Eco-Case Based Reasoning (Eco-CBR) for Supporting Sustainable Product Design

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Abstract A major challenge for any manufacturer is including aspects of sustainable development in product design. These are related to the social, environmental and economic impacts of the proposed product. This paper proposes the development of an eco-case based reasoning (Eco-CBR) method for supporting sustainable product design. This approach is intended to be used to help industrial decision-makers to propose solutions to new product design feature requirements by reusing solutions from similar cases and their past experience. Information related to the solutions contains details of product dimensions, life cycle assessment (LCA) concerning their impact on carbon footprint, water eutrophication, air acidification and the total energy consumed by the product and related processes throughout its entire life cycle. These solutions also contain estimations of the manufacturing, environmental, end-of-life (EOL) and economic costs. The method is demonstrated using a case study that considers the design of the set of medical forceps, based upon identifying and utilising information related to the similarities within the existing cases in the CBR library. The paper demonstrates how this method can help the designer to shorten the process of design and contribute information that can itself maintain and add to the knowledge contained within the case bases stored in the library.

Keywords. Eco-CBR, LCA, costing, product design.

1. Introduction

Sustainable product design represents a complex domain where past experiences are frequently used to solve new design problems [1]. Product sustainability needs to be evaluated from both environmental and economic perspectives. The maximum benefits of eco-design are achieved by reducing the environmental impact and cost for the whole product life cycle [2]. In reality, it is a challenge to strike an appropriate balance between environmental elements while keeping the production cost as low as possible. This challenge led to the following research question: how can past experience enable and support sustainable product development at an early design stage? The eco-case based reasoning (Eco-CBR) method introduced in this research meets this challenge by storing and manipulating eco-design product knowledge within a case base library.

CBR is an artificial intelligence (AI) tool and computational modelling technique used to solve a new design problem. Several studies have been focused on the

application of CBR to support decisions in product design [3, 4, 5, 6]. The CBR method is used to find similarities to previous cases based upon product features. These cases can then be retrieved and reused in a process that adapts the information and knowledge they contain to the new case.

This paper takes this approach further with the development of the Eco-CBR method. This uses the integrated eco-design decision making (IEDM) framework, which was previously engineered [2] to ensure that product development embraces environmental and economic considerations throughout the product life cycle. This approach is demonstrated using a case study that considers the design of medical forceps. The aim of this study is to show how the approach can be used to develop a sustainable product design by finding similarities to previous cases in the CBR library and by using the accessed knowledge to generate a solution. The particular problem used here is to configure a lower environmental impact based upon the estimation of manufacturing, environmental, transportation and economic costs. The intention is that such solutions will help designers improve the quality of the designed product while enabling them to choose optimal manufacturing and end-of-life strategies during the design stage.

The next section gives a brief overview of related work on CBR. The Eco-CBR method is described in Section 3. The case study and discussion are presented in Section 4. The final section draws the conclusions.

2. Background and related work

CBR is a widely used and important tool for storing product design knowledge using a case base library. In this context, a case is a piece of knowledge representing an experience. It can contain past knowledge regarding the content of the case and the context in which the knowledge can be implemented. A case can be an account of the event, a story or a record. Typically, it includes the problem that describes the state of the world when the case occurred and the solution to that problem [7].

The application of CBR to sustainable product development is a growing area. It includes the development of the Communication and Decision Support Environment for Managing Concurrent Engineering project (CODESCO) [4]. This is an application of CBR to new product development, which can be used as a practical communication and decision support environment for managing concurrent product development. In other work, Takai [8] implemented a CBR approach to storing information about various products in a knowledge base and defined a new product concept, retrieving a cluster of products and adapting the cost from existing cases to the new case. Kuo [9] proposed a hybrid AHP-CBR method to determine recycling strategies for a product. The same hybrid method for evaluating remanufacturing processes was used to support the integration of economic and environmental cost models to determine the end-of-life (EOL) strategies for a product [10]. A forecasting model to design eco-products based on the use of Teoriya Resheniya Izobretatelskikh Zadatch (TRIZ) and CBR evolution patterns has also been outlined [5, 6] and used to accelerate the process and help

designers to reduce the environmental impact throughout the life cycle of their products. Jeong et al. proposed solution to approximate Life Cycle Assessment (LCA) using CBR for the eco-design of products [11]. However, the resulting solution only shows the percentage of the LCA without providing recommendations to overcome the problems for the target case.

