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A multi-criteria assessment of robotic disassembly to support recycling and recovery

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ABSTRACT

Use of robots in product disassembly is growing in popularity, mainly due to ever-increasing labour costs in both developed and developing countries. However, currently there are no approaches for assessing the trade-offs between environmental benefits, technological feasibility and economic viability of robotic disassembly. The work presented in this paper aims to justify the future application of robotic disassembly in products end-of-life management by assessing its sustainability through multiple factors (i.e. environmental, technological and economic performance). This paper proposes a framework for the multi-criteria assessment of robotic disassembly to support recycling and recovery, which consists of three main stages: analysis of recycling options, selection of assessment criteria, and evaluation of disassembly operations. A decision support tool has also been developed to compare the results from different recycling scenarios based on manual and automatic disassembly. A number of automotive electronic components have been used as case studies to illustrate the application of the framework and its associated decision support tool.

1. Introduction

The rapid growth in generation of End-of-Life (EoL) products has led to increasing effort to develop technologies and processes for product recovery in the form of material recycling, component reuse and product remanufacturing. In this context, disassembly operations are reported to improve the economic and ecological performance of various product recovery applications (Vanegas et al., 2018). The majority of the disassembly operations are still performed manually due to several factors, including larger variety and the uncertainty of the quality and quantity of EoL products, and the related need for operating flexibility. Over the past two decades, there has been acceleration in research focusing on introducing increased automation in disassembly applications, including the use of robotic cells (Torres et al., 2004; Weigl Seitz et al., 2006; Wegener et al., 2015; Kelly, 2016).

Automated robotic disassembly has demonstrated the potential for reducing operating times, minimising disassembly costs and improving the working environment (Işıldar et al., 2018). However, a key remaining question is how to assess the long-term sustainability of automated robotic disassembly compared to other recycling alternatives. A number of models have been proposed to consider the profitability and feasibility of manual disassembly systems, but very limited research targets evaluating environmental performance, technological feasibility and economic viability of robotic disassembly (Vongbunyong and Chen, 2015).

This paper proposes a novel framework for assessing automated robotic disassembly based on a number of user-defined criteria. The initial section of the paper provides an overview of relevant existing assessment and multi-criteria decision-making approaches. The latter part of this paper describes the proposed framework and illustrates its application to various automotive electronic components.

2. Review of relevant assessment methods

2.1. Environmental assessment

To evaluate the environmental impact of a product or the performance of different recycling/recovery scenarios, Life Cycle Assessment (LCA) has been widely used as a standard methodology that considers the potential impacts from all stages of the product lifecycle. However, performing a complete LCA can be time consuming depending on the complexity of the product (Bicer and Dincer, 2018; Seppälä et al., 2001), and its results are usually too complex and detailed to be interpreted by most business decision makers. Therefore, a number of simplified LCA methods have been proposed such as the 'Eco-indicator 99'. This is a tool to help product designers evaluate the environmental

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Table 1
Multi-criteria decision making theories and models.

Theory and Model	Contribution	Practice
Multi-attribute utility theory (MAUT)	The development of a normative model to provide theoretical insights	e.g. evaluating the sustainability of suppliers (Ladd, 2013)
Generalised additive models	Combination of values on the many criteria into one overall value	e.g. management of municipal solid waste (Li et al., 2012)
Analytical hierarchy process (AHP)	Development of a linear additive model, deriving weights and scores	e.g. assessing the production of electronic parts (Tseng et al., 2009)
Outranking method	Eliminate alternatives that are in particularly dominated	e.g. identifying the most appropriate waste management processes (Queiruga et al., 2008)
Weighted aggregate method	Each alternative is weighted against the others to reflect the importance of the assessment criteria	e.g. selecting the optimal waste management option (Arunagiri and Gnanavelbabu, 2014)
Goal programming method	Combine the logic of optimisation in mathematical programming to meet specific requirements	e.g. evaluating the compatibility issue between recycling alternatives (Lyeme et al., 2017)
Fuzzy sets	Capture the idea that natural languages are not precise in discussing problems	e.g. assessing remanufacturing options of product designs (Wang and Chan, 2013)

performance of a product over its life cycle by using a single score (i.e. eco-indicator point) which is calculated for the total impact using predefined values for use of raw materials, undertaking production processes, transportation, and also recovery and recycling activities. Another simplified LCA tool is the 'Eco-compass' which was developed by Dow Europe (Fussler and James, 1996). This evaluates or compares component(s) or scenario(s), and aims to provide a simple, visual summary of significant environmental issues associated with a product (Bennett et al., 1999). The number of such simplified LCA tools is rapidly increasing, which includes Cumulative Energy Demand (Huijbregts et al., 2010), Material Input per Service Unit (Wiesen et al., 2014), Spider (or Polar) Diagrams (Agarski et al., 2012), and Environmental Check Lists (Canter, 2010).

