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INTEGRATING ECO-COMPASS CONCEPT INTO INTEGRATED PRODUCT AND PROCESS DEVELOPMENT[1]

PINGTAO YAN, MENGCHU ZHOU[2], DONALD SEBASTIAN *, AND REGGIE CAUDILL **
DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING
* CENTER FOR MANUFACTURING SYSTEMS
** MULTI-LIFECYCLE ENGINEERING RESEARCH CENTER
NEW JERSEY INSTITUTE OF TECHNOLOGY, NEWARK, NJ 07102-1982 U.S.A.

Our previous work introduced an integrated product and process development (IPPD) methodology. Different product development issues are formally described as constrained optimization problems that are solved using a life locus tree. This paper proposes to integrate the concept of eco-compass into the methodology. Eco-compass evaluates environmental impact using six indices: mass intensity, energy intensity, health and environmental potential risk, revalorization, resource conservation, and service extension. Plus cost and benefit, an eight-index vector is set up to evaluate the performance of processes, life phases, and a product's different life loci. As an example, we consider the development of a business telephone. By applying the proposed approach and eco-compass life cycle assessment data provided by NJIT's LCA research group, we can select the optimal telephone design and its associated production, usage, and recovery processes.

1 INTRODUCTION

The requirements for timely products that have the highest quality, lowest cost, and most customer satisfaction are increasing year by year. Recently, concurrent engineering, also known as life cycle engineering or integrated product and process development (IPPD), has attracted special interest for coping with these requirements [Ishii, 1990; Allen, 1990; Syan and Menon, 1994; Shina, 1993; Taylor, 1997]. The fundamental philosophy for realizing concurrent engineering is to start considerations from a wider and more comprehensive viewpoint, then construct an integrated decision making problem, and finally solve it concurrently [Yoshimura, 1994].

In parallel with concurrent engineering, design for environment (DFE) is another concept whose time has come. It is a deliberate and thoughtful effort by both government and industry to acknowledge the importance of environmental preservation while supporting industrial growth [Fiksel, 1996]. The practice of DFE is becoming essential in today's industrial environment, as major firms recognize the importance of environmental responsibility to their long-term success. Many experiences suggest that DFE can offer

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[2] The corresponding author.

competitive advantages in cost reduction, design innovations, performance improvement, and new customer attraction. They also suggest that DFE must be deployed within an integrated system framework in order to provide useful guidance for decision-making needed in product development. The most recent trend is to extend DFE to multi-lifecycle engineering research and practice. Multi-lifecycle engineering approach takes a systems perspective and considers fully the potential of recovering and reengineering materials and components from one product to create another, not just once, but many times [Caudill, 1998; Zhou et al., 1999].

Inspired by the research challenges in these two new developing areas and the inherent relations between them, we formulate a systems approach to concurrent engineering, which also addresses multiple objectives including environmental considerations as an important part. By this approach, manufacturing firms can design their industrial products and systems to achieve both economic efficiency and environmental quality. This approach is reported in [Yan *et al.*, 1998a, 1999] as an integrated product and process development (IPPD) methodology. In this methodology, a product's entire life cycle is considered in an expected life cycle structure (ELCS) consisting of life phases such as design, production, use and upgrade, and end-of-life recovery. A process is defined as a basic unit of activity that is performed in a product's life cycle. Product development is a complicated group of process selections to constitute an optimal or satisfactory life cycle for a product. Some common interesting features are extracted from each process and represented mathematically as an index vector, by which all sorts of physical processes can be compared. Based on this, different product development issues are formally described as constrained optimization problems that are solved using a life locus tree. The methodology is successfully applied to personal computer development [Yan *et al.*, 1998b].

Appropriate selection of an index vector is important to the successful application of the IPPD methodology. It usually consists of two parts of indices: one characterizing industrial profitability, and the other characterizing environmental impact. In our previous work, industrial profitability is conveniently evaluated using two indices: cost and benefit. However, the meaning of environmental impact is vague and the evaluation data has been reasoned without a concrete method behind it.