Although considering aspects of sustainable product development, previous works do not combine the main factors in sustainability, which are environmental, economic and social. Therefore, it is the aim of this current research to provide a platform for considering all of these factors and their solutions within the Eco-CBR method.

3. Eco-CBR Method

This section introduces the Eco-CBR method, which integrates CBR with eco-design factors into the new product design process. Figure 1 shows the proposed operation of the Eco-CBR method. The cycle starts with an initial description of a problem, which defines a new case without solutions. This new case is formed around a number of sustainability input features. It is used to retrieve cases from the case base library. The retrieved cases are selected from data that are stored in the library within defined sustainability groups. After retrieving these cases, the designer will in effect reuse the identified solutions to propose the new case solution. The suggested solutions will contain information about LCA, estimations of cost and product design evaluation and relate them to details, such as new dimensional requirements.
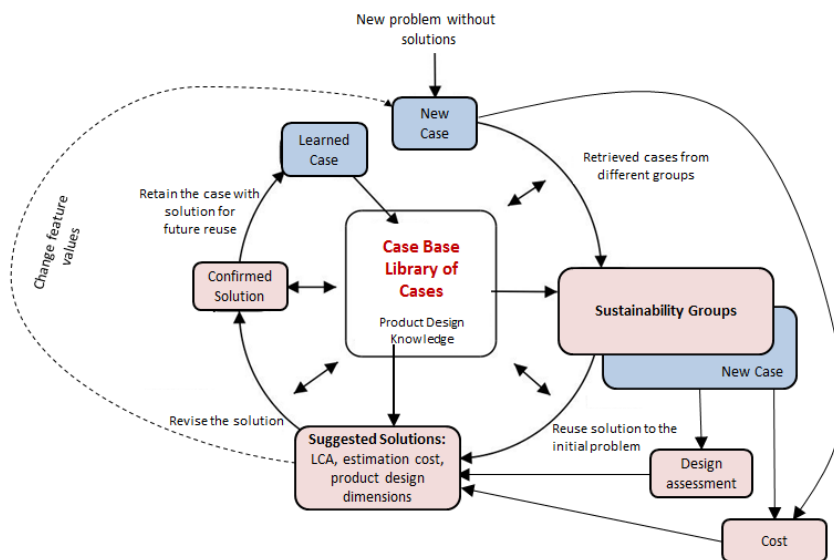

Figure 1: The Eco-CBR cycle.

At this stage, the designers have two options:

i. If the solutions are not valid, they can modify the feature values and run the process again in order to improve the product, or
ii. The solutions will be accepted, revised and adapted to the new case.

When a designer is satisfied with the solutions, the case will be retained, and the library is updated by storing a new learned case. This process will increase the library of cases and can be accessed in future, re-using solutions for the next new case.

In the process of calculating the similarity between cases, features and a set of weights per group need to be assigned. These weights are not fixed, allowing the decision maker to assign their importance according to the characterisation of the studied product. This method enables the searching process to be more efficient and adaptable to the requirements of the user.

During the searching process, a global similarity per group is calculated using equation (1). The non-numerical local similarity or numerical local similarity is calculated using equations (2) and (3), respectively. These equations are used to calculate the similarity between the new case and the existing cases in the library. An exception for equation (2) will be made in the case study section in order to adapt the tool. Equation (3) is used to normalise the numerical features to provide a significant effect on the global similarity. This application means all the local comparisons will be in a range [0,1]. It helps in the setting of the weight, since the not normalisation component also has to be considered [12,13,14]. The existing cases with the highest similarity to the new case are then retrieved.

Global similarity (GS):

$$GS_i = \frac{\sum_j w_{ij} * S_{jk}}{\sum_j w_{ij}} \quad \forall i \qquad \left. \begin{array}{l} \text{Where i is a group of features,} \\ \text{j is input features and} \\ w_{ij} \text{ is a set of weights per group} \end{array} \right. \tag{1}$$

Non-numerical local similarity:

$$\begin{array}{ll} IF\ NC == Lib_k & \rightarrow S = 1 \\ Else & \rightarrow S = 0 \end{array} \quad \left. \begin{array}{l} \text{Where } Lib_k \text{ is the k-case from} \\ \text{the case base library and} \\ NC \text{ is a new case} \end{array} \right. \tag{2}$$

