Design for Environment in conceptual product design – a decision model to reflect environmental issues of all life-cycle phases

Miriam A. O'Shea

Institute of Business Information Systems, University of Hamburg, Germany

Miriam O'Shea studied industrial engineering and management at the Technical University of Hamburg. In 1997 she started work at the University of Hamburg in the Institute of Business Information Systems as well as her doctoral studies. Her research interests comprise the areas of computer supported planning, product development and sustainable design.

It will be shown that a modelling approach for the conceptual design of products that considers the environmental aspects of all phases of the product's life-cycle is still needed. Next, a taxonomy of the various categories of environmental aspects is developed and the options for incorporating these into the planning of the early phases of product development are highlighted. In the following article, a new modelling approach is introduced to fill the gap and its usefulness is shown in a case-study of a pencil-sharpener. For the task of implementing the disposal phase's costs in the mathematical model two options are compared that differ in the level of detail on the one hand and in the amount of work needed for the analysis on the other hand. The case-study's results show that even in the early stages of product development, it is possible to include the consideration of the environmental impact into the decision process and that the resulting conceptual design exhibits these environmental considerations in the choice of the configuration elements activated.

Introduction

In many industrial countries an increasing environmental consciousness towards products both by the legislative and by the market can be observed (Bullinger and Bopp 1998). Moreover, there is evidence that incorporating environmental friendliness into the design of products does not necessarily result in higher product costs, but rather can lead to reductions in costs of development, assembly, packaging, service and disposal of up to 50% (Bullinger and Bopp 1998; Eichert 2000). Advantages in marketing and technology leads from further positive aspects of including environmental issues in the design of products (Eichert 2000).

In general it can be stated, that the implementation of optimisation routines in De-

The Journal of Sustainable Product Design **2**: 11–28, 2002

sign for Environment (DfE) is rarely done. Compared to a manually conducted assessment, the advantage of employing a planning algorithm lies in the high number of different design concepts that can be evaluated. Especially in the area of the early phases of product development the consideration of environmental aspects in decision models is often limited due to the lack of information. However, the early phases of product design offer the strongest influence on the environmental impact. This article aims at developing a framework for the consideration of several environmental aspects in a mathematical model that serves as the basis of a planning algorithm.

First, a short literature review will be given to demonstrate the need for a modelling approach covering environmental aspects in the conceptual planning of consumer products. Second, a taxonomy of the various categories of environmental issues that are connected to the product‘s life-cycle is established and options for incorporating these in the planning of the product‘s concept are highlighted. Third, the prerequisites (the modelling framework) and the modelling approach itself will be presented with the help of a case study of the design of a pencil-sharpener.

Literature review

A literature review in the area of optimisation tools for DfE revealed very little integration of environmental aspects into the planning in conceptual design (see O’Shea 2002; Hanssen 1996). Most of the approaches found in literature employ a single aspect like recycling costs (e.g., Spengler and Rentz 1996), disassembly planning (e.g., Spengler and Rentz 1994; Navin-Chandra 1993; Gungor and Gupta 1997; Lambert 1997; Johnson and Wang 1995; Penev and de Ron 1996) or waste reduction (see Fu et al. 2000). An optimisation model that spans the complete product life cycle can be found in CYCLOPS (see Hanssen 1996). The model is based on a set of matrices to compute an Environmental Impact Index (EII) as a weighted average of all potential impacts of the various product life-cycle phases. Unfortunately however, by combining the impacts of the different phases into one evaluation criteria the resulting model provides rather limited options for later analyses of the design (e.g., for design improvements or treating single environmental impacts as hard restrictions).

The approach presented here aims at incorporating not only a single but various environmental aspects into the conceptual product design in an adequate manner without combining the information on the environmental impact of different phases into one index value. In the following, a taxonomy will be presented that facilitates the analysis of the ability to include DfE issues in the evaluation of the conceptual product design.

A taxonomy of the categories of environmental issues in design

So far, the aspect of recyclability, which covers the issues of dissassembleability and the economical as well as the ecological impact of the end-use-options chosen, has attracted the most attention within the research community (see also Ishii 1998). To ensure a holistic evaluation of the environmental impact, a DfE-approach should also cover the manufacturing, usage and disposal phases (see Anderl et al. 1999). Within all the phases of the product life-cycle the aspects of resource and energy consumption, emissions and waste in respect to land, water and air, as well as noise generation have to be considered (see Eichert 2000; Eyerer et al. 1990; Schuckert 1996). Additionally, the phase of disposal requires the integration of the above mentioned aspect of recylability as a criteria for the environmental evaluation. Table 1 exhibits the resulting taxonomy, described by the dimensions *phases of the product life-cycle* and *aspects of environmental influences*.

As the early phases of product development have to be characterised as highly qualitative and undetailed, a short analysis has to be undertaken to decide which evaluation criteria can be employed in that phase. Following the philosophy of life-cycle design, the conceptual design elicits not only the general realisation principles for the product‘s function as defined by the tra-

		manufacturing	usage	disposal
resource / energy consumption		×	×	×
emissions / waste	land	×	×	×
	water	×	×	×
	air	×	×	×
noise		×	×	×
recyclability (dissassembleability; environmental impact of end-use options				

Table 1: Dimensions of environmental evaluation criteria

ditional systematic design approach, but also potential production and disposal processes. Consequently, the evaluation scheme can cover all the entries in Table 1.

Case study: Design of a pencil-sharpener

In the following, the design of a pencil-sharpener will be used to present the decision process for generating environmentally sound products. To keep the size of the case-study within the scope of an article, a very small product has been chosen. Therefore, it is not possible to show the complete functionality of the approach. For more detail, the reader is referred to O'Shea (2001).

Decision variables

As the feedback of the evaluation information to the design process is essential, the decision variables have to include both the product representation and the environmental structures. In the following, first the decision variables describing the product structure ((1) functional and fastening configuration elements and (2) design attributes) and second the decision variables determining the environmental influence outside the product structure ((3) choice of production process and (4) level of disassembly) are presented.

Functional and fastening configuration-elements
In existing decision models for product design the decision variables of the product structure are represented either by quality elements (marketing oriented approaches) or by technical solution elements (engineering based approaches) (see O'Shea 2002). Here, the second scheme is employed and the technical solution elements, that represent the realisation of the product's functionality, are referred to as functional configuration elements.

The functional configuration-elements are to be enriched by fastening configuration-elements. These are inevitable for the integration of environmental aspects, when questions like disassembleability have to be answered (see also O'Shea 1999, p. 49). For every product function and fastener one or more configuration elements are developed. A complete design concept then exists in every combination of selecting one configuration element per function or fastener (see Figure 1). Combinations of configuration elements that are incompatible with each other are identified. In Figure 1 these are represented by a solid line connecting the configuration elements in question.