Motivated by the successful use of eco-compass technique for benchmark studies of existing and new products, this paper proposes to evaluate environmental impact using eco-compass as a critical part. Section 2 briefly introduces the concept of eco-compass, and Section 3 integrates eco-compass concept into the IPPD methodology. Development of a business telephone is used as an example in Section 4. Eco-compass life cycle assessment data is provided by NJIT's LCA research group. Applying the proposed approach, we can select the optimal telephone design and its associated production, usage, and recovery processes. Some typical search results are discussed in Section 5. This paper concludes that the proposed approach has the potential to industrial product development.

2 ECO-COMPASS

Life cycle assessment (LCA) is a useful tool in analyzing the environmental impact of a product by calculating the inputs and outputs of each stage of a product's life cycle [Caudill *et al.*, 1998]. However, LCA data is usually too complex and detailed to make sense to most business decision makers. Consequently, there is a need for a means of weighting the inputs and outputs to clarify important issues and make comparisons between options.

The eco-compass technique, developed at Dow Europe, is a comparative tool to evaluate one existing product with another, or to compare a current product with new development options [Fussler and James, 1996]. The eco-compass has six dimensions, intended to encompass all significant environmental issues. Two of them are largely environmental: health and environmental potential risk, and resource conservation. Four of them are of business as well as environmental significance: energy intensity, mass intensity, revalorization, and service extension. These six dimensions are explained as follows [Fussler and James, 1996; Caudill *et al.*, 1998].

Mass intensity reflects the change in the material consumption and mass burdens associated with the product over its life cycle;
Energy intensity captures the change in the energy consumption associated with the product throughout its life cycle;
Health and environmental potential risk detects the change in the environmental burdens associated with the product over its life cycle;
Revalorization evaluates the ease with which remanufacturing, reuse, and recycling of the product can be carried out;
Resource conservation detects the change in the conservation of materials and energy associated with the product over its life cycle; and
Service extension measures the extent to which service can be delivered to the product throughout its life cycle.

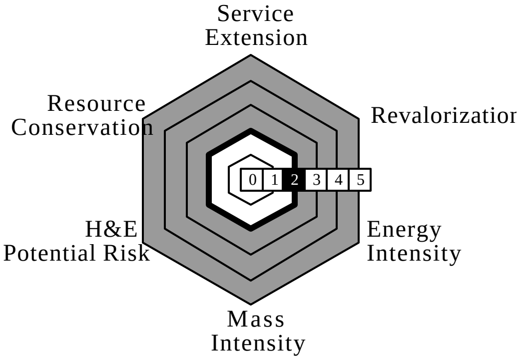

Figure 2.1 Diagram of eco-compass.

Using eco-compass, one of the products to be compared is chosen as the base case. The base case always scores a 2 in each of six dimensions. The alternative product is then given a score relative to this base case on a scale of 0-5 in each dimension. The precise score depends on the percentage increase or decrease in performance. The diagram of eco-compass is as shown in Fig. 2.1.

3 INTEGRATION OF ECO-COMPASS CONCEPT INTO IPPD

Eco-compass uses six dimensions to evaluate significant environmental issues associated with a product over its life cycle. Therefore we propose to use these six dimensions as six indices in the index vector of our proposed IPPD methodology [Yan *et al.*, 1999] to provide a more detailed and precise evaluation of a product's environmental impact. Plus two other generally used indices evaluating industrial profitability, i.e., cost and benefit, the index vector **c** then consists of eight indices:

$$\mathbf{c} = \begin{pmatrix} \text{Mass Intensity} \\ \text{Energy Intensity} \\ \text{H \& E Potential Risk} \\ \text{Revalorization} \\ \text{Resource Conservation} \\ \text{Service Extension} \\ \text{Cost} \\ \text{Benefit} \end{pmatrix}.$$

These eight indices are then used to evaluate the performance of processes, life phases, and a product's different life loci.

