, 1996). New dumps will not be opened. Remaining alternatives for treating discarded products are incineration and recycling. The former is a suitable method for small products without toxic components. Especially metals such as iron and aluminum can be easily recovered after incineration. However with respect to plastic materials it is a waste of resources. Products containing toxic components cannot be burned without previous treatment to remove hazardous components. As natural resources are being depleted and prices for materials rising, disassembly for the recovery of utilizable materials can prove to be profitable as well as the remanufacturing of obsolete products.

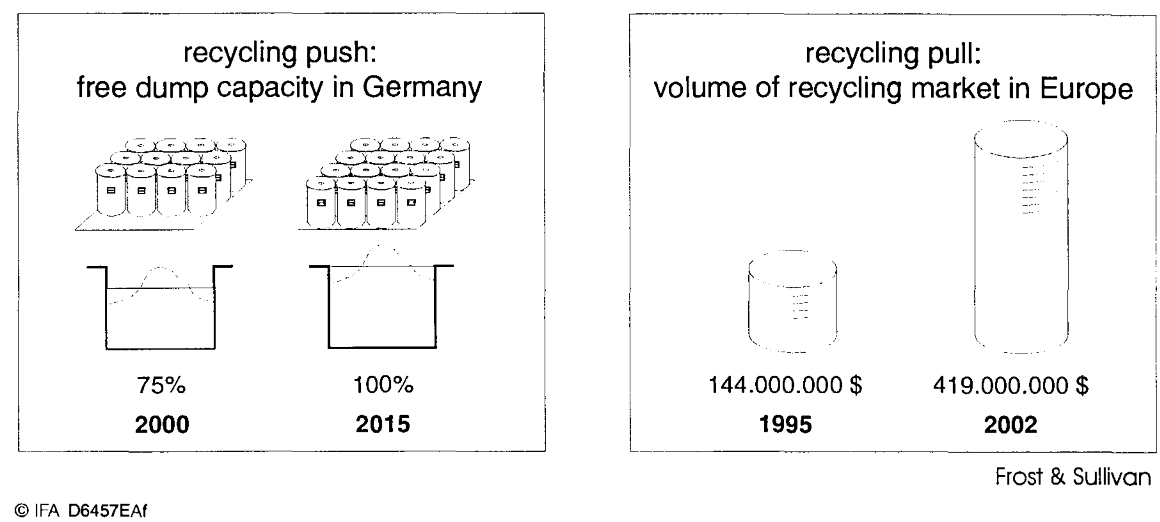

Fig. 1: Economic Push and Pull to Recycling

One reason pulling companies into recycling is *legislative pressure.* In various countries, new environmentally friendly laws enforce the recycling or remanufacturing of various products. In Germany especially the car and office-automation industry is coming under pressure. In the car industry, a law from 1998 requires cars to be handed over to a certified car recycling company at the end of their life, creating a new and attractive field of business. For business electronics such as computers and printers a federal law is about to be enacted.

These factors pushing and pulling companies into recycling create a market for the industrial recycling of electronic products that is rapidly growing (Fig. 1). In Europe in 1995, it had a volume of $144 million and is predicted to expand to $ 419 million by the year 2002 (NN, 1996).

These facts show that recycling is not only ecologically necessary, but also becoming an attractive business field for small, medium-sized and large companies. Many companies are therefore going into disassembly and recycling today. The scope of recycled products ranges from small electrical tools to cars to large electrical installations. Bosch, for example, takes back electrical tools from its customers for recycling. Mercedes disassembles its cars in order to recover spare parts and Siemens takes back discarded PC's and recycles 88% of their components (VDI, 1998). There are already some small companies which recycle up to 20,000 tons of discarded electrical consumer products a year in order to retrieve metals and plastics. Many other companies follow similar strategies.

In conclusion, the large volume of products and their annual growth promise an expanding industry on the last level of the supply chain. An effective and flexible way to deal with such amounts is described in this paper.

1.2 The Problem of Disassembly

The major challenge for disassembly planning and control is the broad spectrum of products to be disassembled. The problem of disassembly can be characterized by

- the enormous variety of discarded products,
- the unpredictable number of incoming products,
- the unknown product properties and
- the unpredictability of the process plans and processing times.

The variety results from manifold product types from different manufacturers and a broad range of model years. Uncertainty about the length and place of use as well as alternative disposal technologies together result in a fluctuating number of products for disassembly. Moreover, influences during use can lead to unpredictable changes in the properties of used products compared to those of new products. Additionally, it is hard to forecast the dynamic market for disassembled components and materials. These circumstances lead to new requirements in the operation of disassembly systems, like high flexibility and on-line control (Seliger et al. 1997b) and create a field for planning and control, in which traditional approaches can hardly be applied.

1.3 The objective system of disassembly

Disassembly has often been seen as a kind of reverse assembly. However, it not only differs from production in its degree of unpredictability but also in different objectives for these two applications (Wiendahl et al., 1998b).