Design attributes
The selection of configuration-elements often does not allow for a sufficient evaluation of the product concept´s functionality, manufacturability, environmental friendliness, etc. Therefore, the approach presented here employs design attributes. The design attributes ($DM_{r,g,s}$) can give more detailed information on the functionality of a configuration-element $KE_{r,g}$ (e.g., the length of the lever for the configuration element *leverage effect*), but can refer to the manufacturing (e.g. thickness of the level, to ensure it stays within the working area of the machines) or disposal process as well. In general they represent values concerning the geometry of the parts or material properties. They are of continuous (e.g., dimensions), integer (e.g. amounts) and/or discrete (e.g. standard sizes) and nature (see Table 2).

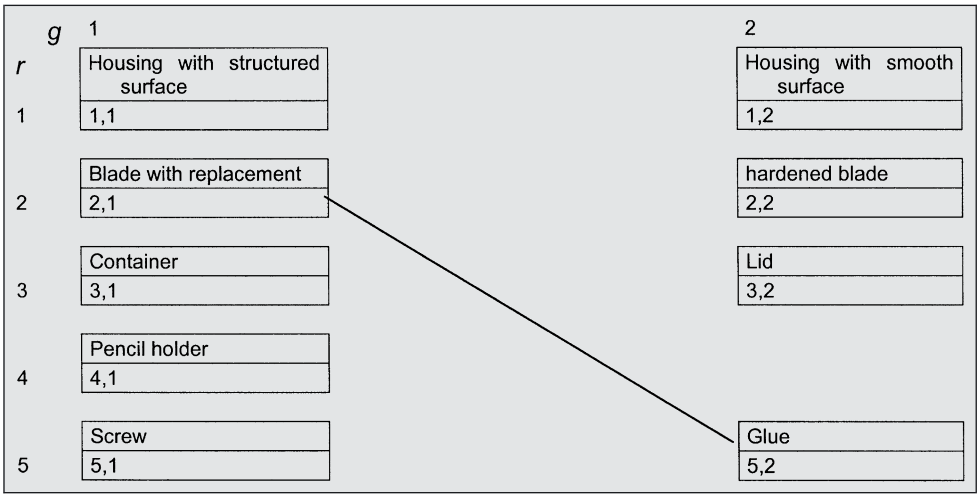

Figure 1: Functions and alternative solution elements for the pencil-sharpener

No.	$KE_{r,g}$	Name
1,1,1	$KE_{1,1}$	number of leading devices
1,1,2	$KE_{1,1}$	length
1,2,1	$KE_{1,2}$	number of leading devices
1,2,2	$KE_{1,2}$	length
2,1,1	$KE_{2,1}$	number of blades per $KE_{2,1}$
2,1,2	$KE_{2,1}$	number of replacements
2,2,1	$KE_{2,2}$	number of blades per $KE_{2,2}$
3,1,1	$KE_{3,1}$	length
3,2,1	$KE_{3,2}$	length
4,1,1	$KE_{4,1}$	length

Table 2: Design attributes $DM_{r,g,s}$ of the pencil-sharpener

Choice of production process

In case alternative processes exist for the production of the product's components, the choice should be left open for the optimisation algorithm to check against the various restrictions, that are formed by the ecological aspects of the environment (e.g. consumption of resources and energy, emissions, waste disposal, etc.). In so doing, it is possible to select the best process and to achieve an optimal design. One production process spans all the manufacturing techniques that are involved to realise the configuration element, e.g. process A: cutting, milling, drilling, surface finish and process B: injection moulding (see Table 3; for the example of the pencil sharpener only one process per configuration element is defined). To ensure that exactly one production process per configuration element is selected and that only those configuration elements that are currently selected to be part of the product design get a production process assigned to them, constraints in the form of special-ordered-sets (for example: three alternative production processes are represented by the binary variables p_1, p_2 and p_3; in so doing the equation $p_1 + p_2 + p_3 = 1$ can ensure that only one production process is selected (value of that production process equals 1)) are implemented in the decision model.

$KE_{r,g}$	production process
$KE_{1,1}$; $KE_{1,2}$; $KE_{3,1}$; $KE_{3,2}$; $KE_{4,1}$	casting
$KE_{2,1}$	milling, drilling, punching
$KE_{2,2}$	milling, drilling, punching, herdening
$KE_{5,1}$; $KE_{5,2}$	procured parts

Table 3: Production processes of the pencil-sharpener

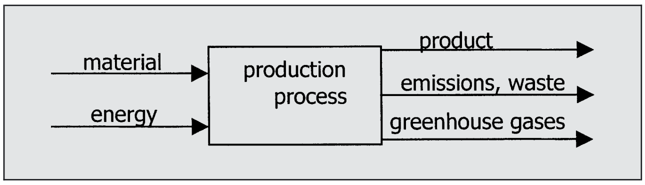

Figure 2: The production phase's influences on the ecology

Level of disassembly

The evaluation of the product or respectively its parts in respect to its/their recyclability involves analyses of the disassembleability as well as of the end-use-options applicable. The disassembleability mainly depends on the fastening methods used to hold the products' parts together. As these are already represented by the decision variables of the configuration elements, no further variables need to be introduced. However, the fastening configuration elements are to be described by parameters regarding their disassembleability and the need for tools for the actual disassembly. The decision regarding the end-use-options can on the one hand be predetermined, following a fixed strategy (e.g., every part is landfilled); on the other hand, this decision can be subject to an optimisation run, during which the optimal level of disassembly is elicited. In the latter case further decision variables are needed: for the level of disassembly a binary variable $U^{Dis\text{-}ass.}_{n}$ is used. Additional decision variables can be employed to represent various end-use options.

Decision model for Design for Environment

The approach outlined here is based on a decision model. The target function aims at maximising the benefit the product gives to the customer to ensure that the company can compete in the market successfully. The general model structure, out of which the environmental part alone is shown here, employs a target-function that maximises benefits to the customer to ensure the product concept meets the functional standard of the market. The environmental aspects (DfE) are represented by restrictions, as it will be depicted in the following.

Design for environmentally friendly production

When manufacturing a product, the consumption of raw material and energy has to be considered, which represents the input side of the production process. On the output side of the production process, the choice of technology can have an influence on the level of emissions, waste and greenhouse gases that effect the environment like air, water and land. Figure 2 summarises the above mentioned aspects in a flow-diagram.

In many instances, limits are given for these measuring elements by the government (Steinhilper et al. 1996, p. 394). In numerous other cases, missing governmental limits are replaced by company-own limits that are part of an *Environment Management System*. In the decision model these values are used as upper or respectively lower limits of inequality constraints. The values on the left hand side of these inequalities are based on the value setting of the decision variables. For the example of the pencil-sharpener no environmental impacts are to be expected within the manufacturing phase.

Design for environmentally friendly usage

The use and disposal phases can be regarded as competing elements, e.g. when concepts that prolong the use phase are based upon chemical processes that change the material properties in a way that limits the options of recyclability. The approach presented here gives priority to the prolongation of the product's usage phase over ease of recycling if consumer goods are regarded. Therefore, the length of the usage phase is part of the evaluation criteria in the target function.