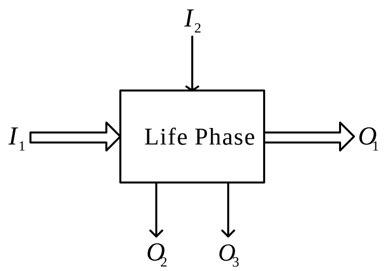

Figure 3.1 Generic model of a life phase.

We characterize two inputs and three outputs for each life phase.

I_1: Input from other life phases. In a simple ELCS, i.e., a structure consisting of a sequence of consecutive life phases, this means input from the previous life phase.

I_2: Input from sources other than life phases. It is divided into three parts:

$$I_2 = I_{2M} + I_{2E} + I_{2O}\,.$$

I_{2M} : Input of materials,

I_{2E} : Input of energy, and

I_{2O} : Input of other forms.

O_1: Output to other life phases. In a simple ELCS, this means output to the next life phase.

O_2: Positive (good) output to places other than life phases. It is divided into three parts:

$$O_2 = O_{2M} + O_{2E} + O_{2O}\,.$$

O_{2M} : Output of materials,

O_{2E} : Output of energy, and

O_{2O} : Output of other forms.

O_3: Negative (bad) output to places other than life phases.

Based on this generic model of a life phase, we can then evaluate each index in $\mathbf{c}$ as below.

(1) Mass Intensity = I_{2M} ,

(2) Energy Intensity = I_{2E} ,

(3) H & E Potential Risk = O_3 ,

(4) Revalorization = Ease with which remanufacturing and disassembly can be carried out,

(5) Resource Conservation = $(I_{2M} - O_{2M}) + (I_{2E} - O_{2E})$,

(6) Service Extension = Ease with which service can be delivered to a product,

(7) Cost = I_{2O}, and

(8) Benefit = O_{2O}.

For general considerations, the index of revalorization is only applicable to remanufacturing, recovery, or recycling related processes and life phases, and the index of service extension is only applicable to processes and life phases related to product use.

From the evaluation equations above, it is noticed that index vector $\mathbf{c}$ is only concerned with the interactions between the product's life phases and their surrounding environment. Flows inside each life phase or among the life phases are not considered in $\mathbf{c}$ and are determined by process selections in the life phases.

Using this eight-index vector $\mathbf{c}$, we can then follow the methods and procedures in the IPPD methodology [Yan *et al.*, 1998a, 1999] to search for an optimal life locus for a target product. The steps are summarized below: (1) Set up an expected life cycle structure (ELCS) for the target product and make simplifications if necessary to obtain a simple ELCS; (2) Identify all the possible processes in each life phase of the product's ELCS; (3) Calculate the index values for each process; (4) Set up a life locus tree consisting of all the possible life loci for the target product; (5) Search in the tree for an optimal life locus. A variety of search algorithms can be used, e.g., exhaustive search, heuristic search, etc.

4 A CASE STUDY: BUSINESS TELEPHONE DEVELOPMENT

In this section, we apply the extended IPPD methodology to a business telephone development. Eco-compass LCA data is provided by an LCA research group at NJIT [Caudill *et al.*, 1998; Al-Okush, 1998]. From this example, we can see how the proposed approach uses LCA data and works effectively in real applications.

(A) Expected life cycle structure

First of all, we need to set up an expected life cycle structure (ELCS) for business telephone. For the illustration purpose of this case study, we apply a coarse granularity to life phases and expect a business telephone to have a typical life cycle structure as shown in Fig. 4.1.

Product: Business Telephone

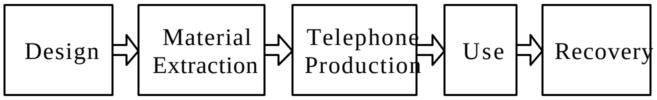

Figure 4.1 An ELCS for business telephone.

It has five consecutive life phases: (1) Design; (2) Material Extraction; (3) Telephone Production; (4) Use; and (5) Recovery.

(B) Processes

We then have to identify the possible processes in each life phase of the telephone's ELCS. A coarse granularity is applied to processes in each life phase.