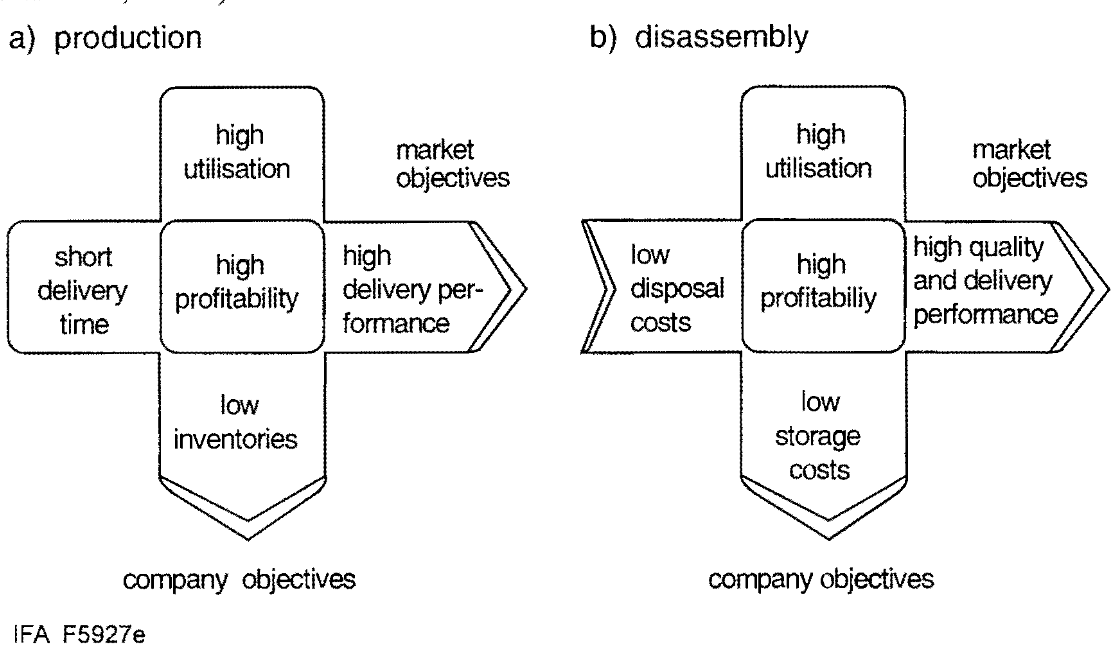

Fig. 2: Objective System in Planning and Control of Assembly and Disassembly

In production and disassembly an objective system consists of both market and companies objectives (Fig. 2).

In production a continuous competition of orders for the limited resources within the company can be identified. This results in a conflict of objectives, between the interests of the customer and those of the company. The customer wants his products to flow through the company as fast a possible and demands a high degree of punctuality. From a company's point of view, high utilization and low inventories are the major, yet conflicting, objectives.

In disassembly a similar conflict between the interests of the company and the customer exists. However in disassembly, delivery time and punctuality do not play an equally important role.

Moreover a trade-off between the two markets (the market where the disassembling company obtains its products and the market where it sells components and materials) is important. For the first market (the input market), the disassembly company is a service company that has to solve disposal problems, and for the other market (the output market) it is a materials supplier. Therefore cheap recycling has to be offered to the customer while still guaranteeing good quality materials in agreed amounts to the buyer. With the company objectives, a trade-off between high utilization and low inventories has to be found. The difference to production is that not only is the capital tied up in the product a problem but also the storage of big volumes of low-value products.

This leads to the need for new disassembly methodologies to cope with the above described objectives. Methods from planning and control of production can still be applied to a certain extent, though they require some adaptations to this field of application.

2. Architectures of disassembly systems

Three fundamental architectures can be identified: the disassembly-line, the flexible disassembly cell and the single workstation. Each of these has its special characteristics, strengths and weaknesses (Wiendahl et al., 1998a). In the following they will be briefly described:

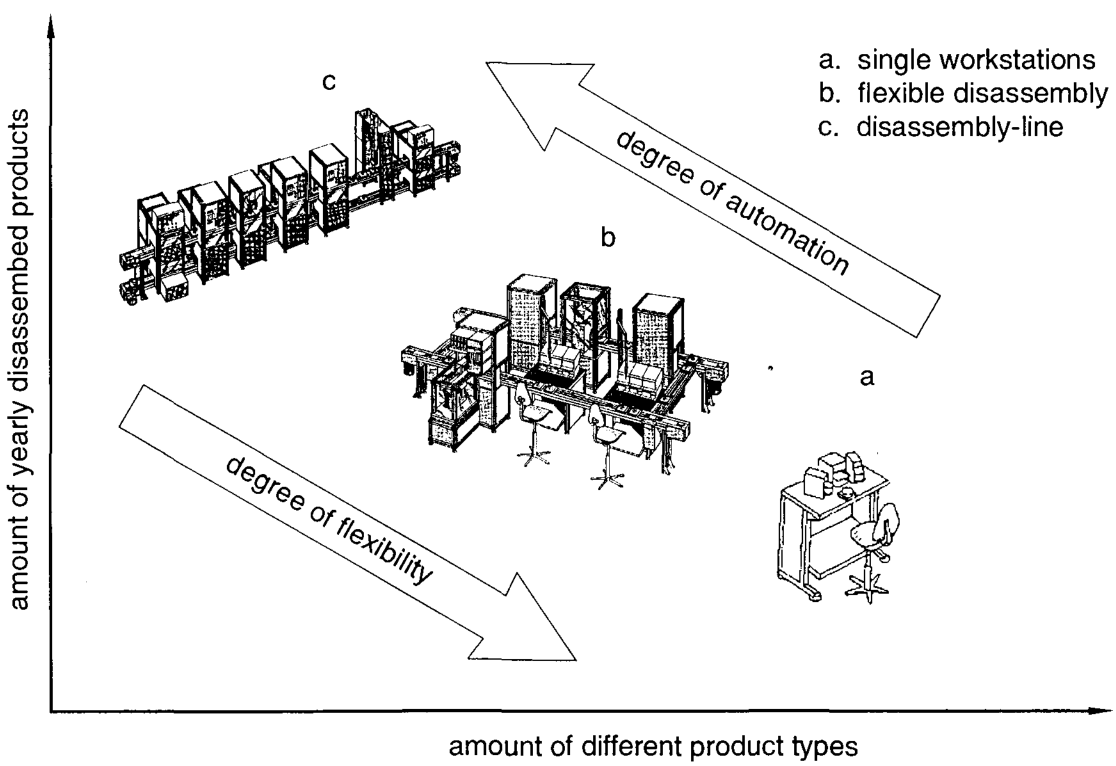

Fig. 3: Characteristics of different disassembly-system architectures

The *single workstation* is the most common layout to be found in industry. The reason for its widespread application lies in the small investment costs and in the high flexibility with respect to different products (Fig. 3a). Due to its high degree of manual work, it is not very efficient. The value adding work constitutes a small ratio of the overall work, as much transportation of discarded products and parts is done. Additionally this layout is only capable of processing low numbers of products.

The *flexible disassembly cell* combines flexibility with efficiency. It consists of manual or automated workstations that are flexibly connected by a transport system. Additionally control mechanisms have to control the transport and the automated operations. In the disassembly cell, the actual process of disassembly is still mainly done by the worker as only he is capable of managing an unpredictable process. The advantage of the disassembly cell is high productivity and flexibility, though it of course requires much space (Fig. 3b).