Numerical local similarity:

$$S = \frac{\min(NC, Lib_k)}{\max(NC, Lib_k)} \tag{3}$$

If $(NC == 0\ \&\ Lib_k == 0)$ then $S = 1$

The searching process will provide solutions detailing the LCA, estimations of cost and product design dimensions. Reusing the information in the case base library, the solution is first analysed based on the environmental impact to the product

lifecycle of material, manufacturing process, transportation, product use and EOL. The environmental impact consists of carbon footprint (CF), energy consumption (EC), air acidification (AA) and water eutrophication (WE). In order to benchmark this result, a process of translation from quantitative to qualitative data is performed based on the data from the library. These data are set to one of five rankings: 'very high', 'high', 'medium', 'low' and 'very low'. With this conversion, the interpretation of the LCA data by the designer is better supported.

The cost estimation of the solution is considered next. The economic cost will be presented in the form of a range. It is calculated as minimum and maximum cost from new case (NC) and retrieved case (RC) from the case library as shown in equation (4). The difference between the limits of the range will be used to evaluate whether the estimation of costs is close to the actual costs. Five categories of cost have been considered as shown in the Table 1.

$$\text{Economic cost range} = [\min (NC, RC), \max (NC, RC)] \tag{4}$$

Table 1: Categories of Cost Solutions

Types of Cost	Description	Formulas
Purchasing (Pc)	Purchasing cost for the material.	Purchasing cost for the material in gram
Manufacturing (Mc)	Manufacturing cost for the product per unit and per production.	Mc = Direct cost + Labour cost + Overhead cost
Transportation (Tc)	Transportation cost is based on the types of transportation used from manufacturing region to use region.	$Tc = \dfrac{\left\{\left\lceil \frac{Volume * Weight}{Box\ Capacity} \right\rceil \cdot Deliver\ cost\right\}}{Volume}$
Environmental (ENc)	Environmental cost is based on the calculation of environmental impact to product life cycle.	ENc = CF cost + EC cost+ AC cost+ WE cost
End of Life (EOLc)	EOL cost is based on the calculation of the EOL product to recycle, incinerate and landfill.	EOLc = (Landfill cost + Incinerated cost) – Recycle Value
Economic (ECOc)	Economic cost is the total cost for the product life cycle including raw material, manufacturing, transportation and EOL product.	ECOc = Pc + Mc + Tc + ENc + EOLc

The last solution is related to product dimensions. The design will be assessed with the most similar case to get a solution. The first task is to study and select the dimensions that are critical to the performance of the product. Then, look for the most similar case. If the similarity is high enough, the design can be considered

sustainable. However, if it is not suitable, then a list with a sequence of dimensions, from worst to best, will be created, which the designer will adapt to the new case.

4. Case study and discussions

The application of the developed Eco-CBR method is demonstrated in the design of medical forceps shown in Figure 2. These sterile single-use medical forceps are used primarily for ear, nose and throat (ENT) surgery. The aim of this study is to produce a new more sustainable product design by finding similarities to previous cases held in the CBR library and by using the experiences from these similar cases to generate the solution.

The case base library of the product design knowledge is developed first. Currently, this library contains 72 cases of designs for medical forceps. Table 2 shows the list of features used in the library. These features are divided into two sections, which are problem and solutions. The problem features are divided into four groups: transportation, material and manufacturing process, EOL product and design dimensions. The solutions' features are divided to the three sustainability groups: LCA, estimation costs and design dimensions.
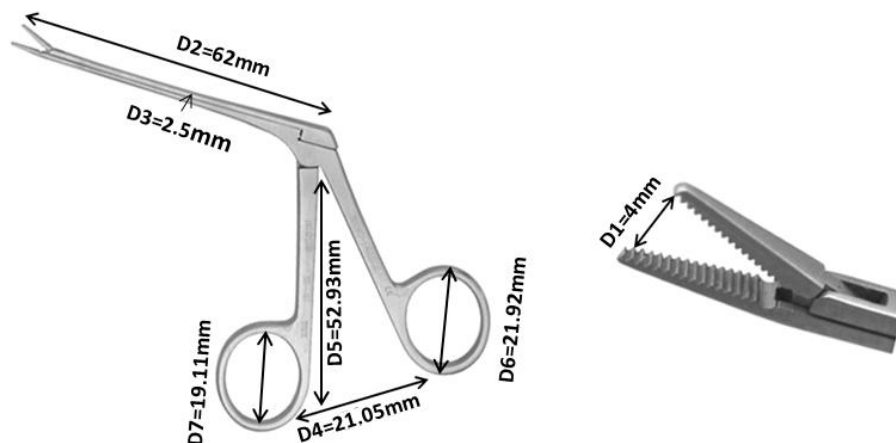