Design for environmentally friendly disposal

DfE related to disposal phase spans the control of the consumption of the ingoing streams of raw material and energy and the outgoing streams of emissions, waste and greenhouse gases similar

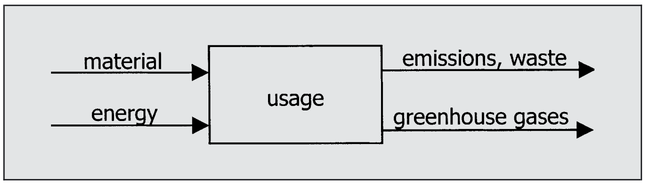

Figure 3: The usage phase's influence on ecology

to the phases of the production process and usage, as well as the issues of the recyclability of the product (see Figure 4). The restrictions imposed by the ingoing and outgoing streams of energy and material form constraints in the decision model as presented above.

In respect to the issues of recyclability, the following aspects have to be considered. If the recycling of the product as a unit cannot be undertaken, then the recyclability of the product is determined by the recyclability of its components as well as by its disassembleability. Besides the monetary aspects of recycling, other DfE metrics might be considered (see Hopfenbeck and Jasch 1995, p. 120 ff.; Barg 1991, p. 68 a. p. 71; Bullinger and Bopp 22.01.1998, p. 9; Nissen and Toberer 1993, p. 89):

- number of different material types; homogeneity
- ability to be combined with different material types
- harmfulness of the material
- disassembleability; number of insoluable fasteners; type of fastener

Due to the low level of detail of the information available in conceptual product design, the modelling approach presented here, is limited to DfE metrics like:

(a) number of critical elements or respectively fasteners (for a fixed level of disassembly)
(b) number of insoluable elements or respectively fasteners (for a fixed level of disassembly)
(c) number of elements not disassembled (for a variable level of disassembly)
(d) number of different material types (for both strategies of a fixed and a variable level of disassembly)

These and further indicators can be implemented in the decision model as restrictions.

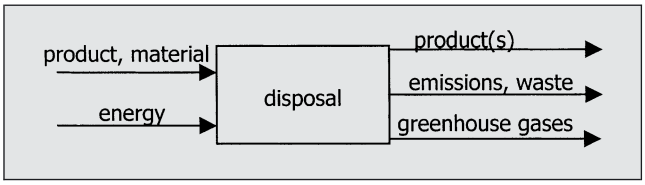

Figure 4: The disposal phase's influences on the ecology

Again for the example of the design of a pencil-sharpener, no specific constraints are to be considered.

Monetary aspects of design for environmentally friendly disposal

As there is a growing interest in including the disposal phase into the responsibility of the manufacturer, a modelling concept for the disposal costs and their integration in the manufacturing costs of the product is introduced here. Until now, this aspect has rarely been considered in decision models for product design (see note 1). According to the hierarchy of end-use-options (see Kriwet 1994, p. 36; O'Shea 1999, p. 77), the value hierarchy that is displayd in Figure 5 can be derived.

The differences of the options mentioned in Figure 5 can be found in the reservation or respectively non-reservation of the initially intended usage or respectively originally applied manufacturing process (Barg 1991, p. 64):

- reuse: secondary usage for the original purpose
- re-utilisation: secondary usage for a different purpose
- recycle 1. order: secondary application of the original manufacturing process (e.g. aluminium can ⇒ aluminium can)
- recycle 2. order: secondary application of a different manufacturing process (e.g. newspaper ⇒ cardboard box)

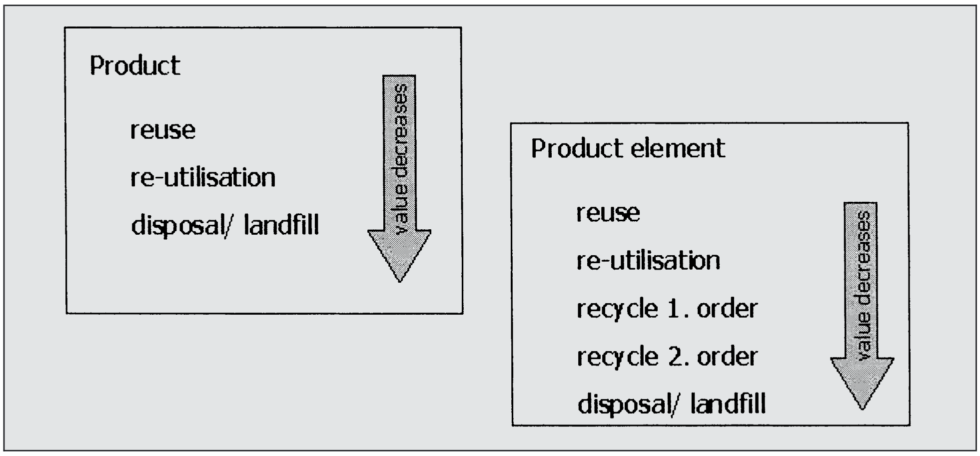

Figure 5: The value-hierarchy of different end-use-options

The reuse of the product as a whole for the original purpose reserves the greatest part of its initial value. However, the option to reuse the product as a whole implies that the product is in a good enough state to be restored. As an alternative, the product can be landfilled, not restoring any value but on the other hand incurring costs for the disposal. The disassembly of the product leads to a reduction of the value compared to reusing the product as a whole; on the other hand, it is possible that higher value end-use-options can be applied to single elements of the product than can be applied to the product as a whole (e.g. a car that has been damaged in an accident as a whole can only be landfilled, disassembled single parts like tyres, seats, radio etc. can be reused for their initial or a different purpose). As the end-use-options of a product as a whole greatly depend on what the state the product is in when the product is returned at the end of its usage phase and therefore are affected by the way the product has been used and/ or repaired, aspects that are unknown in the phase of the conceptual product design, the approach presented here concentrates its efforts on the analysis of product parts. Thus, a certain level of disassembly is taken for granted here.

Due to the low level of detail of the information at the early stages of product development, the following issues only will be integrated in the modelling concept (Meerkamm and Rosemann 2000, p. 17):

- material types used
- fastening technologies implemented
- principle assembly structure
- connecting parts in the product structure

According to Spengler (1994, 1996), the modelling of the disposal costs of a product includes the integration of recycling values and restoration costs on the one hand and the disassembly costs on the other hand. The recycling values or disposal costs are influenced by the principle assembly structure, including the choice of the fastening technologies, the material types used, the level of disassembly and the selection of the end-use-options. For the support of the decision on the level of disassembly, two different methods will be introduced in the following, (a) a strategy of fixing the level of disassembly before the analysis starts and (b) a strategy of employing a heuristic algorithm to determine a good level of disassembly. By definition, the strategy of a prefixed level of disassembly as a very simple but certainly simplifying method implies the complete disassembly of the product (as far as possible). The more complex but on the other hand more informative strategy leaving the level of disassembly variable, forces the intro-