The *disassembly-line* is a layout that is suitable for the disassembly of big products of similar types. It consists of workstations that are linearly connected by an automated transport system. It offers the possibility of achieving high productivity but is only suitable for big lot-sizes. Due to the mostly fixed and well-defined operations, automation is possible to a certain extent. A variety of different products cannot be processed simultaneously, as the disassembly line does not fulfill the requirements of flexibility, as not all operations can be done in a sequence and as sometimes backtracking or repetition of operations is necessary (Fig. 3c).

3. Planning and control of disassembly

3.1 Functions of planning and control in disassembly

Planning and control can greatly contribute to increase the profitability of processes. The role of planning and control in disassembly can be seen in providing information, supporting decision finding and minimizing non-value-adding work through automation.

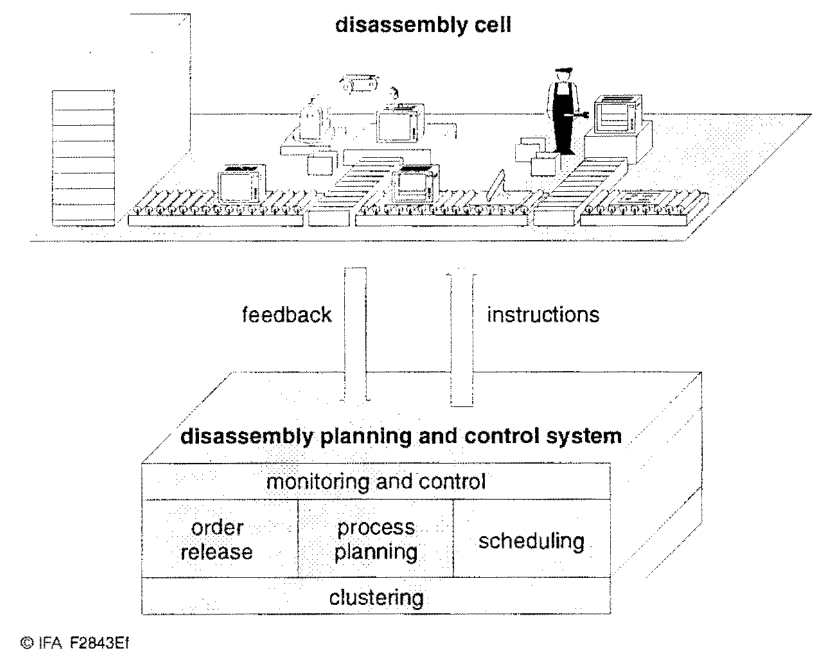

Fig. 4: Components of a Disassembly Management System

As in manual workstations, every operation is done by the same worker and no division of labour exists; no need for accompanying planning and control arises, except the assignment of products to workplaces. In the disassembly line, process planning and scheduling are already fixed by the system's linear architecture. Here only order release and clustering are functions of planning and control. In disassembly cells, planning and control can help to take advantage of the system's flexible structure and increase its overall profitability.

In Fig. 4, the major components of a disassembly cell are depicted: the input buffer, the automated and manual workstations, the manual or automated transport system, buffers for the disassembled parts and components and an underlying system for planning and control.

Five general functions of disassembly planning and control can be identified (Wiendahl et al., 1998b): clustering, scheduling, process planning, loading planning as well as monitoring and control. The functions are ordered hierarchically: clustering is done before the actual disassembly.

Order release, process planning and scheduling are done simultaneously to it. Monitoring and control act as interfaces between the process and its underlying planning decisions:

Clustering deals with the systematic classification of a given set of objects (Hentschel, 1996). The objects are described by characteristic properties. Clustering aims at processing homogeneous product spectrums at the same time at the same system, leading to economies of scale, minimizing set-up times and using the same resources for the different operations.

It is the task of *scheduling* to find the best way of getting the products through the system in order to minimize processing times and/or costs (Van Brussel, 1990). It determines the sequence of operations on stations. Since disassembly is carried out with a high degree of unpredictability about the product and the process, deterministic approaches as applied in PPC are not sufficient. Therefore methods capable of predictively drawing up simple schedules and reactively adapting them to changed conditions are required. For disassembly, prototypes for such flexible scheduling systems already exist, based on genetic algorithms (Wiendahl et al. 1998b).

In *process planning*, the disassembly strategy is fixed in principle. This includes the definition of the single operations as well as their sequence. For this, methods such as graph theory or Petri-Nets can be applied (Zussman et al., 1994 and Scholz-Reiter et al., 1998). In process planning a distinction is made between predictive and reactive process planning. In the former, the general process of disassembly is fixed. In reactive planning, plans are adapted to the specific properties of the product and the actual process.

Order release determines which products enter the disassembly process and at what time. In production planning and control, a wide range of methods is available. Here objectives such as minimizing set-up times and improving utilization are aimed at. Load-oriented production control (Wiendahl, 1988) has proved to be a suitable and very flexible method for the order release.

Monitoring and control has to function as an interface between the different planning and control modules and the real process. It monitors the progress of the disassembly process and detects malfunctions as well as defects. By this, the disassembly planning and control is always kept current to the actual process. Information can come from e.g. the robot controls, sensors, and from manual input of the disassembly worker. Reversely, it sends commands generated from planning and control to the system. Here an important part is sending control commands to the robots and the transport system.

3.2 Integration of the planning and control functions in disassembly

The functions of planning and control in disassembly described above can be developed modularly and can be linked together to form a system. Three major requirements for the functions can be identified: the functions have to work simultaneously, have to manage the interdependencies between each other and have to be adaptable.

The requirement of working *simultaneously* is caused by the high degree of unpredictability that is due to the unknown type, state, processing times and probabilities of the process and product. Therefore functions have to cope with sparse information and have to be capable of adapting to information that is gained in the course of the process.

The requirement of working *interdependently* is caused by the need of simultaneously planning and controlling the process while it is performed. Due to its unpredictability, sequential process planning, order release and scheduling are not possible. Moreover while the process is running, its process plan, schedule and release commands are generated and synchronized. Corresponding to this process plan, the operations have to be scheduled. Order release has to insert products corresponding to the actual system state and the actual schedule.

