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ESTIMATING RECYCLING COST AT PRODUCT DESIGN STAGE

1. Introduction

Designing is a process of gradually defining the features of the object, from general to more and more specific. It involves actions and events that occur between the moment when a problem appears and the time when documentation describing problem solution, that meets the functional, economic, and other pre-defined requirements, is reade [1, 2]. It is a complex process, very important in the life cycle of any product. Decisions made in the design stage affect the manufacturing costs [3] and determine actions that will have to be performed in the final phase of the product's life cycle (after it has been withdrawn from service). Research and production experience has shown [4] that modern recycling technologies give the most significant results if they are implemented at the early stages of product development, i.e. in the design stage. Therefore, the earlier the environmental impacts are identified and included in the life cycle of a product, the better the results of such actions. Ecodesign, increasingly popular, is an approach where special consideration is given to environmental issues at the early stages of design to reduce the product's adverse impact on the environment in further stages of its life cycle. It is also related to legal issues, as manufacturers are legally forced to observe certain standards for material recovery from end-of-life products. Manufacturers who apply ecodesign increase their market competitiveness as their products have better quality and are more environmentally friendly [5]. Eco-awareness campaigns, growing in popularity and scope, encourage consumers to purchase environmentally friendly products. Consumers also choose "green" products because they use less energy, which directly translates into reduced household maintenance costs. Unfortunately, products designed in line with ecodesign are often more expensive than traditional goods. In most cases the very production cost of the "green product" is not higher, but shelf price is affected by research and development expenses related to innovations in the construction or production of the new product.

2. Legal assumptions

In every household there are at least few electrical and electronic appliances: TV set, a fridge, washing machine, etc. The number of such appliances is growing, compared to what people used to own in the 1990s (approx. 2 appliances per household). Nowadays computers, mobile phones, DVD players, microwave ovens, and are used. On average, there is up to 10 electronic or electrical appliances and devices in a household (which means approx. five times more than 15 years ago). The life cycle of such products is estimated at 8 to 12 years, but taking into account the pace of development of the electronic industry, e.g. innovations in mobile phones or computers, some devices are discarded sooner – some of them even every year. As a result, household waste stream includes growing amounts of electrical and electronic waste. The products are a valuable source of raw materials, which can be recovered at the end of the product's life cycle and used again in the same or different purpose [11].

Eco-awareness is growing, and yet environmental impact would not be considered in product design and end-of-life management but for restrictive formal requirements. Manufacturers still see costs, efficiency and customer satisfaction as the most important factors in developing innovative products. On the other hand, end-users are most interested in the price and quality of the product.

In many Western European countries companies are required to search for ways to reduce waste or eliminate it already at the product design stage, and manufacturers are required to take action to enable product recycling.

Natural environment protection actions, which aim at preventing waste risks, begin from waste prevention or reduction and replacing acutely hazardous wastes with non-acute hazardous wastes. Firstly, it involves appropriate production technologies, which minimize the amount of waste. Secondly, it requires the use of less hazardous materials. Finally, waste recovery and treatment technologies must be implemented.

Therefore, the European Parliament and the Council published the Directive 2012/19/EU on waste electrical and electronic equipment (WEEE), recasting Directive 2002/96/EC, which regulates the management of waste electrical and electronic equipment and introduces main targets for collection, recovery and recycling for such waste [10, 12]. The Directive is aimed at reducing waste equipment in the waste stream, ensuring its re-use and recycling, minimizing the disposal of waste, and improving the functioning of the supply chain – manufacturers, distributors, consumers, and organisations that recycle electronic and electrical equipment.

For Poland this means the obligation to comply with the new EU target by increasing the current level of electrowaste collection.

The Directive defines how to address the main objectives as regards:

- designing goods – taking into account disassembly and material recovery,
- selective collection – obligating manufacturers and distributors to establish a system of collection of used products, achieving the selective collection target of 4 kilograms per head of population per annum,
- processing waste electrical and electronic equipment,
- achieving minimum recovery rate of 70-80% of the average weight of the product, depending on product category,
- creating information for electrical equipment users – how to locate WEEE collectors, consumer's role in recycling, potential impact on the natural environment and human health,

- creating guidelines for recycling plants – manufacturer provides information about re-use or recycling possibilities no later than one year after the product has been marketed, placing manufacturer identification on equipment,
- establishing a system for information exchange and reporting – a register of manufacturers, registering quantities and categories of marketed equipment.

