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Computer-aided design assessment of products for end of life separation and material handling

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ABSTRACT

A methodology is presented for the estimation of recyclability indicators of product designs. It combines an automated CAD-integrated disassembly sequence generation algorithm and a recyclability assessment module. The algorithm employs collision detection and CAD feature recognition for the extraction of disassembly tiers and sequences of specific components. This information together with the components' characteristics, including materials, is then processed by the corresponding module, which is capable of providing an initial evaluation about the product's recyclability. The methodology is demonstrated through an industrial case study, involving rear axle designs that are associated to different truck models.

1. Introduction

Recycling and reuse of products and their components are still not fully and systematically considered by contemporary product engineers and designers [1,2] during the design phase. This is partly due to the fact that the designers do not have standard tools to automatically assess their designs, since the CAD tools do not typically provide any metrics regarding the recyclability of the designer's choices. On the other hand, CAD systems have grown from graphics editors, with few built-in design functionalities, to sophisticated tools, providing information on the characteristics of a designed product, including simulation of its functions [1]. Recyclability indicators, however, focus more on the materials and usually disregard any metrics that concentrate on the requirements of reusing components, concerning the dismantling or separation phases [3].

Recent research studies mostly focus on mechanisms for the assessment of a product's recyclability used as part of modern PLM systems that are capable of handling disassembly information with limited support from CAD tools [4]. However, the PLM systems are out of the range of the designers' influence [5]. This creates the necessity for CAD-integrated mechanisms. Furthermore, although information about the costs of recycling materials is available, there are no mechanisms for the estimation of the dismantling assemblies' cost, since the latter heavily depends on the complexity, pertaining to the process of product disassembly. This problem persists not only for product designers but also for dismantling centres.

In order to accurately estimate early enough the disassembly cost, detailed representations of the disassembly process should be available at the design phase of a product. Currently, assembly/disassembly representations are limited in terms of the comprehensiveness of process information [6]. This creates the need for additional mechanisms that can help engineers generate this information manually, increasing, however, the overall complexity of an engineering project [5]. In the following sections, a methodology, which comprises both the extraction of disassembly information and the relevant calculation of the pertinent recyclability metrics, is presented.

2. Assessing recyclability and reusability

A number of recyclability indicators have been proposed in the literature. These indicators may refer to the materials used in the product or to the processes required for its dismantling and recycling. These approaches focus, in principle, on providing feedback on the potential value that can be extracted from a product at the end of its useful life (EoL).

The indicators solely concentrating on the materials used, typically provide a percentage of the material's mass that can be recovered in relation to the total mass of the product [7]. Since these indicators only provide the potential value to be extracted from EoL products in terms of mass, they do not provide any feedback on the actual cost of recycling the product. Also, a few indicators have been proposed considering as recycling output only the materials that have value over a certain threshold, i.e. the percentage content with high recyclability index [3]. Similarly, the recyclability rate is one of the metrics, which again uses the mass of a certain recyclable component multiplied by an index that expresses the recycling rate of components that have the same material. This indicator has been used together with other factors, in order to provide alternative dimensions or materials of certain components for the products' recyclability optimisation [8].

Although most indicators may express the potential recycling value, they do not take into account the economic feasibility of

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recycling or reusing a product's components. Another indicator that expresses the profit to loss margin is the $PLM_{recycle}$, which provides the gains minus the costs of recycling a product. However, the great challenge for this indicator is the estimation of the values used for the disassembly costs [3].

Considering the existing processes for the handling of products, after the end of their useful life, there are discrete steps to be carried out, the first of which is dismantling the product and separating it into reusable and recyclable components. From the perspective of a dismantling centre, the savings from the disposal can be considered unrelated, since a possible disposal would yield no profit. A product's post-recycled value, when considering standard recycling costs per mass, is always proportional to the pre-recycled value of the material. Therefore, a new indicator, called Economic Feasibility for Recycling or Reuse (EFRR) is proposed in this paper. This indicator provides a monetary evaluation that is required both for the materials and the processes for the manual separation of the EOL products.

$$EFRR = \frac{\sum_n m_i Vr_i - \sum_n Cd_i}{\sum_n m_i}$$

where n, total number of components; m_i, mass of component i (kg); Vr_i, value of pre-recycled material of component i (€/kg); Cd_i, cost of disassembly for component i (€).

3. Calculation of cost for disassembly

In order for the cost of disassembly to be estimated during the design phase, the disassembly processes have to be defined first. Since this is a time consuming process and would normally require the direct input of all pertinent information by a process engineer, an algorithm has been developed that is capable of identifying the necessary processes and their relations.