The requirement of *adaptivity* is due to information about the product and the process gained in the course of the physical disassembly. If, for example, it is found out that a process cannot be performed as planned, it is adapted to this situation. If e.g. unscrewing is impossible, drilling might be the alternative operation. In this case the schedule too would have to be adapted by removing the unscrewing operation and inserting the drilling operation in front of the drilling station.

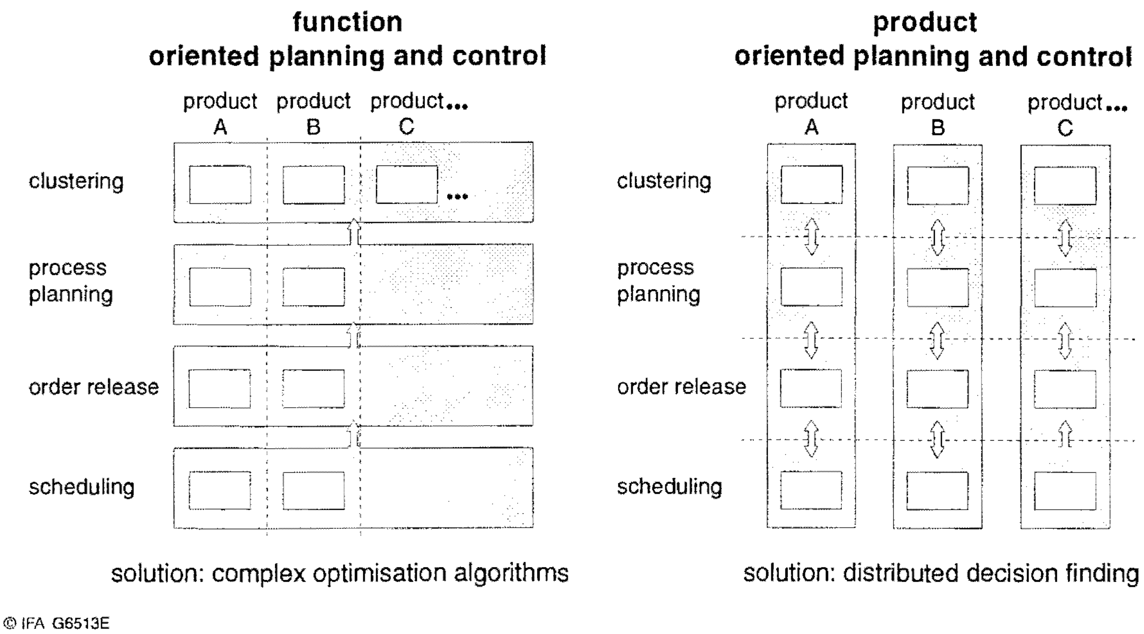

Fig. 5: Function and product oriented planning and control in disassembly

Two ways of dealing with such a complex planning and control system can be identified (Fig. 5):

Different software modules can be developed that solve the functions independently. These modules have to adapt themselves to changing parameters and current process information. The modules also have to be able to communicate with each other, in order to synchronize plans. This function-oriented approach requires the development of complex optimization algorithms. In the following section such an approach is described in more detail.

For big disassembly systems, the optimization problem is beyond the capability of single problem solvers. An alternative approach is therefore to reduce the complexity by using distributed planning systems in a product-oriented planning and control approach. To each product, a decentralized decision finding system is assigned, which does all the planning for the product from determining the time of release to the process plan to scheduling its operations to stations. These small planning systems for each product can be realized by means of agent-systems, which locally search for optima (Wiendahl et al., 1998c). This does not require complex optimization algorithms, but creates a high communication and coordination effort between the different modules.

3.4 An algorithm for handling the planning and control complexity

As described above, the question of adapting plans and schedules to changes and coordinating plans is crucial. In this section the function-oriented approach to solving the problem's complexity is described.

The algorithm that ensures all plans and schedules are valid all the time and are performed simultaneously consists of six steps (Fig. 6):

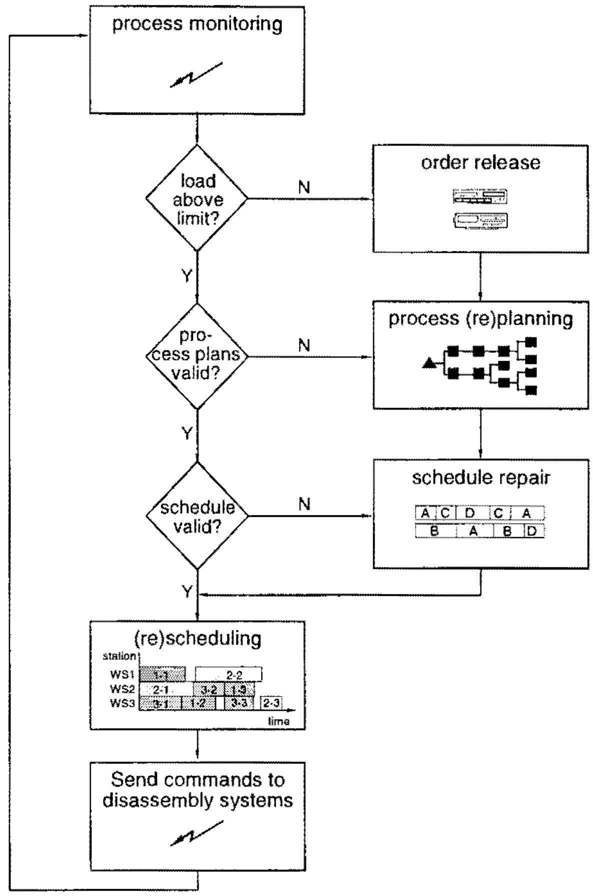

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Fig. 6: An Algorithm for Disassembly Planning and Control

In the *first step*, the actual process is monitored. Information is received by sensors, robots or the worker. This information is then sent to the planning and control system. It can be realized for example by using controllers and the interbus-technology.

In the *second step*, the workload of the system is calculated. If the workload in the system has fallen below a critical load limit, a new product is inserted into the system. The strategy for determining a product is to select a product which needs operations that can be done on idle workstations. The workload waiting in front of the workstation is calculated by the scheduler and sent to the order release. Then the order release triggers the process planner to create a plan for this product and the scheduler, to incorporate the new operations into the existing schedule.