Figure 2: Medical forceps

Figure 3 shows the process of the application Eco-CBR method for the medical forceps. This process starts with the design problem which is defined as a new case. Table 3 shows the input values and weights assigned by the designer for each feature in the new case. Usually, weights vary according to the product, and it has great effect on the similarity computation result. In this study, a real number between 1 (less important attribute) and 5 (very importance attribute) has been used as a weighting scale. These weights are not fixed, allowing the decision maker to assign their importance according to the characterisation of the studied

product. This method enables the searching process to be more efficient and adaptable to the requirements of the user. In this study, weights has been set according to the previous study made on the same product by the authors [2].

The information from retrieved cases will be reused in the solutions entry for the new case. Weights for volume and material cost are not given because these features are not considered to find the similarities, but they are used for the calculation for cost estimation.This new case consists of information for four groups:

i)   Transportation (origin from UK, product usage in UK, transport used is train where the distance is 1250km)

ii)   Material and manufacturing process (material is PEEK, weight is 3.50g, manufactured by injection moulding, recycling content inside the product is 50%, production volume is 10,000 and material cost is £0.03 per gram)

iii) End-of-life product (recycling rate is 50%, incinerate is 0% and landfill is 50%)

iv)   Product dimensions (D1 is 5mm, D2 is 55mm, D3 is 5mm, D4 is 20mm, D5 is 45mm, D6 is 20mm and D7 is 19mm)

Table 2: List of Features in the Case Base Library

Problem Features			
Transportation	**Material and manufacturing process**	**EOL product**	**Design dimensions**
Origin Destination (Dest) Types of Transport (Transp) Distance (Dist)	Material (Mat) Weight (W) Manufacturing process (MP) Recycle content (RC) Volume (Vol) Material Cost (MatC)	Recycled (Rec) Incinerated (Inc) Landfill (Landf)	Jaw dimension (mm) = D1 Length shaft (mm) = D2 Thick shaft (mm) = D3 Opening moveable handles (mm) = D4 Handle length (mm) = D5 Handle outer diameter (mm) =D6 Handle inner diameter (mm) = D7
Solution Features			
Environmental impact		**Estimation cost**	**Product design dimensions**
Carbon footprint (CF) Total energy consumed (EC) Air acidification (AA) Water euthrophication (WE)	Quantitative measurement for the material, manufacturing, use, transport and EOL	Purchasing (Pc) Manufacturing (Mc) Transportation (Tc) Environmental (Ec) End-of-Life (EOLc) Economic (ECOc)	Analyse the design dimensions and store the product design dimension

Table 3: Input Values for Features and Weights (w) Assigned for a New Case

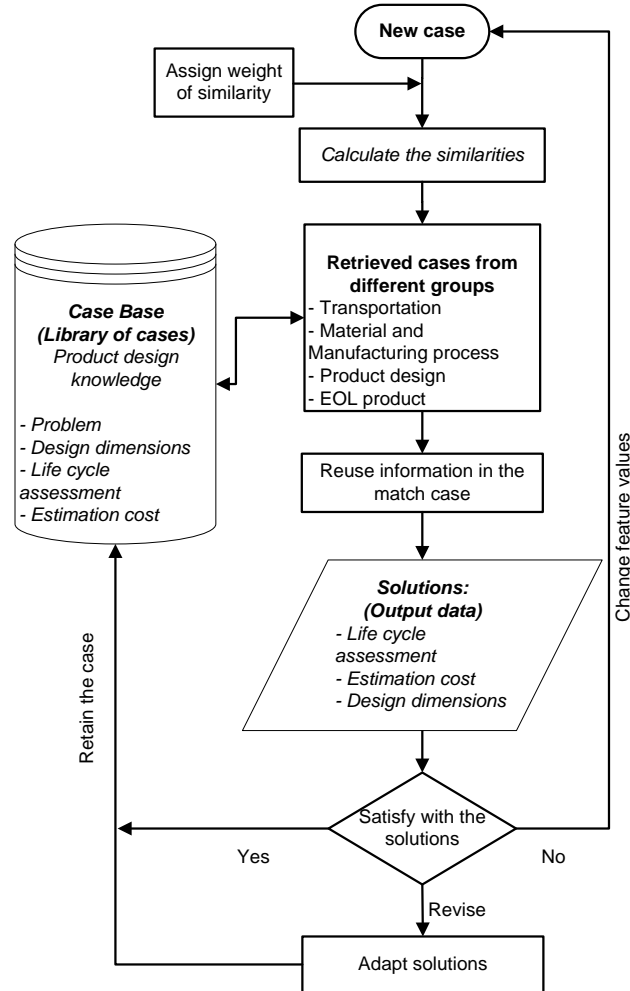| Group Categories							
Transportation	**w**	**Material and manufacturing process**	**w**	**EOL product**	**w**	**Design dimensions**	**w**
Origin = **UK** Dest = **UK** Trans = **Train** Dist. Plane = 0 Dist. Train = **1250** Dist. Truck = 0 Dist. Ship = 0	2 2 5 5 5 5 5	Mat = **PEEK** Weight = **3.50g** MP= **Injection moulded** RC= **50%** Vol = **10000** Mat. Cost = **£0.03/g**	5 2 5 2	Rec= **50%** Inc= **0%** Landf= **50%** Mat= **PEEK**	1 1 1 2	D1 = **5** D2 = **55** D3 = **5** D4 = **20** D5 = **45** D6 = **20** D7 = **20**	1 1 1 1 1 1 1