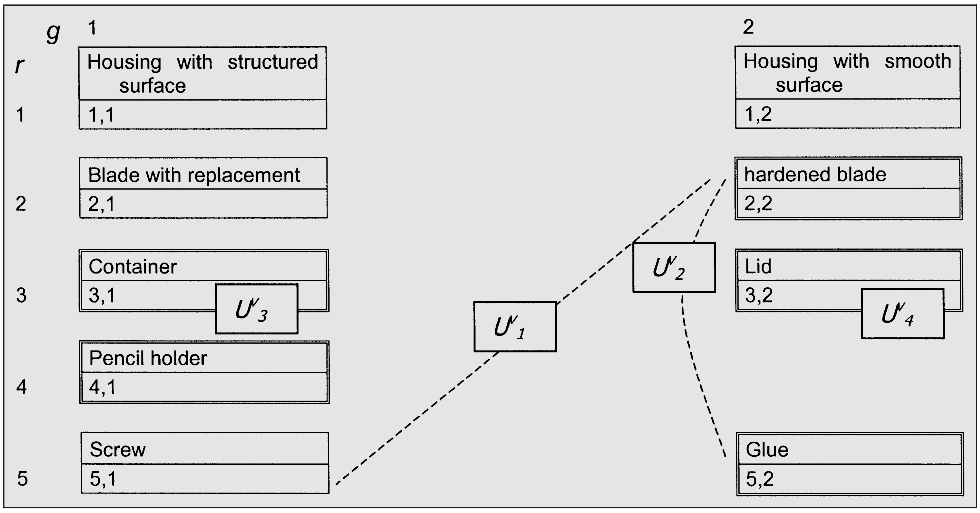

Figure 6: Configuration elements in a morphological chart with highlighted critical elements and connecting fasteners

duction of an additional decision variable. This represents the level of disassembly within the decision model. To further give the product development team the greatest flexibility possible, the pool of end-use options should span all entries of Figure 5. In the following, the simple case of differing between recycling and landfill only is applied to ensure the scope of the article is not exceeded. For this modelling alternative a single binary variable per configuration element is needed to indicate whether the element is to be recycled or not.

Fixed level of disassembly
In the case of a fixed level of disassembly, every fastener that can be disassembled, is to be disassembled at the end of the product's life-cycle. Thus, the resulting costs are not optimised and are probably a little bit higher than the costs that would arise when applying an optimisation algorithm. This method should be applied to simple and/or small projects or when a rough analysis of the end-of-life costs is sufficient. To reduce the amount of effort needed to conduct an analysis of the life-cycle phase of disposal, not all fastening elements are scrutinised, but only those that connect critical product elements.

Def. 1: An element is called critical, if it can neither be recycled on its own nor in connection with other elements of the product.

In case the fastener that connects a critical element to other elements cannot be disassembled, all elements that are part of this assembly have to be disposed of and disposal costs arise. If, on the other hand, the fastener can be disassembled, the most valuable end-use option available to each element of the assembly can be assigned and recycling values as well as disassembly costs have to be calculated.

Step 1: Highlighting of critical elements
In the functional hierarchy of product elements (see Figure 6) groups of homogenous end-use options and material types are searched for. Those elements, whose end-use option or material type does not conform to or cannot be combined with the mainstream end-use option/material type-combination of the product are highlighted in the functional hierarchy by a double-lined frame.

Step 2: Analysis of fasteners that connect critical elements
In the following, all fasteners that connect critical elements to other (critical) elements are analysed. A dotted line represents the combination of a critical element and a fastener,

KE	$RV^{Rec}_{r,g}$	$D^{Disposel}_{r,g}$
Material-based		
$KE_{1,1}$	25 MU/WU	–20 MU/WU
$KE_{1,2}$	25 MU/WU	–20 MU/WU
$KE_{2,1}$	25 MU/WU	–20 MU/WU
$KE_{2,2}$	–	–20 MU/WU
$KE_{3,1}$	–	–30 MU/WU
$KE_{3,2}$	–	–30 MU/WU
$KE_{4,1}$	–	–30 MU/WU
Part-based		
$KE_{5,1}$	0,01 MU	–0,015 MU/WU
$KE_{5,2}$	–	–0,015 MU/WU
MU: monetary unit; *WU*: weight unit		

Table 4: Recycling values/disposal costs of the configuration elements $KE_{r,g}$

if both exist in separate configuration elements (see Figure 6).

In the decision model, every possible combination of a fastener with a critical element will be represented by an indicating variable U_i^v. During the course of the run of the solution algorithm this variable holds the value of one if the combination is activated (both the critical element and the fastener are selected) and the value of zero if one of the elements (either the fastener or the critical element) is not selected as part of the product configuration. In case one configuration element includes both the critical element and the fastener (e.g. injection moulded pencil-sharpener container with thread), then the variable U_i^v is set according to the value of that configuration element alone. Moreover, it is possible that a critical element is not connected to any fastener at all, as the pencil holder $KE_{4,1}$. Consequently, no variable is defined for that case.

Step 3: Determining the recycling values/ disposal costs and disassembly costs
After the indicating variables U_i^v have been introduced, additional information on the disassembleability and the need for tools for the disassembly is necessary. For this reason, the binary parameters $u_i^{disass.}$ and u_i^{tool} are implemented (see Table 5).

In the following, the variables U_i^v are used for the calculation of the recycling values/ disposal costs $RV_{r,g}$ of the configuration elements $KE_{r,g}$ and the calculation of the disassembly costs $K^{Disass.}$ (for the example of the pencil-sharpener, see Table 4). A distinction should be made between recycling values and disposal costs that are material-based and those that are part-based. Therefore, Table 4 is organised into two sections.

	U_1^v	U_2^v	U_3^v	U_4^v
$u_i^{disass.}$	1	0	1	1
u_i^{tool}	1	0	0	0

Table 5: Parameter values $u_i^{disass.}$ and u_i^{tool} for the example of the pencil-shapener

It can be seen that for the example of the pencil-sharpener the selection of the critical element 'glue' forms a restriction, all the other critical element/fastener-combinations can be disassembled (see Figure 6). When deriving the equations, it has to be considered that other configuration elements outside the critical element/fastener-combination can be affected (e.g., the combination glue/hardened blade has an impact on the housing). Following the strategy of a fixed level of disassembly, where every part that can be disassembled is chosen to be disassembled, the recycling value $RV_{r,g}$ of every configuration element $KE_{r,g}$, except for $KE_{1,1}$, $KE_{1,2}$ and $KE_{2,2}$, can be set to their most positive end-use-option available (e.g., $RV_{2,1} = 25$; $RV_{3,1} = -30$). The recycling values of $KE_{1,1}$ and $KE_{1,2}$ have to be left variable, their values depend on whether the critical element 'glue' is activated in the product design or not. In case the critical element 'glue' is selected as a fastening element, the housing cannot be separated from the blade and therefore has to be landfilled ($RV_{1,1} = -20$), if not the housing can be disassembled and recycled ($RV_{1,1} = 25$). The $RV_{r,g}$ of $KE_{2,2}$ can be set to -20 as it cannot be disassembled independent of whether the configuration element 'glue' is selected or not. For more detailed information on the phrasing of the equations in this and the following section see O'Shea (2001).

The calculation of the disassembly costs can be conducted on the basis of the number of connections that can be disassembled and the information on whether a tool is needed to perform the disassembly of these connections.

Variable level of disassembly

As an alternative to the procedure illustrated above, the level of disassembly can be left variable. This method should be applied to complex and/or large projects or when a detailed analysis of the end-of-life costs is necessary. Besides the information on the recycling values/disposal costs of the configuration elements and the costs of disassembly, knowledge concerning the product part assembly structure is used within the optimisation. The product part assembly structure is represented by the so-called disassembly hierarchy (see Figure 7).