In the *third step*, the process plan is inspected to check if it is still valid. If an operation has been signalized by the system as impossible to process, an alternative process plan is generated. The schedule is then repaired corresponding to the new plan.

If the schedule is no longer valid, schedule repair is done in a *fourth step.* Reasons for rescheduling can be a disruption, a machine breakdown or a workstation being idle, while others have a big workload waiting in front of them. The main objective of scheduling is to provide high utilization.

In a *fifth step*, the schedule is improved. This aims at improving the order of the operations in front of workstations with respect to the monitored real processing times of operations and the location of the products in the transport system.

In *step six,* the newly generated data is sent to the disassembly system. Data can be transportation commands, robot commands and information to the worker on his workstation about the next operations. Then the process is monitored again, starting at step one. This loop works continually running all throughout the disassembly process.

3.5 Case study of planning and control in a flexible disassembly cell

A prototypical disassembly planning and control system has been established as part of a combined German-Israeli project. It is based on a flexible disassembly cell at the Technion in Haifa, Israel.

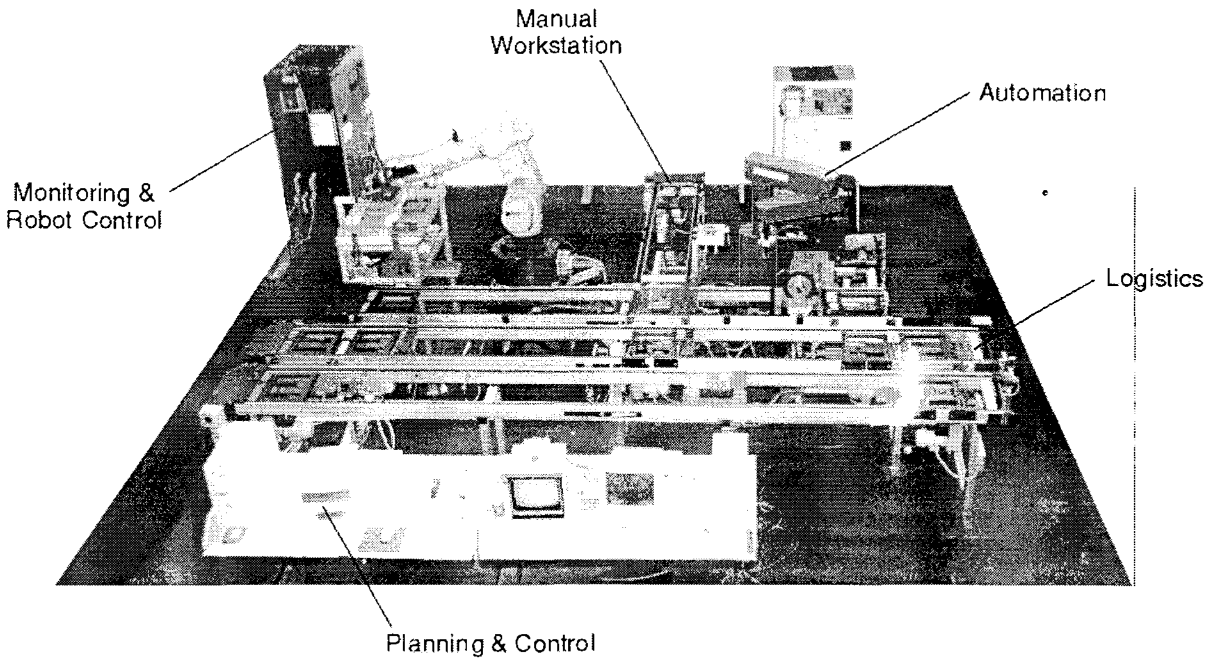

Fig. 7: Example of a Flexible Disassembly Cell at the Technion in Haifa

Fig. 7 depicts the disassembly cell with its components. It contains two automated workstations and a manual workstation. The transport system consists of a circular structure of conveyors. It has belts transporting pallets and lifts to move a pallet from one belt to another. Products are fixed to square pallets. The transport system serves for transporting and for buffering pallets. The planning and control system is implemented on a IBM Compatible Pentium 100 Personal Computer. The modules are programmed in C++, Visual FoxPro® , Visual Basic® and Matlab®. Information is sent to the system and received from there by a dispatcher. Communication between the modules is solved using DDE. The planning and control system, developed in a German-Israeli research project, is not only connected to the hardware of the system but also linked to a simulation module. This allows the testing of functions and decisions or the simulation of disassembly processes in quick-motion.

The disassembly cell serves as a testbed for planning and control as well as for the development of automated disassembly solutions. Whereas automated disassembly proves to be very difficult, it was found that big rationalization potentials are offered by an optimized planning and control.

4. Conclusion

Disassembly is a crucial element of both recycling and remanufacturing. Due to its high content of manual work, efforts have to be made to increase its efficiency to be able to compete with new materials and products. Automation alone cannot solve this problem, as it is hard to realize in this highly uncertain field. Flexible disassembly cells are hybrid systems that offer a feasible tradeoff both of flexibility and efficiency.

In this environment, planning and control can contribute to the reduction of non-value-adding work. It offers potentials for rationalization in respect of the division of labour, finding the optimal process plan, reducing set-up times, optimizing inventories, improving the utilization in the cell, routing products through the system and controlling operations that are feasible for automation.

Methods capable of controlling dynamic processes with high unpredictability can be utilized in disassembly for remanufacturing, where work has to be done under similar conditions. This enables remanufacturing systems to work on demand, to handle unstable and unpredictable processes and to process many different lot sizes at the same time, to react quickly to missing parts or tools and to meet changing customer requirements.

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Re-use of Glass Bottles in A Developing Country: some specific problems of a clear-beer manufacturing company[1]

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Abstract

This paper discusses the management practices of returnable glass containers of a clear-beer manufacturing company in a setting of a developing country. The problem of large-scale transportation with other situational factors are presented. The focus is on the production problems that result from the current return process. Through this study a demonstration is made on how standard problem solving techniques can be used to influence management decisions when handling complex problems.