3.1. Collision detection algorithm and components' information

The algorithm's core utilizes the collision detection features of modern CAD systems in order to identify extraction paths of components that are collision free (Fig. 1). Moreover it manages to extract specific information about the product's components. The input required by the product engineer or designer is limited to the selection of a base component to be regarded as fixed during disassembly. The first step of the algorithm is the identification of the main components and parts of the assembly. This includes all the sub-assemblies at each level of the assembly tree. The second step is the extraction of all the relevant information that will directly or indirectly be used in the following steps. This information includes:

- Part constraints: The constraints defined during the product's creation. The main constraints used are the axes' coincidence and the parts' faces contact. All constraints are stored with reference to the parts they are applied to.
- Part material: The material defined by the designer for each part is stored as its reference.
- Process information: During design, some pieces of process information, such as the edges or points to be welded, are available. These are stored together with the relevant specifications, such as reference parts and the welding seams' length.

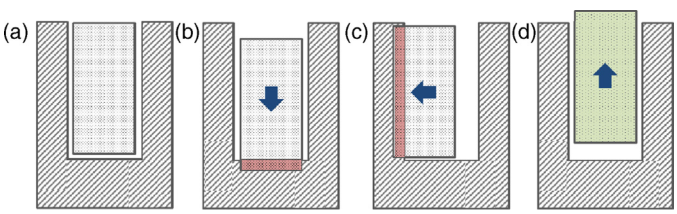

Fig. 1. Extraction path analysis from (a) initial position to (b),(c) paths where collision is detected, to (d) a collision free path.

The specific steps of the core algorithm aiming at the definition of the disassembly precedence diagram are described in the next paragraphs.

Removal of fasteners: The algorithm identifies the primary and secondary fasteners at the first level of the assembly tree. All parts, whose text descriptions contain the words "bolt", "screw", "clip", "wedge", "pin", "nut" and "washer" are hidden from the CAD scene.

Components moving and collision detection: The collision detection routine, works by moving the parts to the global and local axes and by checking for any collision with other parts (Fig. 2). Each part is moved by a specific predefined step towards the final position, which is calculated on the basis of the bounding box dimensions of the entire product. The parts referenced to constraints are initially moved to the relevant axes. For example, if a part's main axis coincides with that of another part, it is moved towards the directions of the axis first (main and opposite). If a part can be moved at least one step towards one direction, before colliding with another, it is returned to the previous position and re-moved to the other remaining directions (Fig. 1). The algorithm thoroughly checks all possible alternatives with all the parts in one run. At the end of the run, all the parts that could be removed were hidden and stored as parts of the components in the nth disassembly tier (with n being the number of the algorithm's iterations). The routine is repeated until only the base part(s) remain in the scene. The collision detection sensitivity is dynamic and is configured by the part's material. For example, the metal parts' collision sensitivity is 0.1 mm, while the plastic parts' is higher, depending on the type.

Singular extraction and disassembly relations generation: In the previous routine if a part has more than one extraction paths, the algorithm stores only the shortest one calculated by following the steps performed by the algorithm. Based on the tiers defined earlier, each component is moved towards the opposite extraction axis by one step. Collision detection is performed only targeting at the components that belong to the next tier ($n + 1$). If a collision occurs with these components, a direct link is stored between these components. If not, then the component is linked to all the components of the next tier. After all components of one tier have been checked, they are removed and the algorithm moves to the next tier until all tiers have been checked.

Association of fasteners to components: Based on the tiers defined earlier, each component together with the primary fasteners are reintroduced (all fasteners except the nuts and washers). Similarly

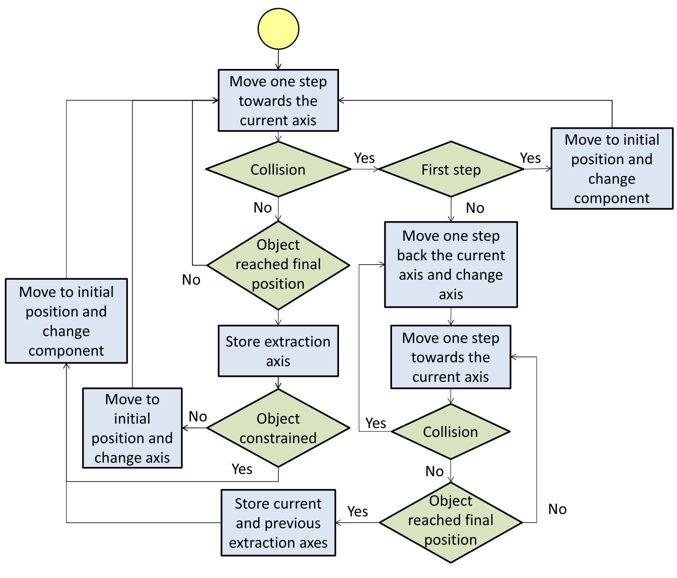

Fig. 2. Example logic of the core collision detection algorithm.