Prioritizing 'Design for Recyclability' Guidelines, Bridging the Gap between Recyclers and Product Developers

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Abstract

This paper presents a Design For eXcellence (DFX) method for recyclability, resulting in a practical tool for product engineers. The tool enables an assessment of concept products as well as existing products and focuses on small domestic appliances recycled by shredding. The method enables quantifying recyclability performances of products by integrating a set of design guidelines, a recycling performance evaluation method, and prioritized improvement suggestions. After having the method implemented into a design support tool, a number of tests were executed. The preliminary tests of the method yield promising results, meeting expert expectations.

Keywords:

Design, recyclability, tool

1 INTRODUCTION

With increased environmental awareness and depleting resources, efficient recycling of products becomes more of an imperative requirement for both society and producers. WEEE Forum (European Associate of Electrical and Electronic Waste Take Back Systems) reported their 38 members collected approximately 2 million tonnes of WEEE in 2009, out of which 93.998 tonnes are small domestic appliances [1].

Most products available nowadays in the market are not designed with the end of life scenario of recycling in mind. In order to change this current situation, companies have to adopt new design paradigms where the ability to recycle a product is taken into consideration from the start of product conceptualization. In this context, this paper presents a Design For eXcellence method, focusing on maximizing a product's recyclability. Recyclability is here defined as; the affordance a product has for recovering as much components and materials as possible (quantity) with the highest possible purity (quality) by the least amount of effort (ease) with existing recycling technologies.

The 'ability' part of Design for Recyclability (DFR) is a performance indicator [2]. The performance indicator expresses how well the product can be recycled. Design for Recyclability enables engineers in obtaining an indicator score of the recycling performance after applying the method, while the currently widely used term, Design for Recycling, purely focuses on method and directions.

The development of Design for Recyclability methods has currently taken more importance, especially in Best in Class industries, as a way to standardize and popularize the implementation of such approaches within companies.

Actually, various publications describe design for recycling/ recyclability guidelines [3-10]. Most of them are very general and do not provide concrete steps, actions or solutions. For example, they propose to 'minimize material diversity', without stating which materials to avoid or to prefer. Often guidelines concern 'recycling' in general and not a specific industrial recycling process, containing various guidelines for manual disassembly, automated disassembly, and dismantling. Most sets of guidelines described are a combination of different recycling processes. This may be the desired approach when a product is intended to be recycled by different recycling processes. Alternatively, designing a product by focusing on a specific likely recycling process can result in fewer compromises and minimising the guidelines required to be considered, thus making applying the guidelines easier. At present the most specific information is outlined in the VDI 2243 guideline, providing a checklist, practical hints, and examples [11].

Additionally a model linked to CAD to assess the recyclability of a product is reported [12]. The model evaluates a specific product for which design choices are already made. On the other hand the purpose of the guidelines is to support engineers in making these design choices at the front end of the design process, before the product is developed.

Design for Recycling guidelines have been around for two decades, yet closed-loop recycling is still more of an exception than standard practice. It is assumed that general design guidelines are not sufficient to achieve (improved) closed-loop recycling or that the guidelines are simply not applied. The currently available guidelines seem to lack a combination of concrete instructions, prioritization, and recyclability performance feedback.

Therefore, this paper describes a DFX methodology capable of providing engineers with clear and complete Design for Recyclability guidelines, as well as the possibility to assess a product to obtain an indication of its recyclability performance. Section 2 describes the theoretical basis for developing a DFX methodology. Section 3 presents the application of the DFX methodology. Weighting factors of the different strategies are applied to enable a product recyclability assessment. Weighting factors for the strategies also prioritize the strategies and thereby enable engineers to select the most important strategies to optimize design towards better recyclable small domestic appliances. In section 4 the tool to support engineers in developing better recyclable products is presented. Section 5 presents the preliminary results to validate the Impact Assessment Method (IAM). The conclusion is stated in section 6.