Reaching the target recovery rate of 70-80% of the average weight of the product is not an easy task. Therefore already at the design stage manufacturers should consider how to change or redesign the product to reach the goal.

3. Ecodesign assumptions for recycling

3.1. Choice of materials

Ecodesign is of particular importance for household equipment, as the appliances consist of numerous components made of plastics. Plastics can be recycled and re-used to make new products. Therefore, recyclability of household equipment is crucial. A product should be designed to include the largest possible number of standardised and recyclable materials. It is important to properly label the materials to make them easily distinguishable in disassembly and recycling. A product made in line with ecodesign principles should have enhanced usability, i.e. it should be possible to re-use it (or its selected parts). Also, procedures for dealing with end-of-life product should be established (collection and recycling of the product), and it should have a disassembly manual. When designing a recyclable product one must remember that the materials that must be recovered should be located close to each other, and there should be easy access to all the parts to be removed.

The choice of materials for household appliances should be made with regard to their compatibility. The more compatible materials are used in the product, the less time it takes to separate them. Incompatible materials are those which cannot be recycled or which degrade the secondary raw material. During a traditional recycling process the material is shredded, and then the resulting mixture is divided into groups, until consistent fractions are obtained. The recycling process is simplified and accelerated if appropriate, compatible materials are selected already at the design stage. Recycling-oriented design strategies aim at developing areas related to product re-use and disposal. For example, such strategies are focused on the reduction of recycling cost. Another aim of ecodesign is to minimize the consumption of raw materials. Recycling is one of the priorities in product development. Table 1 shows a schematic overview of different aspects to be considered in designing environmentally friendly products.

As mentioned above, the combinations of materials simplify technological processes of recycling. A designer should be familiar with compatible materials and should have access to them. Incompatible materials reduce the quality of secondary raw materials. Therefore, to make recycling possible, we should only use such materials which may be

Environmental aspects of the product		**Longevity** • product longevity • lasting (long-lived) materials
Logistics • optimization of logistics, transport and packaging,	**Concepts of use** • lease agreement- product, • sharing – product,	**Maintenance concept** • maintenance and repair, • product liability,
Recycled products • support for recycled materials markets and used equipment (second-hand) markets	**Functionality** • multifunctional devices, • reduction of unnecessary features,	**Production process** • avoidance of waste, • reduction of hazardous substances,
Raw material productivity • minimization of material, • energy minimization, • use of recycled materials, • the need for eco-innovations,	**Closing the cycle (circulation) of raw materials** • ease of disassembly, • use of renewable raw materials, • **Recycling of waste materials**	**Ecological assessment and optimization** • eco-balance, • information sharing, • design management,

Improving applicability	**Material disposal**	**Waste avoidance**
• improving disassembly possibilities, • improving repair possibilities, • repair, technological development	• material labelling, • minimizing material diversity, • single material products, • avoidance of old "forbidden" materials.	• safe disposal of harmful substances, • maximum use of recycled materials.

Table 1. Recycling as a part of sustainable design and development of products [7, 8]

well combined together. Based on compatibility tables (matrices) a designer defines which materials may be combined to make recycling as simple as possible. Various matrices are used for metal alloys, e.g. aluminium and steel, and for plastics, e.g. thermoplastics [6]. There are also matrices for recycling entire products.

It is also crucial to minimize material diversity to reduce the probability of material incompatibility issues [7].

Designers should also think about the type of joints to be used in the product. Joints should be designed to facilitate quick and smooth disassembly, particularly when the use of incompatible or hazardous materials is unavoidable due to functional reasons.

In integrated recycling compatible materials constitute one secondary raw material with specific physical and chemical properties. For metals, such combination is defined by standards. In contrast, incompatible materials degrade the properties of the recycled material. When the quality of the secondary raw material is too low and it may not be re-used, the material is disposed (often at a landfill site). Therefore, a product should include the largest possible number of compatible materials. If there are components made of other materials, the product should be designed to facilitate separation of two different material groups, e.g. by using temporary joints [8].

3.2. Product recycling

Product recycling depends on certain factors. Whether a product may be recycled or not depends on framework assumptions for recycling, given in Table 2.

Legal aspects determining how to deal with end-of-life products are crucial. They make manufacturers (and particularly manufacturers of household appliances) ensure an appropriate rate of recovered materials and proper waste management. Therefore, the framework assumptions for recycling are taken into account already at the design stage to minimize later recycling costs.

Figure 1 shows the relationship between maintaining product functionality, recycling costs and the costs to be incurred for the storage of incompatible materials.