Step 1: functional hierarchy versus *disassembly hierarchy*

During the conceptual product design the configuration elements of the product are indexed according to their functional hierarchy. For an analysis of the disposal phase of the product this kind of indexing is not optimal. Generally, the ability to reach a product element for the purpose of disassembly and recycling is an important ordering criterion. Elements, that can be reached without the disassembly of any other element, are classified as level 0 elements. Furthermore, those elements that are only restricted by elements of level 0, are included in the level 1 of the disassembly hierarchy, that are limited by elements of level 1, belong to level 2 etc. The resulting order of elements is depicted in Figure 7.

Step 2: Determining the sequence of disassembly

The sequence of disassembly is represented by the disassembly index n and is derived from the disassembly hierarchy. To accomplish this task, the elements of a binding character (they restrict other elements in the disassembly hierarchy) and those of a non-binding character are treated differently. Elements of a binding character limit all those elements that are positioned lower in the disassembly hierarchy; consequently, if an element of a binding character is not disassembled, all following elements cannot be disassembled either and it is likely that recycling is not possible. On the other hand, elements of a non-binding character are not to be included in the sequence of disassembly, as they do not restrict the treatment of any other element. Starting with the highest level in the disassembly hierarchy (level 0) and within each level working from left to right, every binding element is indexed and thus the sequence of disassembly is fixed (see note 2). In the following, it has to be documented for every element n, whether it can be disassembled (parameter $u_n^{DHdisass.} = 1$) and whether a tool is needed if the disassembly is carried

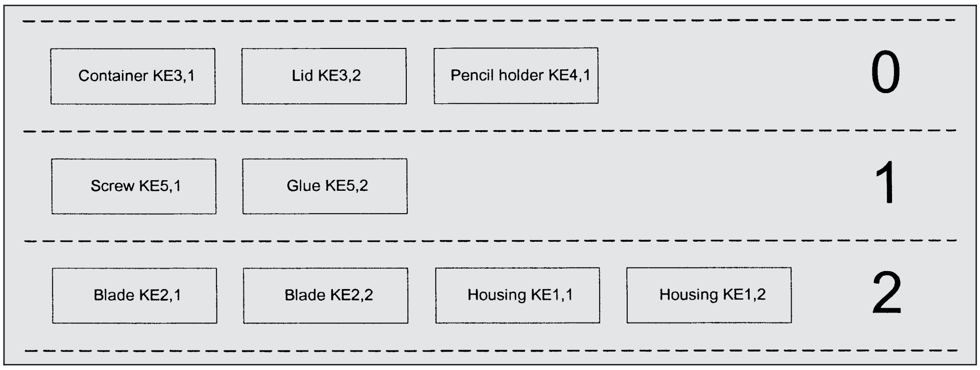

Figure 7: Disassembly hierarchy of the pencil-sharpener

out (parameter $u_n^{DHtool}=1$) (see Table 6).

n	$u_n^{DHdisass.}$	u_n^{DHtool}
1	1	0
2	1	0
3	1	1
4	0	0

Table 6: Parameter values $u_n^{DHdisass.}$ and u_n^{DHtool} for the example of the pencil-sharpener

Besides products with a single sequence of disassembly, more complex products can include groups of elements, that can be disassembled parallel to the main disassembly sequence (for more detail see O'Shea 2002). Especially for products with a high number of elements, the analysis of the sequence of disassembly can be very complicated to conduct. In those cases, a structured approach to elicit natural groups, that enable parallel disassembly, and consider a high number of disassembly constraints is necessary, as it can be found in O'Shea (1999).

Step 3: Determining the level of disassembly

For the translation of the functional hierarchy into the disassembly hierarchy a relationship of identity of the binding configuration elements and their positions in the sequence of disassembly is implemented, e.g., $U_1^{DH} = KE_{3,1}$ (see Figure 8). Consequently, the activation of a configuration element $KE_{r,g}$ of the functional hierarchy is passed into the disassembly hierarchy automatically. Moreover, for every binding element n of the sequence of disassembly a binary variable $U_n^{Disass.}$ is introduced that represents the decision, whether this element is to be disassembled ($U_n^{Disass.}=1$) or not ($U_n^{Disass.}=0$). The value assignment of the solution algorithm is controlled by (a) the resulting disassembly costs and (b) the resulting recycling values/disposal costs. In addition, the following constraints have to be fulfilled:

(a) Only those elements can be disassembled that have been activated as a part of the conceptual product design solution.
(b) The elements that are positioned high in the sequence of disassembly limit the disassembleability of all elements that stand below them.

The formulas for the calculation of the recycling values/disposal costs $RV_{r,g}$ can be derived on the basis of the entries of Table 4 and the value of the variable $U_n^{Disass.}$. For $U_n^{Disass.}=1$ the recycling value is set to its most positive end-use-option available, for $U_n^{Disass.} = 0$ the value of the parameter $K^{Disposal}$ is activated. First the formulas for the calculation of the non-binding elements' recycling values/disposal costs are to be phrased. Ensuing, for every position n of the sequence of disassembly the formulas needed for the calculation of the recycling values/disposal costs of the binding element n itself and of all non-binding elements that are directly connected with the binding element n are to be included in the decision model.

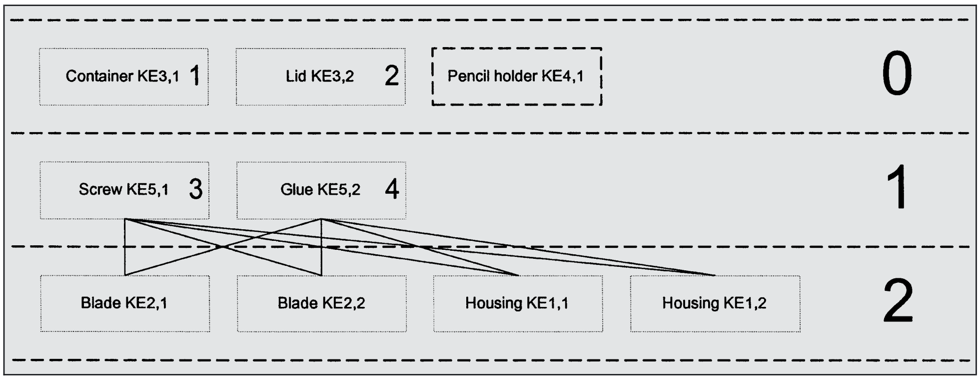

Figure 8: Sequence of disassembly of the pencil-sharpener

The calculation of the disassembly costs can be undertaken according to the actual number of parts selected to be disassembled and the parameter values of $u^{DHtool}{}_{n}$, which indicate whether a tool is needed to conduct the disassembly.