In Design phase, there are four different telephone designs: D1, D2, D3, and D4. They correspond to four generations of business telephones: D1 ('65), D2 ('78), D3 ('89), and D4 ('97) [Caudill *et al.*, 1998; Al-Okush, 1998]. The pictures of these four designs are as shown in Fig. 4.2.

Figure 4.2 Four designs of business telephones. (Upper left: D1, upper right: D2, lower left: D3, lower right: D4).

In Material Extraction phase, each telephone design Di may select a material extraction process from two possibilities, ME$i1$ and ME$i2$. They use different processing technologies and have different performances. Each process generates all the materials needed in a telephone, i.e., plastics, steel, aluminum, copper, etc.

In Telephone Production phase, each design Di has two alternative production processes, TP$i1$ and TP$i2$. They correspond to the use of different production equipment and therefore have different characteristics.

In Use phase, Di may be used in two different patterns, U$i1$ and U$i2$. They correspond to different utilization frequencies of the telephone and bear different characteristics.

In Recovery phase, two recovery processes are considered for each telephone design Di. R$i1$ means shredding/separation of a telephone for material and energy recovery, and R$i2$ means landfilling.

(C) Indices

A process in a telephone's life cycle is characterized by eight indices, i.e., mass intensity, energy intensity, H & E potential risk, revalorization, resource conservation, service extension, cost, and benefit. Revalorization is only applicable to recovery processes Rij ($i = 1, \ldots, 4; j = 1, 2$), and service extension is only applicable to use processes Uij ($i = 1, \ldots, 4; j = 1, 2$).

Applying the concept of tangible characteristics [Yan *et al.*, 1998b], we calculate the index values for each process. The data for processes ME$i1$, TP$i1$, U$i1$, and R$i1$ ($i = 1, \ldots, 4$) is provided by NJIT's LCA research group [Caudill *et al.*, 1998; Al-Okush, 1998], and the indices for ME$i2$, TP$i2$, U$i2$, and R$i2$ ($i = 1, \ldots, 4$) are calculated based on the following assumptions about each pair of processes:

- ME$i1$ and ME$i2$

The yield rate for material extraction process ME$i1$ is 95% [Al-Okush, 1998]. The yield rate for ME$i2$ is 98%, the energy consumption for ME$i2$ is 10% greater than ME$i1$, its H & E potential risk is 2% less, and its cost is 5% greater than ME$i1$.

- TP $i1$ and TP $i2$

Telephone production process TP $i2$ consumes 10% more energy than TP $i1$, its H & E potential risk is 10% greater than TP $i1$, and its cost is 20% less than TP $i1$.

- U $i1$ and U $i2$

The utilization factor of usage process U$i1$ is 3% [Al-Okush, 1998]. U$i2$ has a utilization factor of 12%. Consequently, U$i2$ consumes more energy than U $i1$, and incurs more H & E potential risk. The benefit of U $i2$ is 3 times that of U $i1$.

- R $i1$ and R $i2$

R $i1$ means shredding/separation of the telephone. Metals in the telephone are recovered for reuse, and plastics are recovered for its embodied energy. R$i2$ simply landfills the telephone. Therefore the energy consumption for R$i2$ is 0, its revalorization index is 0 because remanufacturing, reuse, or recycling does not happen, and its benefit is also 0. The only cost for R$i2$ comes from the cost of the space needed in the landfill and transportation. It is calculated based on the weight of the telephone. The H & E potential risk for R $i2$ is much greater than R $i1$, and it is also calculated based on the weight.

With these reasonable assumptions and the real data provided in [Al-Okush, 1998], we list the index values for all the possible processes in a telephone's life cycle as in Table 4.1. The following abbreviations for indices are used: MI (Mass Intensity), EI (Energy Intensity), H&E (H & E Potential Risk), RV (Revalorization), RC (Resource Conservation), and SE (Service Extension). Indices RV, SE, and Benefit are the higher the better, and all the other indices are the lower the better. The unit of indices is US dollar ($).

Table 4.1 Indices for processes in a telephone's life cycle.