2.2. Technological assessment

Technological assessment is defined as "the systematic study of the effects that may occur when technology is introduced, extended, or modified, with emphasis on the impacts" (Coates, 1976). This type of assessment is often used to improve decision making through understanding the challenges, capabilities and opportunities of applying technological and scientific innovations (Scolve, 2010). Porter and Cunningham (2005) define a procedure for technological assessment in which technology description and forecasting is used to highlight the impact of changing technology and its direct applications. In the recycling studies, disassemblability is widely used as one of the technological performance indicators (Sabbaghi and Behdad, 2018) based on a series of parameters such as weight, structure, size, material composition, the manual force for disassembly, and the degree of precision required (Desai and Mital, 2003). Other research has focused on criteria such as disassembly sequence planning and economic analysis (Neto et al., 2018). However, the majority of technological assessment procedures are designed for manual disassembly, not for automated robotic disassembly.

2.3. Economic assessment

The Cost-Benefit Analysis (CBA) approach is the most commonly used evaluation methodology to assess economic performance (Wholey et al., 2010). This can be used to support decision-making across a broad range of scenarios, including the development of environmental and social policy as well as in the adoption of new technologies or processes. CBA could also provide a holistic approach by extending economic analysis to include both direct and indirect benefits and costs (Wholey et al., 2010). In waste recycling applications, the majority of economic assessment methods are developed focusing on specific product, process or technology (Ghosh et al., 2015), for example for vehicle or PCBs recycling. Other economic comparisons have included scenarios involving various shredding, separation procedures, and material recycling and refining processes (Kripli et al., 2010). More recently, other economic assessment methods have been proposed such as Life Cycle Costing (LCC) (Reich, 2005), Cost-Effectiveness Analysis (CEA) (Finnveden et al., 2007), and Full Cost Accounting (FCA) (Bryant, 2003).

2.4. An overview of multi-criteria decision-making techniques

One of the key challenges for a holistic assessment of recycling options is the need for simultaneous consideration of a number of viewpoints. In this context, a number of general purpose multi-criteria decision making criteria have been developed, which are often complex processes to integrate multiple attributes from various viewpoints into a single measure of utility (Zeleny, 1982). Such multi-criteria analysis has been widely used in waste management and resource efficiency research due to its ability to integrate both monetary (economic) and non-monetary (environmental, social) criteria into a single assessment procedure. A range of theories and models used for the multi-criteria analysis are summarised in Table 1.

At present, the majority of product recovery and recycling practices put the main emphasis on economic benefits, and thus other aspects are often neglected. This is in contrast to the main principle of sustainability, in which ecological and social considerations are as important as economic performance. A number of performance indicators associated with each assessment consideration are listed in Table 2. Some of these indicators have been used by the proposed multi-criteria decision making tool, as outlined in the remaining section of this paper.

3. The multi-criteria assessment framework for robotic disassembly

The proposed multi-criteria framework for assessing robotic disassembly considers the three commonly used criteria for measuring the performance of similar applications, namely environmental benefits, technological feasibility and economic viability. This is achieved in two stages: 1) individual assessment for each criterion and 2) generating an overall sustainable performance based on a combination of the three criteria, as depicted in Fig. 1, and described below.

3.1. Stage 1: individual assessment for each criterion

The method used to assess the environmental benefits of robotic disassembly is adapted from the Reusability, Recyclability and Recoverability (RRR) approach proposed by Ardente and Mathieux (2012) in which a number of key issues associated with resource efficiency and waste management have been considered in parallel. In the RRR approach, the assessment method is based on three steps: i) Definition of the various feasible EoL scenarios for products under consideration, ii) Estimation of the recycling/recovery rate for different