2 FUNDAMENTALS

This section explains the approach used for developing the DFX methodology. First, Section 2.1. describes the design process steps that require to be supported by a Design for eXellence methodology. Secondly, Section 2.2. explains the steps that were followed in developing the method.

2.1 The Design Process

A widely accepted generic model of the design process is shown in Figure 1 [13]. According to this, candidate solutions are generated in a creation process. Then they are analyzed to calculate its performance and evaluated to assess whether the design is to be adjusted (path 1), rejected (path 2) or accepted (path 3). Therefore, the four basic processes that need to be supported in a DFX methodology are; Creation, Analysis, Evaluation and Adjustment.

Furthermore, and as described in [14], the types of information content present in a design process can be classified into three, categories, namely; embodiment, scenario and performance.

- Embodiment regards the set of parameters describing the design object, like its topology and its properties.
- Scenario is related to the set of entities describing the flow of energy, mass or information the embodiment is exposed to.
- Performance determines how the embodiment behaves within a certain (group of) scenarios.

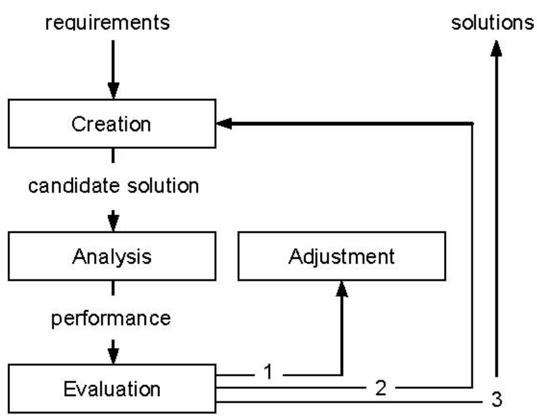

Figure 1: The design process [12]

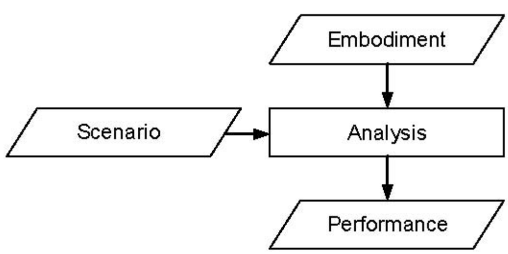

Figure 2: The analysis and the creation process.

From here it follows that an analysis technique allows the quantification and qualification of the performance of an embodiment undergoing a given scenario, as shown in Figure 2. On the other hand, creation is the process of specifying embodiment parameters such that it meets certain performance values for a given scenario. In this sense, design rules have an inverted effect to analysis, since scenario and/or performances help defining the embodiment variables.

From the previous discussion, it can be concluded that the DFX methodology should have a clear description of the following:

1. Types of embodiment, scenario and performance variables involved in the method.
2. An analysis method for calculating the designs performance.
3. A set of design rules to assist the generation of successful solutions.
4. A set of evaluation criteria for judging the performance values obtained in an analysis process.
5. A set of adjustment rules for improving previously obtained candidate solutions.

The resulting Design for Recyclability method presented in this paper was developed taking this into consideration.

2.2 The DFX Methodology

A Design for eXcellence methodology is developed to generate design guidelines that support product developers to focus on a single variable; X. A number of methodologies [2,15,16] served as a framework for guiding the development of the method. Without entering into details, the Design for Recyclability method was developed by completing the following steps:

- Goal definition: defining the application of the DFX method, defining the subject of study, determining the depth of study.
- Subject definition: knowing the initiatives, determining experts to interview, knowing the process (X), determining aspects of attention.
- User operability: determining how the target group should use the DFX method.
- DFX model making: choosing and making the model.
- Evaluation: testing and revising the model, determining future activities.
- Model revision: revising the model according to the outcome of the evaluation.