Figure 3: The Eco-CBR method for sustainable product design.

The next step is to process the similarity function between the new case and existing cases in the library by using equation (1) for global similarity and equations (2) and (3) for the local similarities. As discussed in Section 3, equation (2) has been modified for origin and destination features to show a local similiary of 1 if the locations share the same inland production.This process is illustrated in Table 4 for the transportation group by showing the new case values, equations used, weight implied, local similarity and case retrieved from the library.

In this case, the local similarity of each feature will be calculated in the global similarity for the transportation group (GS_{trans}). Here, the global similarity 0.97

shows that the result obtained from the retrieved case gives the highest similarity to the new case.

$$GS_{trans} = \frac{\sum_j w_{ij} * S_{jk}}{\sum_j w_{ij}} = \frac{2*1 + 2*1 + 5*1 + 5*1 + 5*0.8 + 5*1 + 5*1}{2 + 2 + 5 + 5 + 5 + 5 + 5} = \mathbf{0.97}$$

Table 4: Case Retrieved for the Transportation Group

New case features and values	Equation	Weight	Local similarity result	Library case
Origin = UK	Non-numerical	2	1	UK
Destination = UK	Non-numerical	2	1	UK
Transportation = Train	Non-numerical	5	1	Train
Dist. Plane = 0	Numerical	5	1	0
Dist. Train = 1250	Numerical	5	$\frac{\min(1250, 1000)}{\max(1250, 1000)} = 0.8$	1000
Dist. Truck = 0	Numerical	5	1	0
Dist. Ship = 0	Numerical	5	1	0

Table 5 shows the retrieved cases and global similarity for the groups in material and manufacturing process, EOL and design dimensions with the respective values of 0.98, 1.00 and 0.86. The solution for this retrieved case can be reused for an adaptation to the new case.

Table 5: Retrieved Cases with Similarities

Group Categories			
Transportation	Material and manufacturing process	EOL product	Design dimensions
Origin = **UK** Dest = **UK** Trans = **Train** Dist. = **1000**	Mat = **PEEK** Weight = **3.65g** MP= **Injection molded** RC= **50%** Vol = **10000** Mat. Cost = **£0.03/g**	Rec= **50%** Inc= **0%** Landf= **50%**	D1 = **4** D2 = **62** D3 =**2.5** D4 = **21.05** D5 = **52.93** D6 = **21.92** D7 = **19.11**
Global similarity= 0.97	Global similarity= 0.98	Global similarity= 1.00	Global similarity= 0.86

The next process is the case adaptation. In this Eco-CBR method, the process of adaptation represents an important step, as it translates the retrieved solution into the appropriate solution for the current problem (new case). Table 6 shows the output solution based on the specific categories of the (a) environmental impact, (b) the estimation of cost and (c) revision of product design dimensions.