When a product was designed for multiple re-use (e.g. after renovation), there is no need to remove materials. The cost of adjusting the product for recycling reduces maintenance cost of the entire product. At disassembly (dismantling) the product loses its functions. During disposal it is not important to disassemble the parts and group them; fraction compatibility is determined only during direct processing, and groups are adjusted. When equipment is not disassembled but shredded, there are limited possibilities of using material properties. Such materials are identified on the basis of grain size spectrum. Incompatible raw materials are arranged into grain size classes and removed accordingly. When it is not possible to group materials by grain size, it is necessary to return to the initial phase to separate incompatible materials.

Taking into account the production cost and product functionality, it is not possible to design and then manufacture a whole product made of 100% highly recyclable material. Each household appliance is made of at least several kinds of materials. Therefore, apart from the principles related to

Legal assumptions	Laws, regulations, management of regulations and standards which may facilitate or hinder recycling.
Economic factor	In the absence of mandatory recycling of a product or material, recycling depends on economic factors.
Technological processes	Product and material recycling depends on technological capabilities. Materials for which recycling technology has not been developed or which contain harmful substances are disposed.
Logistics	Recycled equipment and materials should be collected, transported and stored in a manner appropriate for further processing.

Table 2. Framework assumptions for recycling used products [7, 8]

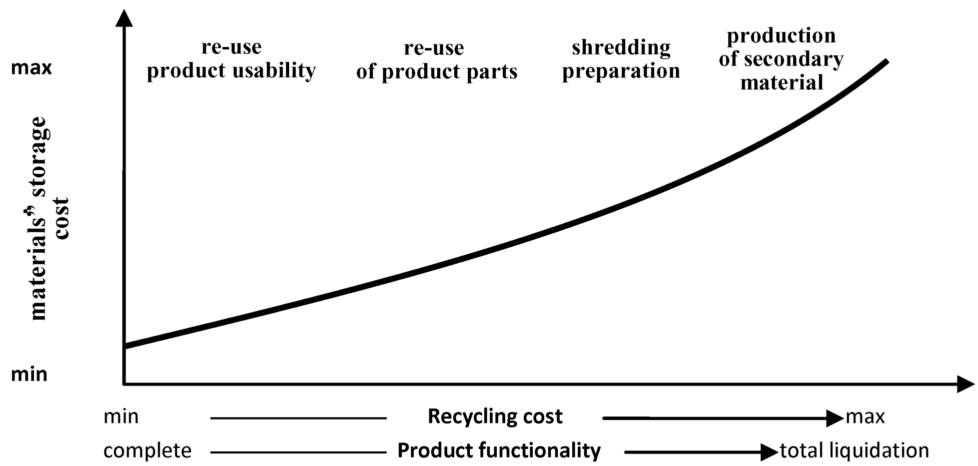

Figure 1. Recycling costs of the finished product [7, 8]

the proper selection of material, it is necessary to use simple joints to facilitate disassembly and reduce the time and cost of recycling.

3.3. Functions of joints in products

One of the basic tasks of a product designer is to select appropriate joints. Each designed product is composed of a number of individual parts, which together with their joints form a functional whole. Joints must be selected with a view to easy disassembly, but they have also other functions. They affect the shape of the product, selection of technological processes, cost, technical performance, reliability, durability and safety. Next to mechanical properties joints have also other features, which include electrical conductivity, density, etc. Joints in products are selected based on their functions. Due to ecodesign requirements the joints between components to be separated (for recycling) should be as simple as possible (easy access to the joint, the use of standardized disassembly tools, etc.) The joints used in the product will determine the type of disassembly type to be used. Table 3 lists three basic disassembly types and their features.
Designed equipment and parts intended for re-use after renovation require joints which may be re-connected, e.g. screws. Chemical and thermal separation of materials results from their specific material properties. Not all material joints may be broken and it calls for an appropriate recycling strategy.