The DFX methodology is a systematic step wise approach with associated actions to generate Design for X guidelines.

3 THE DFX METHOD: DESIGN FOR RECYCLABILITY

The development of the method here presented is commissioned by Philips Royal Electronics. Boundary conditions of the tool were determined for small domestic appliances, to be recycled in Europe, utilizing shredding recycling systems. The tool is created with ambitious guidelines, intending that products designed with these guidelines are effectively recyclable nowadays, as well as in the coming years. The foreseeable recycling processes and candidate future legislation are taken into account during development. This ensures that the materials are valid for the coming years. This is necessary as Product Life Cycles (PLC's) experience a delay that can take up to a decade or longer, from being produced to actually reaching the disposal and recycling stage. Only considering Europe, there are over 1000 recycling companies. The origin of the waste these companies recycle varies: packaging, building/construction, agriculture, automotive electrical/electronic and other markets. Of the 57 Waste Electrical and Electronic Equipment (WEEE) recycling companies 56 use 'size reduction' as a recycling technology [17]. It is assumed the size reduction technology is shredding, the three recyclers involved in the development of the DFR method utilize shredding as a size reduction process for WEEE, indicating that shredding can be regarded as the common European WEEE recycling process.

Topic	Expert
Content of guidelines and strategies	Chemical experts (Royal Philips Electronics) Legislation expert (Royal Philips Electronics) Material expert (Royal Philips Electronics) Sustainability experts (Royal Philips Electronics) Recycling company experts (Van Gansewinkel Group)
Formulation of guidelines and strategies	Design experts (University of Twente) Psychology expert (University of Twente)
Creation of Impact Assessment Method (IAM)	IAM expert (University of Twente) Decision making expert (University of Twente) Multi criteria analysis expert (University of Twente)
Prioritizing WF’s of Impact Assessment Method (IAM)	Recycling company experts (Van Gansewinkel Group, REMONDIS, Eco-Systèmes)
Knowledge management	Knowledge management expert (University of Twente)
Feedback on use of tool	Systems architect (Royal Philips Electronics) Product architect (Royal Philips Electronics) Development engineers (Royal Philips Electronics) Design engineers (University of Twente)

Table 1: Conducted expert interviews.

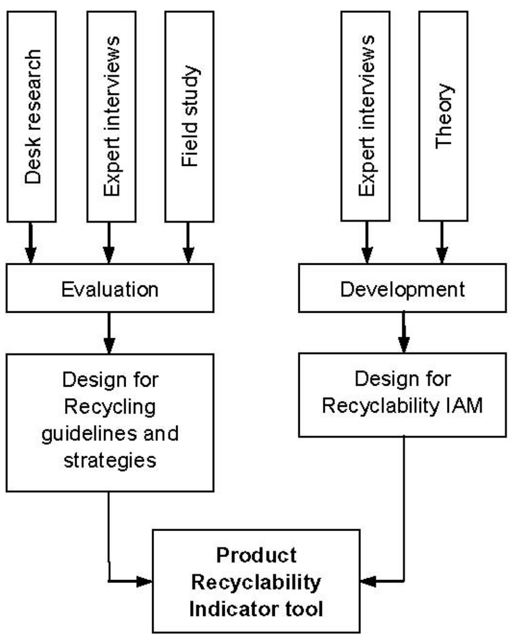

Figure 3: Practical execution of DFX methodology.

A literature study was performed to form a starting basis of the guidelines already available, followed by a patent study to obtain insight into the technologies that could potentially lead towards an improved future recycling process. Subsequently observational visits and studies are performed to the recycling facilities to provide the link between theory and the important firsthand experience. During these stages many expert interviews were conducted to gain further necessary practical insight. These experts were involved to ensure the right knowledge on each different topic is included, table 1. The practical execution of the DFX methodology is visualized in figure 3.