Keywords: reuse; packaging; bottles; developing countries

1. Introduction

Manufacturing involves the transformation of input materials into intermediate materials which are later transformed into either products we consume or, for instance, products which package these goods. The manufacturing process requires, apart from other input quantities, materials and energy, with the resulting products having some energy value embedded in them. Once the final product (in this case, the package) has served its useful purpose, the material in it still contains the embedded energy. Some of that energy investment as well as some of the materials may be recovered through recycling/re-use with other financial and environmental benefits (i.e. such as the reduction of demand for raw materials, the reduction of waste disposal, etc..)

In the case of glass containers, the greatest conservation potential is in the product re-use which requires very little reprocessing energy (Steinmeyer, 1992). The returnable glass bottles can be cleaned to remove food residues and labels, and refilled up to about 12 to 25 times before they are either discarded or recycled into new bottles (Poshtar, 1996).

In many less developed countries, for example, returnable glass bottles account for the majority of drink sales. Open or closed systems are often used by manufacturing of drinks. A closed system for returnable glass bottles consists of labour-intensive container collection, transportation of containers and container washing. A closed system is often more complex than an open system of one-use containers.

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This paper presents the experience of a beer brewing company in the control of returnable glass containers. The investigation details the current practice, situational factors, and explores management alternatives of returnable glass bottles.

2. XYZ Breweries Company

2.1. History

XYZ Breweries Company (the name of the company is disguised to preserve confidentiality) was established as a private company in 1963. In 1968, the Zambian Government, through Industrial Development Company Limited (INDECO), nationalised the company through an initial acquisition of 55% of the shareholding and, later, a further acquisition of 20% of the shareholding.
Until 1994 the company operated from two production locations, one in Lusaka (the Central Division) and another in a town called Ndola (the Northern Division, three hundred and twenty-one kilometers north of Lusaka) and distributed its products through 13 warehouses (or depots) located throughout the country.
In 1994 as part of the Zambian Government's privatisation programme, the assets and liabilities of the company were split, in terms of a scheme arrangement, with those of the Central Division being transferred to XYZ Breweries Company and those of the Northern Division being transferred to another company.

2.2. Company Features

XYZ Breweries Company operates a brewery situated in Lusaka that produces clear beer for distribution throughout Zambia. The brewery site covers 9.63 hectares. The company currently locally brews four beer brands. The finished products are distributed by transport trucks to 8 warehouses where the finished products are temporarily stored before being distributed to retail outlets. The location of the plant and the warehouses are shown in figure 1. One of the 8 warehouses is at the production plant site.
Since privatisation, the company has been experiencing a steady growth of sales and has an estimated market share of 70%. Sales in hectolitres since privatisation as well as the forecast for the 12 months ending 31 December 1998 are presented in Table 1.

Year	Employment (persons employed)	Sales (in '000 hectolitres)
1995	500	461.67
1996	482	432.02
1997	486	448.49
1998*	470	500.00

*: Forecast figures
Sources: XYZ Breweries Company Prospectus, 27 March 1997and XYZ Breweries Company Annual Reports,31 December 1997

Table 1: Employment and sales in the last 4 years.

As the current sales growth is expected to be sustained at least through the short to medium term, one of key issues the plant has to cope with is the management of glass bottle flow.

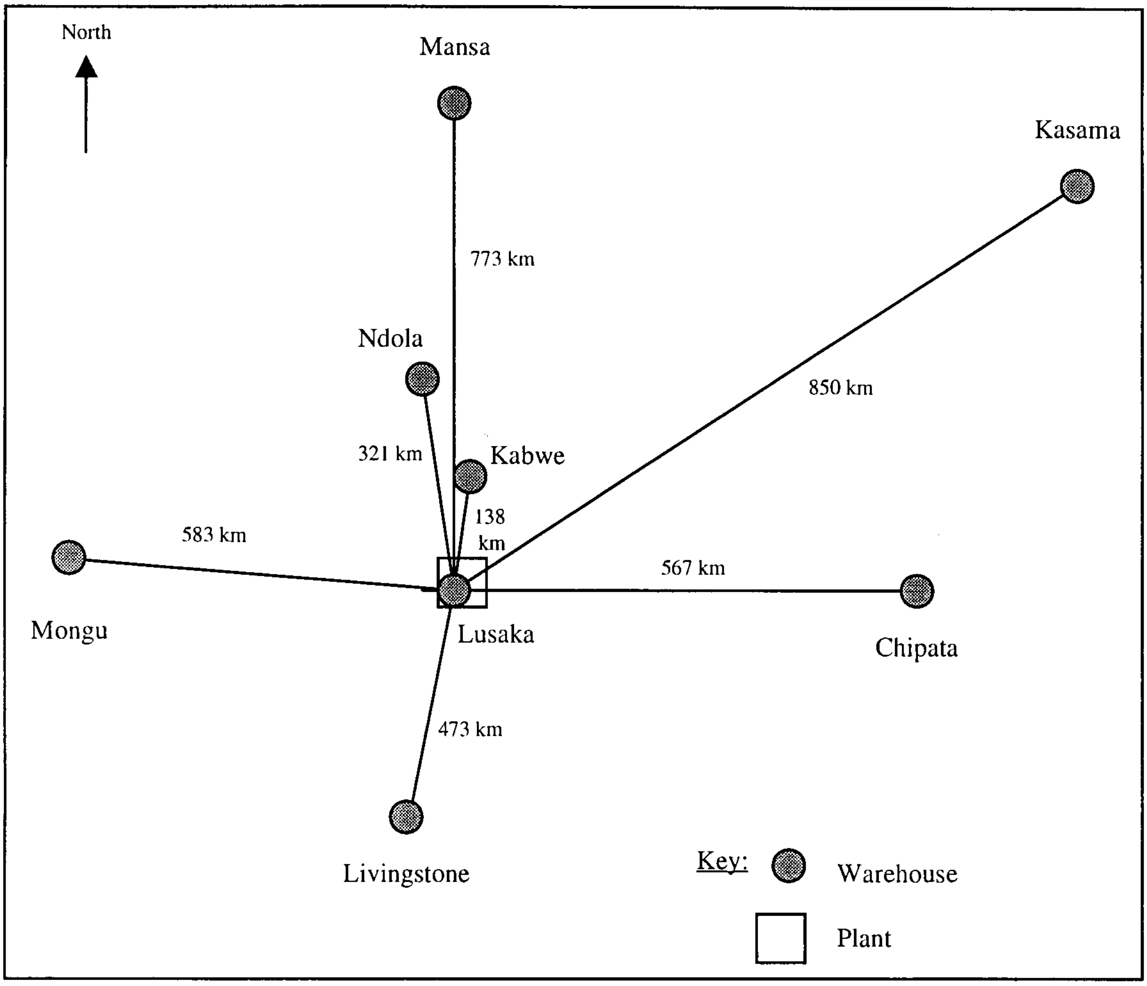

Fig.1: Plant and warehouse locations

2.3. Beer Production and Packaging

The production process of clear beer consists of two main subprocesses: the brewing and bottling subprocesses. Figure 2 shows the outline of beer production process. The brewing