4. Estimating recycling cost at product design stage

The above mentioned aspects related to product recycling are undoubtedly linked to the possibility of incurring different generic costs. First, considering recyclability at design stage generates costs related to developing improved products, and second, recycling in itself is associated with certain costs. A product should be designed to minimize recycling cost. Pro-recycling actions do not have to be associated with costs. Organizations which manage their own used products may benefit, e.g. by selling recycled materials as secondary raw materials for further purposes, including production, or by re-using those materials (reduced cost of purchasing raw materials or secondary raw materials from suppliers) [9].
At the design stage we cannot precisely calculate future recycling costs, but the costs can be estimated. These costs are related to the current situation on the recycled materials market, namely, to the purchase prices of raw materials. Additionally, there are costs incurred by recyclers disassembling products and recovering re-usable materials. Recycling costs are also related to the transport of end-of-life products (e.g. fuel costs), storage of such products and storage of products and materials selected after disassembly. Therefore, when estimating the cost of recycling at the design stage we should compare them for different variants of the same product and select the best solution (most cost-efficient). However, one must bear in mind that reducing the cost of recycling may not change the product functionality, consumer's interest or product safety. The research conducted by the authors of this paper led to the development of a method for estimating recycling cost at product design stage.

4.1. Disassembly cost

The cost of disassembly is a component of the total product recycling cost. One of the key factors influencing disassembly cost is its time, which in turn depends on the type of disassembly and uniformity of joints.
In the case of uniform joints, fewer tools are needed to disassemble the product, which saves time and reduces costs. Since disassembly can be manual, automated or mechanical, there are two types of disassembly costs:

- manual disassembly cost – where disassembly time is key, as it affects the pay of the worker, the only cost in this case. When the worker uses electrical or pneumatic tools, the total cost includes also the energy consumed by the tools. The values are so low, however, that most often they are disregarded in the estimates of the total cost,
- the cost of mechanical and automated disassembly – it is a much more complex case, most often considered individually. This means that it is only possible to calculate the costs for a particular disassembly line, the structure of which depends on the dismantled products and on the resources of the organization. Therefore, apart from the employee's salary the cost of depreciation of machinery and equipment, costs of energy and other infrastructure, which is very difficult to estimate if there is no specific disassembly line.

4.2. Recycling costs

Apart from disassembly costs, recycling costs are the second component which affects the total recycling cost. The factors that influence its value is the mass of the material

Disassembly type	Description
Non-destructive disassembly	Time-consuming, most often manual disconnection of components. Partial automation possible (reversed assembly), but for a small number of products.
Partially destructive disassembly	Destruction of connecting elements while maintaining the entire parts e.g. desoldering, drilling screws, etc.
Destructive disassembly	Defining spots other than joints to enable the separation of materials for disposal, most often by shredding.

Table 3. Product disassembly types [7, 8]

and profit on sale, in the case of material recycling, or the cost of disposal or storage, in the case of disposal or storage. According to the law, recycling is understood as material recycling or raw material recycling with the exception of energy recycling. Therefore, due to the type of joints between parts and materials, certain assumptions can be made:

- permanent joints are not removable due to excessive cost and imprecise separation of material components,
- sets or parts made of recyclable materials generate a profit from the sale of such sets or parts to recycling organizations. Such sets include:
  - sets permanently joined, consisting of at least one part made of a material with limited compatibility in relation to other parts, provided that it does not adversely affect the recovery of raw materials,
  - permanently joined sets consisting of compatible parts,
  - temporarily joined sets, where regardless of material compatibility single material parts may be separated in disassembly,
- sets or parts made of disposable or storageable materials generate losses resulting from fees charged by recycling companies. Such sets include:
  - sets permanently joined, consisting of at least one part made of a material with limited compatibility in relation to other parts, provided that it adversely affects the recovery of raw materials,
  - permanently joined sets consisting of at least one part made of material incompatible to other parts,
  - parts made with harmful materials.

4.3. Estimating the total recycling cost of the product

A sale profit or material disposal/storage cost is the product of material mass and the rate of disposal/storage, respectively.

It may be generally assumed that recycling cost is the difference between the profit from selling recyclable and reusable materials, and the total costs incurred for disposal or storage, as shown in Figure 1. A negative result means a loss, a positive result – a profit.

$$\text{RECYCLING COST} = \sum_{i=1}^{n} \text{PROFIT} - \sum_{i=1}^{n} \text{COST} \tag{1}$$

It may be generally assumed that the total recycling cost is the total profit on materials which may be sold after disassembly, and the cost is the total cost incurred for disassembly, disposal of hazardous waste, transport to waste disposal landfill (see formula 2). A negative value indicates a loss (cost) (the organization must pay extra), and a positive value means a profit.