3.1 Variables and Parameters

First 6 *consequences* to be prevented are defined. The consequences apply to the output of the recycling process. The recycler wants to prevent these consequences in order to maximize the quality and quantity of the output material stream. Following this, 5 *types of materials or components* are defined which cause these consequences. Finally the *strategies* prevent the product design from containing these types of materials or components.

Therefore it follows that the:

- Scenario variables: are the strategies.
- Embodiment variables: are materials and connections.
- Performance: are the consequences.

3.2 Creation Support

Literature on Eco-design [3-10] provides general guidelines for designing products with increased recyclability. However experience indicates that engineers prefer more specific directions in order to know how to design better recyclable products. Therefore, the method in this paper approaches design support on two levels, namely, higher level guidelines, and a more specific strategy level. The guideline level consists of 7 guidelines which describe a general objective. The strategies, which are grouped by guidelines, describe in specific terms the actions and decisions required to achieve the objective of the guideline they are coupled to. Special attention has been paid to the formulation of the strategies to avoid misinterpretation. An example of a guideline is:

Guideline; Minimize material diversity.

And an example of a strategy to achieve this guideline is:

Strategy; Do not use polymer blends. Blends like PC-ABS cannot be separated into PC and ABS. Use mono materials instead of blends. Pure materials are supremely recyclable (if the material is recyclable).

Another example of how to achieve this guideline is:

Strategy; Do not use more than 5% master batch in plastics; carrier plastic and additives like flame retardants, stabilizers, fillers and strengtheners like glass fibers. These substances impede recycling by altering the density of the plastic causing it to end up in other plastic fractions polluting them, or causing pollution to the initial plastic fraction, degrading its quality. The maximum of 5% master batch is taken over the end result of the plastic batch after manufacturing processes like injection molding, extruding, etc.

As the example shows, the guideline describes an objective, while a strategy describes a way to achieve this objective. A total of 7 guidelines and 39 strategies were developed. Confidentiality prohibits describing all of them.

3.3 Analysis Method

The performance indicator that measures the degree of recyclability of a product is here defined as Product Recyclability Indicator (PRI). Its lowest value is 0% recyclability efficiency, which represents a product when best suitable for energy recovery. Whilst its highest value is 100% recyclability efficiency, which represents that the product meets all the objectives stated in the guidelines. In order to develop an analysis method that can be used to calculate the PRI, each strategy has been provided with a weighting factor that describes its importance in making the product recyclable. The PRI is calculated by adding all of the weighting factors attributed to each of the strategies that have been used during the design of the product. The values of the weighting factors are based on concrete input extracted from the recycling industry. The transformation of weighting factors to recyclability efficiency has been regarded as the Impact Assessment Method (IAM).

Multiple versions of the IAM are created and tested, resulting in a workable and refined IAM. The final IAM version consists of a structure of 6 *consequences*, 5 *types of materials or components*, and 39 *strategies*. The analytical hierarchy process tree of IAM is displayed in figure 4. Weighting factors of the variables and parameters were obtained accordingly:

Consequences: Three large recyclers in Europe used Multi Criteria Analysis (MCA) to provide the consequences with weighting factors (WF). This is used to obtain the relative importance of prevention of each consequence based on daily practice. This empirical input strengthens the reliability of the IAM.

Materials and components: An MCA is used to identify the extent of severity each type of material or component causes the consequence. This is the most uncertain part of the IAM as it is based on the intuition and experience of a relevant expert. However, the expert should be familiar with both the recycling process and product development. The MCA is therefore an approximation of reality based on the opinion of this expert. The WF of the consequences and the WF of how severe each material or component causes the consequence is put in a sub criteria analysis to generate WFs of the different types of materials or components.

Strategies: WFs of how well each strategy prevents a type of material or component from being used are obtained by an MCA. The MCA input is based on logical thinking and is a reflection of reality. A sub criteria analysis of the two previously mentioned weighting factors provide WFs for the strategies. Figure 5 visualizes how the different weighting factors of the strategies are obtained.