Step 4: Implementation of the end-of-life-costs in the decision model

The procedures that have been described in the step 3 of both the strategy of a fixed and a variable level of disassembly deliver values for the recycling values/disposal costs on the one hand and for the disassembly costs on the other hand. In the following section, there is a description of how these values are included in the mathematical decision model for the conceptual design of a product. The recycling values/disposal costs that are material based are volume dependent and are added to the price component of the material costs of the configuration element $KE_{r,g}$. Those recycling values/disposal costs that are not material based, but refer to complete product parts are included in the total costs $KKE_{r,g}$ of the configuration element $KE_{r,g}$ or in case of externally manufactured parts are added to the procurement costs. The disassembly costs are part of the overall product costs K. The overall product costs, including the costs of the disposal phase, are taken care of as a restriction in the decision model to ensure the consideration of the economical impact of the various end-use-options.

Step 5: Heuristic determination of the level of disassembly

The determination of the level of disassembly is carried out by a heuristic algorithm based upon a *Threshold Accepting* algorithm, that belongs to the group of *Mutation-Selection* procedures. The algorithm described in the following section ensures that the constraints outlined above are fulfilled at any one time.

After the random generation of an integer number, that represents the level of disassembly in terms of the position within the sequence of disassembly, all variables $U_n^{Disass.}$ with $n \leq$ level of disassembly are assigned the value of one, all others ($n >$ level of disassembly) are assigned the value of zero. Starting with the first position in the sequence of disassembly $n^* = 1$ it is checked (see note 3), whether that element is activated as a configuration element in the conceptual design of the product ($U^{DH}_{n^*=1} = 1$?). If this is not the case, the algorithm proceeds with the next position in the sequence of disassembly ($n^* = 2$). If on the other hand, the element is activated then the disassemblability is analysed ($U^{DHdisass.}_{n^*=1} = 1$?). In case it cannot be disassembled, for this and all succeeding elements the value of zero is assigned to the indicating variables U_n^{DH} and the recycling values are calculated on the basis of the disposal costs. If on the other hand the element can be disassembled the variable $U_n^{Disass.}$, that indicated the decision on whether the element n should be disassembled, is analysed next. For the value of zero (the element is not to be disassembled), the procedure that has been introduced for elements that cannot be disassembled is applied, (right wing of the process chain in Figure 9). In case the element is to be disassembled, the recycling values/disposal costs for the current position of the sequence of disassembly are to be determined.

The procedure outlined above is repeated for all following positions of the sequence of disassembly until the last position $n^* = n_{\max}$ is reached. The cost determination procedure closes with the calculation of the disassembly costs of the complete design.

After the cost calculations are undertaken, an evaluation of the current value setting of the variables is performed within the *Evolutionary Algorithm* (see note 4). Until the stop criterion is fulfilled, this procedure is repeated and a good if not very good solution is derived by the mechanisms of mutation and selection of the *Evolutionary Algorithm*.

Results of the case study (pencil-sharpener)

The target function employed consists of a number of customer requirements that are to be achieved. The environmental impact of the product design is taken care of by constraints. As only a very limited example can be shown here, the consideration of the

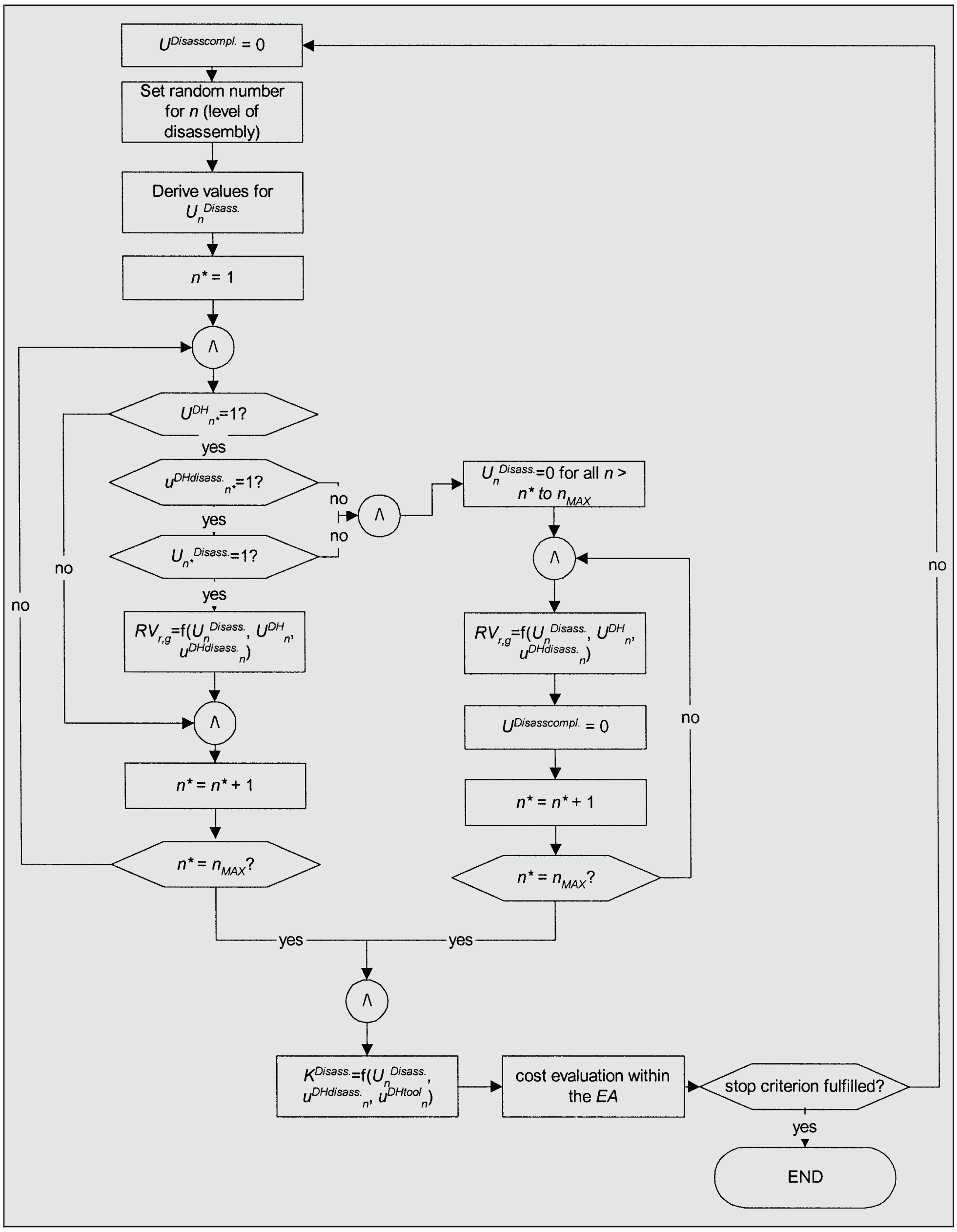

Figure 9: Determination of the level of disassembly

environment depicted in the case study involved the monetary aspects only. The example decision problem of the design of a pencil-sharpener has been solved by a *Mutation-Selection* algorithm, and achieved extremely stable results. The configurational design chosen by the algorithm is presented in Tables 7 and 8.