$$K_{RW} = \sum_{i=1}^{n} K_{MD} - \left(\sum_{i=1}^{n} K_{UMN} + \sum_{i=1}^{n} K_{Odpad} + \sum_{i=1}^{n} K_{Dem} \right) \tag{2}$$

where:
K_{RW} – product recycling cost,
K_{MD} – cost of good materials (recyclable and reusable),
K_{UMN} – cost of hazardous waste treatment,
K_{Odpad} – cost of solid waste,
K_{Dem} – disassembly cost,
n – number of materials on a given product.

$$\sum_{i=1}^{n} K_{MD} = mass \times price\_[kg \times PLN] \tag{3}$$

$$\sum_{i=1}^{n} K_{UMN} = mass \times price\_[kg \times PLN] \tag{4}$$

$$\sum_{i=1}^{n} K_{Odpad} = mass \times price\_[kgxPLN] \tag{5}$$

$$\sum_{i=1}^{n} K_{Dem} = disassembly\_time \times disassembly\_unit\_price\_[rate \times h] \tag{6}$$

The longer the disassembly of end-of-use products, the greater the recycling cost for recovery organizations. Hence, it is most advantageous to design goods with a view to effective and smooth disassembly.

5. Implementation in the computer system

The method for estimating recycling cost has been implemented in a computer system supporting recycling assessment of household appliances.

The application is based on agent technology. The application implements an original method for recycling-oriented product assessment based in indices, a system of suggestions and hints (regarding changes in design parameters of the proposed product to improve its recycling parameters) and an analysis of recycling cost for the product at design stage.

The main task of the multi-agent system is to conduct a recycling-oriented assessment of a designed product in CAD 3D environment based on data from a product model (RmW – recycling product model). The system makes it possible to control recycling parameters of products on an ongoing basis in subsequent versions of the design, suggests potential modifications which may improve the parameters, and estimates disassembly and recycling cost. It supports the designers working in a dispersed structure environment. Each designer who co-designs a product may be located in a different node of the distributed network. Designers receive a computer tool (agent system) which "tracks" their work. Based on the observations the system conducts recycling-oriented assessment of the product, and suggests modifications in the design to improve product recyclability.

The system works with an existing CAD 3D extension, which exports a CAD 3D design to XML files – a material database, and a structural description of the product. The import is performed automatically without the participation of the designer. Programmed agents read information stored in the XML files and conduct the analysis. The method takes into account the guidelines given in directives and standards that are necessary in ecodesign.

Figure 2 presents information about the level of recovery, the number of materials, the number of tools, as well as the estimated recycling cost of the implemented appliance.

The estimated recycling cost includes the cost of product disassembly (expressed in PLN per hour, which is determined

Figure 2. Report from the recycling-oriented analysis, including the assessment of recycling cost

by the estimated hourly rate of the disassembly station worker), the cost of storage or disposal of hazardous materials, as well as the cost of selling raw materials obtained from the product.

6. Conclusions

Recovery of recyclable waste materials is a must in order to conserve shrinking natural resources such as crude oil, uranium, copper, zinc, iron, nickel, or hard coal. For that purpose it is necessary to make seemingly unnecessary objects become valuable again. It is not possible not to produce waste, but the amount of it can be reduced and its usability enhanced [11].
Estimating the recycling costs of products, which at some point will reach their end-of-life status, is not an easy task at the design stage. This involves forecasting how much material can be recovered from the products, and what costs it entails, taking into account not only the cost of product acquisition on the market, but also the cost of disassembly, storage of acquired materials, disposal of hazardous materials or the costs associated with waste removal.

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Key words:
recycling, disassembly, recycling costs, ecodesign.

Abstract:
The paper describes the current legal context of product recovery and recycling, and presents a method for estimating recycling cost at product design stage. Design assumptions are given for household appliances, taking into account end-of-life recycling. The authors describe also the selection of materials and joints which facilitate product disassembly for recycling purposes, as well as product disassembly methods, which are divided into destructive, partially destructive and non-destructive.

METODA SZACOWANIA KOSZTÓW RECYKLINGU WYROBÓW AGD NA ETAPIE PROJEKTOWANIA

Słowa kluczowe:
recykling, koszty recyklingu, ekoprojektowanie.

Streszczenie:
W artykule opisano metodę szacowania kosztów recyklingu wyrobu na etapie jego projektowania. Przedstawiono założenia projektowe artykułów gospodarstwa domowego uwzględniające recykling po wycofaniu ich z eksploatacji. Opisano dobór materiałów i połączeń oraz demontaż wyrobów na potrzeby recyklingu. Przedstawiono sposoby demontażu wyrobów z podziałem na nieniszczący, częściowo niszczący oraz nieniszczący.

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