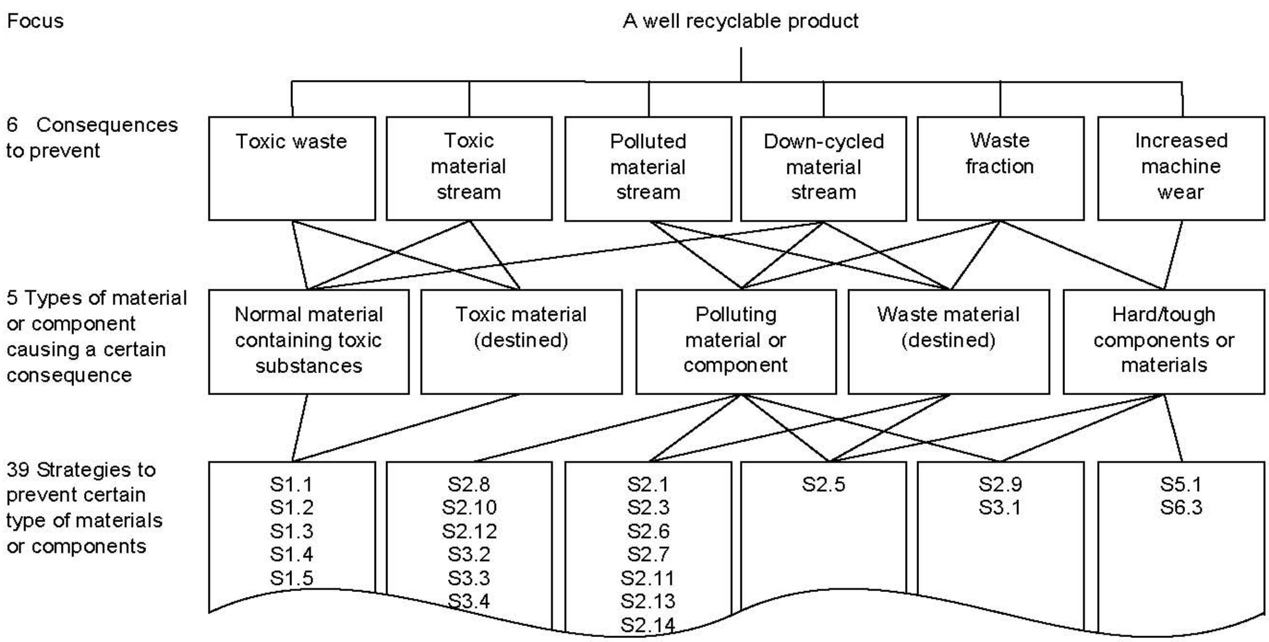

Figure 4: Analytical network process tree.

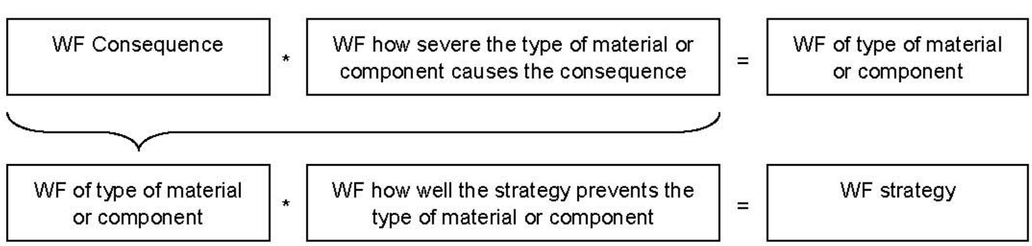

Figure 5: Impact Assessment Method to calculate static weighting factors.