First of all, it becomes apparent that that the environmen-

target value (= customer benefit)		915,9133
costs		4,997
conceptual structure	KE	$KE_{1,1}$ = 1 (housing with a structured surface) $KE_{2,2}$ = 1 (hardened blade) $KE_{3,1}$ = 1 (container) $KE_{4,1}$ = 1 (pencil holder) $KE_{5,1}$ = 1 (screw)
	DM	$DM_{1,1,1}$ = 2 (number of leading devices) $DM_{1,1,2}$ = 25 (length of theehousing) $DM_{2,2,1}$ = 2 (number of blades) $DM_{3,1,1}$ = 100,3632 (length of the container) $DM_{4,1,1}$ = 100 (length of the pencil holder)

Table 7: Solution design concept for the strategy of a fixed level of disassembly

tally unfriendly configuration alternative of using glue as a fastener is rejected, even though it fulfills the requirement of joining the housing and the blade as well as a screw does and is cheaper in terms of manufacturing costs. Second, the hardened blade is favoured over the configuration element of using replacement blades as the hardening of one blade is viewed to be more positive than the selection of multiple blades, as more material would have to be used (see Figure 10). Moreover, the design concepts incorporate a blade with two sharp edges, so that even for two leading devices (for two different diameter pencils) only one blade is needed (see Figure 11). Comparing the results for the two different strategies, it becomes obvious that the results are similar. There are small differences though, showing that the strategy of a variable level of disassembly is superior to the strategy of the fixed level, as it resulted in lower costs for a higher customer benefit.The strategy of the fixed-level of disassembly, which suggested that is was not worthwhile to disassemble the product at all, is not confirmed by the results of the optimisation run.. The reason lies in the cost structure of high disassembly costs and low material worth chosen. Thus, money could be saved by not disassembling the product. The money saved was furthermore used to improve the product's functionality and in so doing the customer-benefit of the design was increased.

target value (= customer benefit)		921,417
costs		4,67
level of disassembly		0
conceptual structure	KE	$KE_{1,1}$ = 1 (housing with a structured surface) $KE_{2,2}$ = 1 (hardened blade) $KE_{3,1}$ = 1 (container) $KE_{4,1}$ = 1 (pencil holder) $KE_{5,1}$ = 1 (screw)
	DM	$DM_{1,1,1}$ = 2 (number of leading devices) $DM_{1,1,2}$ = 25 (length of the housing) $DM_{2,2,1}$ = 2 (number of blades) $DM_{3,1,1}$ = 107,4 (length of the container) $DM_{4,1,1}$ = 116 (length of the pencil holder)

Table 8: Solution design concept for the strategy of a variable level of disassembly

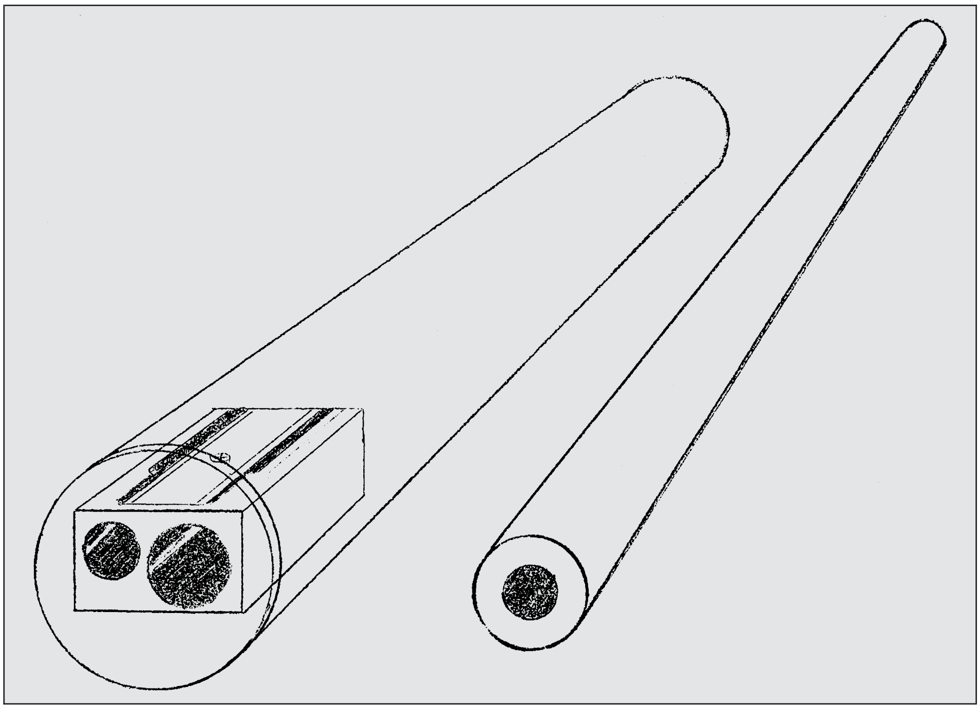

Figure 10: The design of the pencil-sharpener

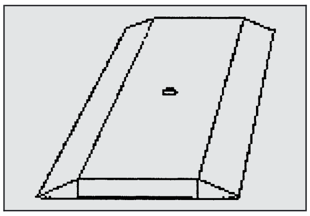

Figure 11: Detail drawing of the blade with two sharp edges

Summary

With the help of a short literature review it could be shown that a modelling approach for the conceptual design of products that considers the environmental aspects of all phases of the product's life-cycle is still needed. A taxonomy of the various categories of environmental aspects of the product's life-cycle has been developed and the options for incorporating these in the planning of the early phases of product development have been highlighted. A new modelling approach has been introduced and its usefulness has been shown in the case study of the pencil-sharpener. For the implementation of the disposal phase's costs two options of varying level of detail have been compared, showing similar results in the general product design but differing in the choice of the level of disassembly and therefore in the cost/benefit-ratio of the design itself as well as in the effort needed for the analysis process. However, both methods produced sound results and should be considered useful in their area of application. The case study's results exhibit that even in the early stages of product development it is possible and useful to include the consideration of the environmental impact into the decision process and that the resulting conceptual design expresses these environmental considerations in the choice of the configuration elements used.

Notes

[1] In Spengler (1996, 1994) a mathematical formulation of the disposal costs can be found that is part of a planning algorithm for life-cycle costs or respectively disassembly. The conceptual stage of

product design is not considered in his work. Hanssen (1996) includes an index-based implementation of the life-cycle economy of design. However, details on the realisation of his approach are missing.

[2] In the following, a simplification shall be used: it is assumed that all succeeding elements are limited, even the ones that are positioned right of the element under study that is positioned on the same level. This simplification, which has a small impact on the accuracy of the results due to the possibility to introduce parallel groups, that run besides the main stream of disassembly, results in a much simpler and faster solution algorithm as the information on which positions of the sequence of disassembly are located on what level of the disassembly hierarchy is not needed.

[3] *: current position in the sequence of disassembly

[4] This is done by comparing the current value for the product benefit (including a penalty for exceeding the product cost constraint) with that value that constitutes the best solution reached so far. If the current value is better than that of the best solution, the old best solution is replaced by the new solution; if not the old solution becomes the current solution again.