Process	MI	EI	H&E	RV	RC	SE	Cost	Benefit
D1	0	0	0	0	0	0	0	0
D2	0	0	0	0	0	0	0	0
D3	0	0	0	0	0	0	0	0
D4	0	0	0	0	0	0	0	0
ME11	13.20	2.25	6.28	0	15.45	0	20.00	0
ME12	12.90	2.48	6.15	0	15.38	0	21.00	0
ME21	13.40	2.31	3.57	0	15.71	0	15.00	0
ME22	13.00	2.54	3.50	0	15.54	0	15.75	0
ME31	11.80	0.86	1.25	0	12.66	0	10.00	0
ME32	11.40	0.95	1.23	0	12.35	0	10.50	0
ME41	12.50	1.39	1.95	0	13.89	0	5.00	0
ME42	12.10	1.53	1.91	0	13.63	0	5.25	0
TP11	0	16.20	36.23	0	16.20	0	10.00	0
TP12	0	17.82	39.85	0	17.82	0	8.00	0
TP21	0	8.33	18.63	0	8.33	0	8.00	0
TP22	0	9.16	20.49	0	9.16	0	6.40	0
TP31	0	3.94	8.85	0	3.94	0	6.00	0
TP32	0	4.33	9.74	0	4.33	0	4.80	0
TP41	0	3.89	8.70	0	3.89	0	4.00	0
TP42	0	4.28	9.57	0	4.28	0	3.20	0
U11	0	6.50	14.56	0	6.50	35.00	0	2100.00
U12	0	26.00	58.24	0	26.00	35.00	0	6300.00
U21	0	6.50	14.56	0	6.50	40.00	0	2100.00
U22	0	26.00	58.24	0	26.00	40.00	0	6300.00
U31	0	45.31	101.43	0	45.31	110.00	0	525.00
U32	0	51.20	114.62	0	51.20	110.00	0	1575.00
U41	0	45.31	101.43	0	45.31	130.00	0	525.00
U42	0	51.20	114.62	0	51.20	130.00	0	1575.00
R11	0	1.39	3.12	5.50	-7.55	0	0	0
R12	0	0	116.25	0	0	0	2.33	0
R21	0	0.97	2.20	17.00	-9.94	0	0	0
R22	0	0	82.00	0	0	0	1.64	0
R31	0	0.50	1.11	26.25	-4.38	0	0	0
R32	0	0	41.20	0	0	0	0.82	0
R41	0	0.64	1.46	36.50	-7.19	0	0	0
R42	0	0	54.25	0	0	0	1.09	0

(D) Life locus tree

Based on the data and assumptions made, we can set up a life locus tree for the telephone as shown in Fig. 4.3. For a clear illustration, on each level of the tree, details are only shown for a selected branch.

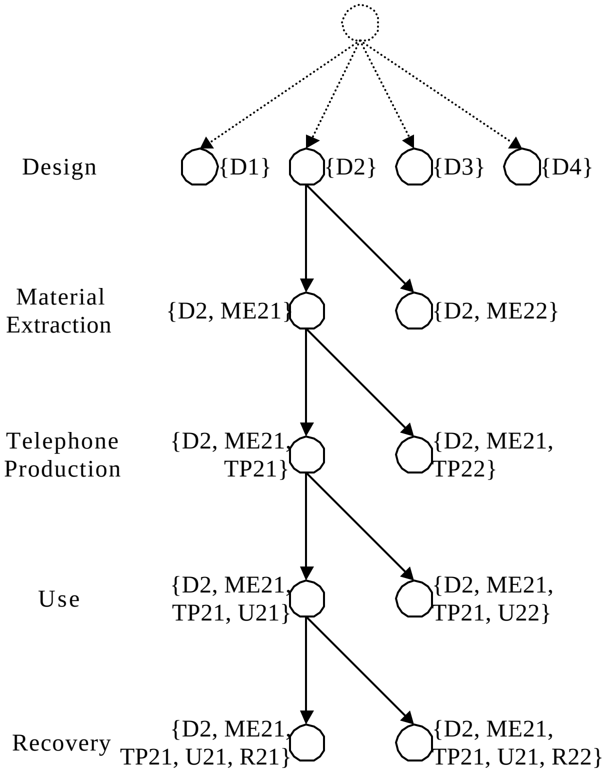

Figure 4.3 A life locus tree for the telephone.