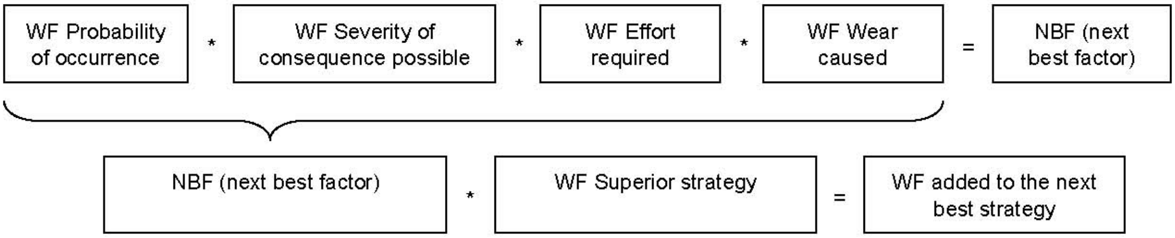

Figure 6: Impact Assessment Method to calculate WF for next best strategies.

Unfortunately the usual static weighting factors are not sufficient because when conditions change, different strategies increase in importance and thus their weighting factors should increase as well. For example when toxic substances are not used there is no need to enable removal. Inversely when toxic substances *are* used, enabling removal of these toxic substances or components gets a higher priority. The solution is to apply dynamic weighting factors. Superior strategies are assigned WFs by the earlier mentioned IAM. Inferior strategies are assigned a fraction of the superior strategy when this superior strategy is not met. Four parameters are determined which cause a strategy to be strictly superior:

1. Increased probability of occurrence of a consequence
2. Increased severity of the consequence possible
3. Increased effort required to prevent a consequence
4. Increased wear caused to prevent a consequence

Each inferior strategy is compared to its superior strategy employing these parameters. The parameters are assigned five grades ranging from 0.1 to 1. When the inferior strategy scores equal on a certain parameter, a 1 is assigned. When the inferior strategy scores worse a lower value is assigned. Multiplying the WFs of the parameters results in the Next Best Factor (NBF). The inferior strategy is assigned the WF of the superior strategy multiplied with the NBF. Note: this only occurs when the superior strategy is not complied with. Figure 6 shows how the weighting factors of next best strategies are calculated to enable dynamic weighting factors.

3.4 Evaluation Criteria

The user of the method indicates which strategies the concept or product complies with to assess its recyclability. The Product Recyclability Indicator score is the sum of the weighting factors of the strategies complied with. This efficiency performance is indicated as a percentage. Whether the result is good or bad depends on the criteria of the company or user. At the time of writing Philips marks a score of <50% as bad, 50 – 75% as average, and ≥75% as good.

3.5 Improvement Suggestions

The method also provides improvement suggestions when an assessment is performed. Here the method selects and displays the top five strategies of priority not yet complied with. These strategies are most significant to further improve the recyclability of the product. In addition, when completed by the user, the tool indicates why those strategies were not complied with and who made that decision.

3.6 The Analysis Method Applied

Product developers can use the analysis method by following these steps:

- Set a recyclability performance indicator objective.
- Select which strategies to comply with to achieve the objective.
- Generate a concept product design complying with those strategies.
- Assess the concept product design on recyclability.
- When the objective score is not achieved developers should take into account the improvement suggestions.

4 THE TOOL

The tool is created including (1) the Design for Recyclability guidelines and strategies, (2) the dynamic weighting factors of the strategies and (3) the ability to assess a concept or product on recyclability. The benefit of combining these three aspects into a single tool is; clustered knowledge, ease of use, and the ability to perform a relatively quick assessment of products recyclability.

Additionally the tool offers improvement suggestions for the assessed product, comprising of the top five strategies with highest priority. Optionally the user can declare why a certain strategy is not complied with and who decided so. This consolidation of information is helpful for possible future redesign or when a similar product will be designed. With the top five improvement suggestions the reason for non compliance as well as the responsible decision maker is clearly indicated.