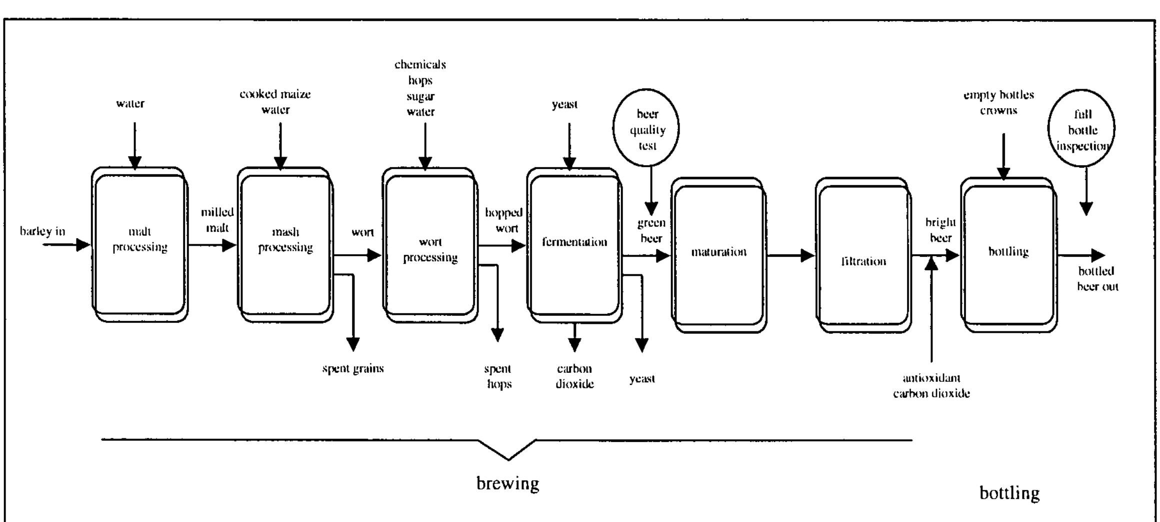

Fig.2: Beer Production

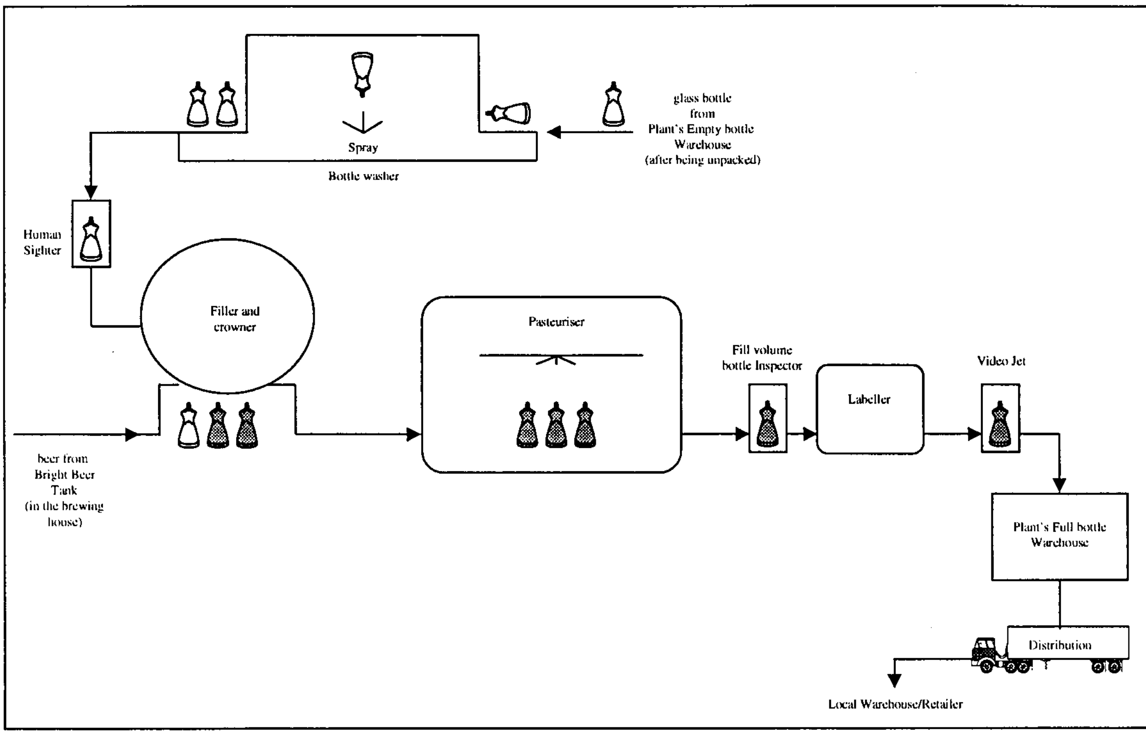

Fig.3: Beer Bottling

subprocess can, however, be sub-divided further into six sub-processes. These are the barley
processing, the mash processing, the wort processing, the fermentation, the conditioning and the filtration. Figure 3 gives more details on beer packaging.

3. Glass Bottle Re-use

3.1. Current Practice

This section provides an overview of key contexts within which bottle re-use takes place.