Reusing the information in the case base library, Table 6 (a) is the first solution analysed based on the environmental impact of CF, EC, AA and WE to the product lifecycle. The process of translation from quantitative to qualitative data is

performed based on the data from the library. These data are set to one of five rankings: 'very high', 'high', 'medium', 'low' and 'very low'. By analysing the new case criteria and matching it with the retrieved case, LCA result in the Table 6(a) shows that CF, AA and WE give 'very low' impacts to the material (PEEK), manufacturing process (injection moulding), use product, transportation (origin in UK, use in UK, transport by train) and 'medium' impact to the EOL product (recycle is 50%, landfill is 50%). For the EC, it shows the environmental impacts to material and EOL are 'medium', with 'very low' impact to manufacturing process, use and transportation.

Table 6: Solutions (Output) to the New Case

Product life cycle	Quantitative				Qualitative			
	CF	EC	AA	WE	CF	EC	AA	WE
Material	0.0647	1.2600	2.20E-04	2.20E-05	Very Low	Medium	Very Low	Very Low
Manufac.	0.0040	0.0750	2.60E-05	9.60E-07	Very Low	Very Low	Very Low	Very Low
Use	0.0000	0.0000	0.00E+00	0.00E+00	Very Low	Very Low	Very Low	Very Low
Transport.	0.000	0.005	1.70E-06	3.80E-07	Very Low	Very Low	Very Low	Very Low
EOL	0.015	0.012	1.20E-05	2.50E-06	Medium	Medium	Medium	Medium

(a) LCA result

Types of Cost	Costs	
	Per Unit	Per Production
Purchasing	[0.070, 0.153]	[00700, 1533]
Manufacturing	[1.92, 1.92]	[19200.00, 19200.00]
Transportation	[0.01, 0.01]	[87.60, 87.60]
Environmental	[0.74, 0.74]	[7362.00, 7362.00]
End of Life	[0.000 , 0.000]	[0000 , 0000]
ECONOMIC COST	[2.735, 2.818]	[27349, 28183]

(b) Cost estimation
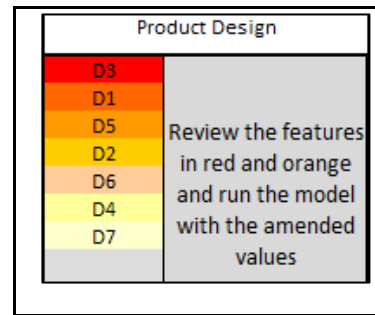
(c) Revision of product design

Table 6 (b) shows the solution for the economic cost that consists of the total cost for purchasing, manufacturing, transportation, environmental and EOL. It is calculated per unit and per production (product volume). The costs in bold in this solution are referred to as the estimated cost for the new case, while for the non-bold costs are referred to as the retrieved case. The economic cost is presented in the form of a range, calculated as minimum and maximum cost from the new case and retrieved case. For the economic cost per unit, the solution is £2.735 which is the minimum limit, and £2.818, which represents the maximum limit. This approach is also applied to the 10,000 production volume of forceps, where the economic cost minimum and maximum range is between £27,349 and £28,182. During the retaining of a new case to the library, the system will give options to the designer either to save the cost based on the estimated cost or the retrieved cost. There is also an option for manually inserting data for the cost (purchasing, manufacturing, transportation, environmental and EOL) based on the user preference.

Table 6(c) shows the last solution related to product dimensions. For this case, the minimum similarity for model acceptance is 0.9. Here, it shows that dimensions D3 (red colour) and D1 (orange colour) should be reviewed again and can be modified by inserting new values into the product dimensions in the new case. This case will then be rerun, and if it is accepted, the new solution will be proposed as shown in the Table 7. However, if the designer considers the model to be valid, the Eco-CBR tool can retain the first solution with the new proposed product design dimensions even if these do not comply with the existing cases.

Table 7: The Iterative Process for Product Design Dimensions (see figure in colour)

Finally, all these solutions can be taken to carry out case adaptation to the current problem with modifications or without modifications when the case can be retained and stored in the case base library.

5. Conclusion

The Eco-CBR method has been designed to be easily and widely applicable to sustainable product development. The application of an Eco-CBR method using a case study relating to the design of a medical forceps has been presented. The retrieval concept applied in the Eco-CBR helps the designer to shorten the process of design by exploring similar cases in the case base library.

Future work will centre on the application of the integrated eco-design decision making (IEDM) framework to develop case base reasoning for the new product development. This can support the wider application of the Eco-CBR, with more informed decisions being enabled at each stage in this framework. To aid this development process, the case base library will be developed to provide a solution to a new case by collaborating with the eco-quality function deployment (Eco-QFD). This will help the designer prioritise the product requirements and eco-design parameters that should be adopted to produce a more sustainable product.

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