To conduct an assessment the user indicates which strategies the product complies with. This set up means the input of the IAM are the design process decisions. The input of decisions enables not only the assessment of products but also concepts. Information and feedback on how to improve the product design is required at an early stage of the product design process when major decisions have yet to be made. Information and feedback at an early stage enables the developers to improve the design before large investments are made. For a Life Cycle Analysis, product data is required, including details such as the exact amount of a certain material. This data is not available at an early stage of product design. The tool enables an assessment of the concept at an early stage because *decisions* not *data* are the input for the tool. This provides information and feedback when it is most needed.

5 METHOD VALIDATION EXPERIMENTS

5.1 Results

Different types of small domestic appliances are assessed to evaluate the validity of the weighting factors in the tool and the product recyclability indicator score. The sustainability expert of Philips set a recyclability performance indicator score for each of the assessed existing products prior to tool assessment. This expected recyclability indicator is solely based on expertise and experience. The results of the assessment are compared to these expectations. In the case where the tool would show a totally different recyclability indicator, contradicting the expert's expectation, the IAM is considered incorrect and requires improvement. Four different types of small domestic appliances are assessed so far. The preliminary results are promising, showing that the results from the assessments align closely with the expert expectations. Some results are displayed in figure 7. The expert consistently sets the expected recyclability score 12 to 16% higher than the results from the tool. There are no large deviations from the expert's expectations. The preliminary conclusion from the Philips experts is that the model is usable and that first indications are that the tool functions accordingly.

Explanation for the consistently higher indicator score of the expert could be; 1) The tool takes candidate future legislation into account whereas the expert does not, 2) the tool takes other aspects into account compared to the expert, 3) the relative importance of the strategies differ for recycler and product developer.

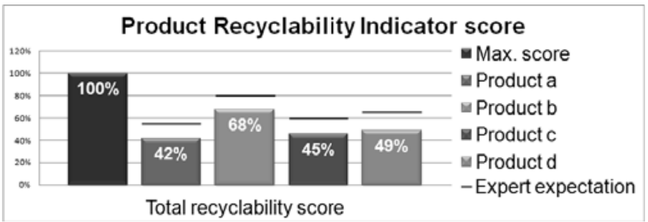

Figure 7: Tool assessment results compared to expert expectation.

5.2 Expert Opinion

Following these experiments the expert's opinion of the tool was gauged. The new developed tool will enhance the awareness and innovation with respect to the recyclability of electronic products. The tool is a bridge between product designers and recyclers of WEEE waste in Europe as it is a complex dynamic tool, however this is hidden behind a clear user interface, and provides a simple interpretable output. For the first time Philips can review products and concept products on recyclability and then use this knowledge to improve closed loop product recycling chains. First product assessments meet the expectations and this new supportive product development tool could lead to new product designs in the future at Philips.

6 CONCLUSION AND RECOMMENDATION

Practical input is utilized in a theoretical model (the tool), to generate practical output. A tool is created to support engineers in developing improved recyclable products. The tool contains all aspects of a complete DFX method. The tool enables an assessment of both concept and existing products to obtain an indication of the recyclability of the product. The preliminary tests of the method yield promising results, meeting expert expectations.

A study should be conducted of how to optimize the IAM. More recyclers can provide input for the IAM to increase reliability of the IAM. Additionally it is recommended to extend the geographical validity of the tool to the United States. It is expected only minor adjustments are required to make the tool valid for products recycled in the US. The method is evaluated by assessing different types of small domestic appliances. It is recommended to evaluate the method by assessing a greater variety of small domestic appliances.

7 FUTURE WORK

Future work will continue on improved product designs to contribute to closed loop WEEE recycling. Philips will continue the implementation and improvement of these kinds of sustainability tools to reach their EcoVision5 targets by 2015.

8 ACKNOWLEDGMENTS

The authors especially would like to thank Piet de Meer from recycler Van Gansewinkel Group and Erica Purvis from Royal Philips Electronics for their cooperation on this project.

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