This tree has 64 life loci, each can be represented as:

$$LL_k = \{\mathrm{D}i, \mathrm{ME}ij_1, \mathrm{TP}ij_2, \mathrm{U}ij_3, \mathrm{R}ij_4\},$$

where

$$k = 1, \ldots, 64,$$
$$i = 1, \ldots, 4,$$
$$j_1, j_2, j_3, j_4 = 1, 2,$$

and

$$k = 16(i-1) + 8(j_1 - 1) + 4(j_2 - 1) + 2(j_3 - 1) + j_4 .$$

The index vector for life locus LL_k is calculated as:

$$\mathbf{c}(LL_k) = \mathbf{c}(\mathrm{D}i) + \mathbf{c}(\mathrm{ME}ij_1) + \mathbf{c}(\mathrm{TP}ij_2) + \mathbf{c}(\mathrm{U}ij_3) + \mathbf{c}(\mathrm{R}ij_4) .$$

(E) Search

We can search in the life locus tree for an optimal life locus. In this case study, we set the optimization criterion as:

$$\begin{aligned} C = {} & w_1\mathrm{MI} + w_2\mathrm{EI} + w_3\mathrm{H\,\&\,E} - w_4\mathrm{RV} \\ & + w_5\mathrm{RC} - w_6\mathrm{SE} + w_7\mathrm{Cost} - w_8\mathrm{Benefit} \end{aligned} .$$

The weighting vector $\mathbf{w} = \begin{pmatrix} w_1 & w_2 & w_3 & w_4 & w_5 & w_6 & w_7 & w_8 \end{pmatrix}^T$, and $w_i \geq 0 \;\; (i = 1, \ldots, 8)$. By selecting different weighting factors, we can obtain different optimal search results to be discussed next.

5 SEARCH RESULTS AND DISCUSSIONS

The optimization criterion for a telephone's life locus is defined in Section 4. Different weighting vectors lead to different optimal life loci, i.e., optimal telephone design and its associated production, usage, and recovery processes. An exhaustive search algorithm is used. When more than one life loci correspond to the same optimal criterion value, we simply select the one that comes first in the search procedure. Table 5.1 provides some typical search results. They are based on different optimization criteria: some based on an individual index, and others based on combinations of all eight indices.

w	$(1\ 0\ 0\ 0\ 0\ 0\ 0\ 0)^T$	$(0\ 1\ 0\ 0\ 0\ 0\ 0\ 0)^T$	$(0\ 0\ 1\ 0\ 0\ 0\ 0\ 0)^T$	$(0\ 0\ 0\ 1\ 0\ 0\ 0\ 0)^T$
C	MI	EI	H&E	- RV
Optimal Life Locus	D3 ME32 TP31 U31 R31	D2 ME21 TP21 U21 R22	D2 ME22 TP21 U21 R21	D4 ME41 TP41 U41 R41
w	$(0\ 0\ 0\ 0\ 1\ 0\ 0\ 0)^T$	$(0\ 0\ 0\ 0\ 0\ 1\ 0\ 0)^T$	$(0\ 0\ 0\ 0\ 0\ 0\ 1\ 0)^T$	$(0\ 0\ 0\ 0\ 0\ 0\ 0\ 1)^T$
C	RC	- SE	Cost	- Benefit
Optimal Life Locus	D2 ME22 TP21 U21 R21	D4 ME41 TP41 U41 R41	D4 ME41 TP42 U41 R41	D1 ME11 TP11 U12 R11
w	$(1\ 1\ 1\ 1\ 1\ 1\ 0\ 0)^T$	$(1\ 1\ 1\ 1\ 1\ 1\ 1\ 1)^T$	$(0\ 0\ 1\ 1\ 1\ 1\ 1\ 1)^T$	$(0\ 0\ 1\ 0\ 1\ 0\ 1\ 1)^T$
C	MI + EI + H&E - RV + RC - SE	MI + EI + H&E - RV + RC - SE + Cost - Benefit	H&E - RV + RC - SE + Cost - Benefit	H&E + RC + Cost - Benefit
Optimal Life Locus	D2 ME22 TP21 U21 R21	D2 ME21 TP21 U22 R21	D2 ME21 TP21 U22 R21	D2 ME21 TP21 U22 R21