Appendix

1. Indices

g : configuration element, $g \in \{1, \ldots, g_{\mathrm{MAX}}(r)\}$
i : ecologically unsound connecting part, $i \in \{1, \ldots, i_{\mathrm{MAX}}\}$
n : position in the sequence if the disassembly, $n \in \{1, \ldots, n_{\mathrm{MAX}}\}$
r : aggregated product function, $r \in \{1, \ldots, r_{\mathrm{MAX}}\}$
s : design attribute, $s \in \{1, \ldots, s_{\mathrm{MAX}}(r, g)\}$

2. Variables

$DM_{r,g,s}$: Value of the design attribute s of the configuration element g of the product function r
K : costs of the product
$K^{Disass.}$: disassembly costs of the product
$K^{Disposal}$: disposal costs for configuration element g of the product function r
$KE_{r,g}$: Information of selection, ... whether the configuration element g of the product function r is selected, binary variable
$KKE_{r,g}$: costs of the configuration element g of the product function r
$RV_{r,g}$: recycling value of the configuration element g of the product function r
$U^{Disasscompl.}$: Indicator, ... whether all positions in the sequence n of the disassembly n are selected for disassembly, binary variable
$U_n^{Disass.}$: Indicator, ... whether the position in the sequence of the disassembly n is selected for disassembly, binary variable
U_n^{DH} : Indicator, ... whether the position in the sequence of the disassembly n is activated, binary variable
U_i^{v} : Indicator, ... whether the connecting part i is active, binary variable

3. Parameters

$U_n^{DHdisass.}$: Indicator,
... whether the position in the sequence of the disassembly n can be disassembled, binary parameter

U_n^{DHtool} : Indicator,
... whether a tool is needed for the disassembly of the position in the sequence of the disassembly n, binary parameter

$U_i^{disass.}$: Indicator,
... whether the connecting part i can be disassembled, binary parameter

U_i^{tool} : Indicator,
... whether a tool is needed for the disassembly of the connecting part i, binary parameter

References

Anderl, R., B. Daum, H. Weißmantel, and B. Wolf (1999), ‘Design for Environment – A Computer-Based Cooperative Method to Consider the Entire Life Cycle’, Proceedings of the EcoDesign ’99: First Internationel Symposium on Environmentally Conscious Design and Inverse Manufacturing, Tokyo: 380–385, IEEE Computer Society, Los Alamitos.

Barg, A. (1991), ‘Recycling-gerechte Produkt- en Produktionsplannung’, VDI-Z 133 (1991), No. 11, pp. 64–74.

Bullinger, H.-J. and R. BOPP (1998), ‘Methoden und Hilfsmittel zur recyclinggerechten Produktentwickling’, online in the internet, http://www.rdm.iao.fhg.de/projekte/toproco/PUBLICATIONS/CIRP D.html, 22.01.1998.

Eyerer, P., Th. Dekorsy and M. Schuckert (1990), ‘Ganzheitliche Bilanzierung ist mehr als Ökobilanz’, io Management Zeitschrift, 60 (1990), No. 7/8, pp. 90–95.

Eichert, C. (2000), ‘Umweltmanagement-Praxis’, Teil 2/4: Stoff- und Energieströme – Argumentations- und Controllinginstrumente für Unternehmens- und Bereichsverantwortliche, Umwelt, Vol. 30, No. 3, pp. 17–19.

Fu, Y., U.M. Diwekar, D. Young and H. Cabezas (2000), ‘Process design for the environment: A multi-objective framework under uncertainty’, Clean Products and Processes 2 (2000), pp. 92–107.

Gungor, A. and S.M. Gupta (1997), ‘An evaluation methodology for disassembly processes’, Computers and Industrial Engineering, Vol. 33, pp. 329–332.

Hanssen, O.J. (1996), ‘Sustainable Industrial Product Systems: Integration of Life Cycle Assessment in Product Development and Optimization of Product Systems’, PhD submitted to the Norwegian University of Science and Technology, online in the Internet: http://home.online.no/ ~ olejh/drgrad.htm, download: 15.12.2001.

Hopfenbeck, W. and C. Jasch (1995), ‘Öko-Design: umweltorientierte Produktpolitik’, Verlag Moderne Industrie Landsberg/Lech, 1996.

Ishii, K. (1998), ‘Design for Environment and Recycling: Overview of Research in the United States’, Invited paper, CIRP 5th Life Cycle Engineering Seminar, Sept. 1998, Stockholm.Johnson, M. and M. Wang (1995), ‘Planning product disassembly for material recovery opportunities’, International Journal of Production Research, 33 (11), pp. 3119–3142.

Kriwet, A. (1994), ‘Bewertungsmethodik für die recyclinggerechte Produktgestaltung’, Carl Hanser Verlag München Wien, 1994.

Lambert, A.J. (1997), ‘Optimal disassembly of complex products’, International Journal of Production Research, 35 (9), pp. 2509–2523.

Meerkamm, H. and B. Rosemann (2000), ‘Ökonomisch-ökologische Produktoptimierung durch recyclinggerechte Konstruktion’, Industrie Management, 16 (2000) 1, pp. 14–18.-

Nevin-Chandra, D. (1993), 'Re-Star, A design tool for environmental recovery analysis', Proceedings of the çth International Conference on Engineering Design (ICED '93), The Hague, Netherlands, pp. 780–787.

Nissen, U. and H. Tober (1993), 'Erfahrungen bei der Durchführung von Workshops zur umwelt- und recyclinggerechten Konstruktion', VDI-Z 135 (1993), No. 10, pp. 88–90.

Penev, K. and A. de Ron (1006), 'Determination of a disassembly strategy', International Journal of Production Research, 34 (2), pp. 495–506.

Schuckert, M. (1996), 'Ganzheitliche Bilanzierung C vom Bauteil zum System am Beispiel von Verkehtsträgern', dissertation, University of Stuttgart.

Spengler, TH. und O. Rentz (1994), 'Methodische Demontage- und Verwertungsplanung – dargestellt am Beispiel des Recyclings von Elektrofahrzeugen', Operations Research Proceedings 1994, Derigs, U., A. Bachem und A. Drexl (Hrsg.), Berlin, pp. 448-453.

Spengler, Th. und O. Rentz (1996), 'Planung von Lebenszykluskosten industrieller Produkte mit Hilfe der Fuzzy Linearen Optiemierung', Operations Research Proceedings 1996, Zimmerman, U., U. Derigs, W. Gaul, R.H. Möhring und K.-P. Schuster (Hrsg.), Braunschweig 1996, pp. 265-270.

O'Shea, B. (1999), 'A Methodology for the Planning of the Disassembly of Consumer Products', dissertation, University of New South Wales (School of Mechanical and Mechanical Engineering), Sydney.

O'Shea (2002), 'Planungsverfahren für die Produktkonzeption unter Berücksichtigung des Lebenszyklusansatz', Deutscher Universitäts-Verlag, Wiesbaden.

Steinhilper, R. and A. Friedel (1996), 'Umweltmanagement', in Bullinger, Hans-Jörg and Warnecke, Hans Jürgen, Neue Organisationsformen im Unternehmen, Springer-Verlag Berlin Heidelberg New York, 1966.