- Beer distribution and empty bottle collection

The beer distribution from the plant is done through the 8 warehouses. Apart from the Lusaka warehouse, the other warehouses are located at various long distances from the manufacturing plant. Independent agents, appointed by the company, handle distribution of beer from warehouses to the retail outlets. The retail outlets are mainly bottle stores, bars, restaurants, etc.. This beer distribution method accounts for 87% of the beer sold. The remaining 13% of the company's beer is distributed through trucks operated by the company. Collection of the 375 ml returnables is performed as follows:
At the retail point (e.g. bottle store, etc.) the beer is bought by the customer and it is either immediately consumed or taken away to be consumed at a later time. In the case where the beer is consumed at the retail point, the empty bottle is immediately collected by the retailer The retailer stores the empty bottles until they are collected by transporters who takes them to the local warehouse and later to the production plant in Lusaka.

If the customer desires to buy the beer for later consumption, the common and normal practice is for the customer to come with his/her own empty bottle and hand it over to the retailer together with the correct amount of money to cover the cost of beer only. The retailer then exchanges them with a filled beer bottle. The collected empty bottle is then dispatched to the production plant in similar fashion as in the case when the beer is consumed within the retailer's premises.

At the plant, the empty bottles are received and accepted into the plant's empty bottle warehouse after they have been delivered by the transporters. The empty bottles are then moved to the depalletizing bay and loaded manually on to the bottle conveyors.
A bottle conveyor system is used to transport the bottles from one process station to an other.

- *Production Problems*

The discussion in this section is focused on production problems that directly results from the re-use of bottle containers in a developing country set-up.

In developing countries, empirical evidence appears to indicate that items or tools, specific or otherwise, tend to be used for various purposes other than the ones the items were first meant for. This can be coined into the phrase 'objective-stretching' tendency as opposed to the 'objective-optimisation'(i.e. tendency to try to get the best from something in line with the objective it was meant for).

In similar way, the bottles that are taken away from the retail outlet are used for other purposes and subjected to other uses after the beer has been consumed and before the empty bottles are exchanged at the retailing point.other than containing the beer. Empty beer bottles are sometimes used in food preparation (i.e. grain grinding, etc..)

In combination with the long distances through which the bottles have to be transported, the often poor road network, the high bottle handling along the beer chain delivery and the long bottle age (since bottles are only removed from circulation until they fail) the company experiences high production losses as result of bottle failures and high customer complaints due to filled bottle containing foreign matter.

An investigation of bottle failures has revealed that the main source of bottle failures are bottle leakers due to chipped and scuffed bottles, bottle crimps out of specifications and bottle crowns (see Table 2). Bottle chipping and scuffing are as a result of the reasons given above, while the others are greatly dependent on the quality of the bottles themselves and crowns.

As regard to foreign matters found in the filled bottles, cumstomer complaint records show that the most common types of foreign matter found are roots of trees and herbs, followed by plastic and rubber packets, and solid substances.

To understand the presence of roots of tree and herbs in bottles, one looks beyond the company's activities. In the less developed countries, modern medical treatment of illness is often supplemented by traditional treatment. In fact in rural and pre-urban areas traditional treatment is often the only option. It is the practice of traditional treatment that it makes use of empty bottles for storing roots of trees and herbs. And when the empty bottles are exchanged at the retail point, the roots of trees and herbs present in empty bottles find their way to the beer production plant and often leave the plant in the bottled beer undetected.

Month Number	Final Product Quality Control: Full Package Failure Rate (Internal Failure)						Customer Complaints (External Failure)		
	Type of bottle failure								
		Due to bottle leakages							
	Due to foreign matter	Crimp (%)	Crown (%)	Chipped Bottles (%)	Others (half fills etc) (%)	Total bottle failures (%)	Due to foreign matter (%)	Due to others (i.e. flat beer, leakers, etc..) (%)	Total (%)
1	0	0	3	82	15	100	100	0	100
2	0	0	3	72	25	100	90	10	100
3	0	0	5	59	36	100	85	15	100
4	0	0	1	53	46	100	87	13	100
5	0	0	3	53	44	100	60	40	100
6	0	0	6	56	38	100	80	20	100
7	0	1	1	35	63	100	90	10	100
8	0	1	3	73	23	100	86	14	100
9	0	0	2	75	23	100	84	16	100
10	0	0	0	71	29	100	79	21	100

Table 2: Full bottle failures and Customer complaints

Present approach to redress the situation

Human sighters are employed to detect chipped bottles and bottles containing foreign matter after the bottles have passed through the bottle washer. The method is that washed empty bottles are passed against light and human sighters have to manually spot the bottles that are chipped, dirty or contain foreign matter.
A culling programme for bad bottles has also been introduced.

3.2 The alternative

The human sighters's ability to sort out good bottles from bad ones has strong limitations. The investigation has revealed that the company can employ both the prevention and the corrective approach.

The prevention approach involves working with retailers. Since the retail points often handle a limited number of customers who are often known to them, the retailers can be used as agents of change to bring about an awareness to customers to refrain from using bottles for other purposes. The retailers may also be encouraged to carry out a pre-screening of the empty bottles they get from customers.

The corrective approach involves aiding or replacing the human sighters. Electronic sighters are one option. These can either be developed in-house or purchased. The basic principle of operation will depend on the fact that the solid matter under discussion is opaque and therefore obstructs light. The bottles under discussion are translucent. The electronic sensors will comprise a light source at one end (either point or distributed) and a receiver or sensor at the other end. The stream of bottles will be passing in between. The receiver of light will trigger an alarm, whenever it senses obstruction in the bottle. Obstruction is sensed by comparing the received intensity of light with a known average which is the reference intensity. The accuracy of the sensor depends on the intelligence in the receiver. If a distributed light source is used, an intelligent sensor with a specified resolution would even be able to determine the size of the solid matter in the bottle.

When developed in-house, the option gives the company the opportunity to improve its technological capability, reduce instances of instrument/equipment malfunctioning due to maintenance problems. It also allows the company to better customise the instrument with possible saving in foreign exchange.

4. Conclusion and recommendations

An attempt has been made in this paper to bring to the fore the problems that a manufacturer of clear beer faces when operating in a developing country, some of which may be totally untechnical.

The implications of the study is that often management may have to look beyond the firm's boundaries to understand the problems facing them and use the community to address product quality improvement.

Additional study is, however, needed to further isolate the effect of situational-cultural factors with those resulting from the classic input supply side. Finally, this study has highlighted only two priority options in dealing with quality production problems, working with retailers and improving process control; similar linkages potentially could be drawn with management efforts to develop bottle supplier relationship.

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