Table 5.1 Optimal life loci corresponding to different weighting vectors.

For example, taking the objective to minimize H&E by selecting $\mathbf{w} = (0\ \ 0\ \ 1\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0)^T$, we obtain an optimal life locus that has minimum total health and environmental potential risk as: D2, ME22, TP21, U21, and R21. This life locus is also the optimal one considering all six eco-compass indices with equal priorities, i.e., $\mathbf{w} = (1\ \ 1\ \ 1\ \ 1\ \ 1\ \ 1\ \ 0\ \ 0)^T$. If we also consider cost and benefit, i.e., $\mathbf{w} = (1\ \ 1\ \ 1\ \ 1\ \ 1\ \ 1\ \ 1\ \ 1)^T$, we should select ME21 instead of ME22, and U22 instead of U21. When $\mathbf{w} = (0\ \ 0\ \ 1\ \ 0\ \ 1\ \ 0\ \ 1\ \ 1)^T$, the optimization criterion $C = I_2 - O_2 + O_3$, i.e., to minimize the product's net negative impact on its surrounding environment (referring to Fig. 3.1). The corresponding optimal life locus is: D2, ME21, TP21, U22, and R21. From these search results and weighting factors, telephone design D2 and its associated production, usage, and recovery processes generally outperform other options.

It needs to be mentioned that the validity of these search results depends on the validity of the assumptions made and LCA data provided, and the weighting factors used.

6 CONCLUSIONS

This paper extends an integrated product and process development methodology such that the optimization criteria include more detailed characteristics to evaluate environmental impact. It integrates life cycle assessment (LCA) results based on eco-compass concept into the methodology. Eco-compass consists of six indices: mass intensity, energy intensity, health and environmental potential risk, revalorization, resource conservation, and service extension. This paper combines these indices effectively to represent environmental impact. This combination can vary with developer's intention and priorities/importance of the corresponding indices with respect to overall environmental concerns. Cost, benefit, and these six eco-compass indices constitute an eight-index vector used to evaluate the performance of processes, life phases, and a product's different life loci. A product's life locus tree is built up by considering its entire life cycle including design, production, use, and recovery life phases as well as their process choices. The optimization is then performed by a search algorithm on the life locus tree. As a case study, we consider the development of a business telephone. By applying the proposed approach and eco-compass LCA data provided by NJIT's LCA research group, we can select the optimal telephone design and its associated production, usage, and recovery processes. This example illustrates the potential of the proposed approach to industrial product development. The presented work can be viewed as a first step towards design synthesis, where design advice can be obtained during the optimization processes in the proposed methodology.

The contributions of this paper are two-fold. One is to integrate eco-compass concept into an integrated product and process development methodology, thus enrich the methodology with respect to concrete evaluation of environmental impact of a product and all related processes in its life cycle. Second, this paper presents a detailed product example and data that can serve as a benchmark study example for different IPPD approaches.

Our future research focuses on the following two directions:

Formal representation of process relations.

Relations among processes in a product's life cycle are an important part of product developers' knowledge and expertise. Formal representation of this part of knowledge is essential to putting the IPPD methodology into practical use by designers, both novice and experienced. Logic and Petri nets are two possible approaches currently under investigation.

Introduction of time variable.

In some product development applications, time-varying process characteristics determine the ultimate success of decisions made. Therefore we plan to introduce time variable into the IPPD methodology and apply the methodology to the development of flexible manufacturing systems.

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