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Product sustainability assessment for product life cycle

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ABSTRACT

The product sustainability assessment is a progress to evaluate sustainability with indicators for product sustainability in the whole product life cycle. However, the current approaches could not deal with the relationships of those closed-loop indicators. This paper is devoted to a graph theory-based product sustainability assessment approach to avoid those closed loops of the evaluation indicators. The hierarchical evaluation system for mechanical product sustainability assessment with energy, environmental, resource, technical, and economic indicators is proposed. The product sustainability assessment approach is proposed with five steps: rationalization of the directed graph of the evaluation system, construction of the hierarchical structure, transformation from reachability matrix to judgment matrix, consistency check and adjustment of judgment matrix, and indicator weight determination and comprehensive assessment of evaluation system. The product sustainability assessment of an underactuated exoskeleton robot is given as an example to demonstrate the proposed methodology.

1. Introduction

As a fundamental industry, manufacturing has made great contributions to the global development. The manufacturing also causes large amounts of energy and resources waste, as well as serious environmental pollution (He et al., 2018c; Huisingh et al., 2015; Khoshnevisan et al., 2015). For example, during the production process of industrial machinery, materials forming process would emit large amounts of exhaust gases, polluted airs, waste water, contaminated soils, and solid wastes (He and Gu, 2016; Ma and Kremer, 2015).

The concept of sustainable development has become an important topic (Caiado et al., 2017; Dyllick and Rost, 2017; Maxwell and van der Vorst, 2003). There are some sustainability assessment frameworks, such as World Business Council for Sustainable Development (WBCSD, 1997), and Organisation for Economic Co-operation and Development for Sustainable Development (OECD, 2002). Many researches have been focused on product sustainability assessment in recent decades (Singh et al., 2009), with a result of valuable contributions (He et al., 2015c, 2015f; Jeswiet and Kara, 2008). The current product sustainability assessment methods could be generally classified into two basic categories: one is a qualitative method, and the other is a quantitative method.

The qualitative methods always measure the quality of indicator rather than its quantity (Ritchie et al., 2013; Thoresen, 1999). A qualitative evaluation checklist is one of the typical qualitative methods (Luttropp and Lagerstedt, 2006). It is a set of indicators used to evaluate the product performance from the qualitative perspective (He and Hua, 2017). It is an easy, qualitative, and subjective way with extensive experience and knowledge. However, there remain many challenges with trade-offs between performance and requirement.

The quantitative evaluation is the systematic empirical investigation of evaluation indicators via statistical, mathematical or computational techniques (Ajukumar and Gandhi, 2013; Clavreul et al., 2014; Eddy et al., 2014). Many quantitative methods were proposed to solve product performance evaluation, such as Analytic Hierarchy Process (AHP) method (Bevilacqua and Braglia, 2000), weighted fuzzy approach (Ghadimi et al., 2012), dynamic programming (He et al., 2015b), directed graph and matrix method (Anand and Wani, 2010; Jangra et al., 2011), product life cycle assessment (He et al., 2015d), life cycle cost approach (He et al., 2015e; Jeong and Lee, 2009), neural network-based fuzzy evaluation (Svalina et al., 2013), relation-based method (Hu, 2014), uncertainty-based method (He et al., 2015a, 2018b), underactuated mechanism for green and lightweight design (Gao et al., 2018), function impact matrix (Devanathan et al., 2010), and structural optimization method (He et al., 2016). Goedkoop et al. (1996) introduced Eco-indicator 95 as a quantitative distance-target

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based on life cycle assessment (LCA) methodology. Fuzzy sustainability evaluation method, which was developed by Hemdi et al. (2013), helps the designers and decision makers to assess products and processes toward sustainability approaches with the consideration on environmental, economic and social aspects. Because of the complex relationships among various evaluation levels and indicators, these indicators might always have some closed loops in the evaluation system. However, all the above methods always focus on the quantification of evaluation indicators without considering the closed loop of those evaluation indicators during the product performance evaluation.

The product sustainability assessment is a progress to evaluate the sustainability of a product in its whole life cycle, which requires an evaluation system containing indicators for product sustainability. However, the relationships among these indicators would be quite complicated, which could be prone to lead that the lower-level indicators control the up-ones and thus to form a control loop among these indicators. Thus, it is difficult to build up a clear hierarchy evaluation system. This paper proposes a graph theory-base product sustainability assessment method to avoid the closed loop of those evaluation indicators. The method is applied to product sustainability assessment with a clear hierarchy for evaluation indicators. If necessary, the sustainability of different types of products could be assessed with the scores of comprehensive sustainability.

In this paper, an underactuated exoskeleton robot is chosen as an example to demonstrate the proposed methodology. As a robot is one of the most important machines in the manufacturing and service sectors, it is necessary to make the sustainability assessment in its life cycle. The product sustainability assessment of the robot is not just based on the amount of environmental footprint in the product life cycle, but also on the comprehensive influence of a variety of indicators: energy, environmental, resource, technical, and economic indicators.

This paper is devoted to product sustainability assessment method based on graph theory. The rest of the paper is organized as follows. In Section 2, the hierarchical product sustainability indicators for product sustainability assessment were put forward. In Section 3, the product sustainability assessment method based on graph theory was proposed. And case study was discussed in Section 4 in detail. Section 5 discussed with the international literature. Section 6 concluded this paper.

2. Product sustainability indicators for product sustainability assessment

The product sustainability indicators are increasingly recognised as a useful tool for product sustainability assessment, which always corporate performance in those fields, such as energy, environmental, resource, technical, and economic improvement. The product is always a complex component evaluated by multiple levels and multiple indicators. In order to deal with it, the primary problem is to develop a scientific and comprehensive product sustainability assessment system. The product sustainability assessment should pick out the main indicators to evaluate. From a systematic analysis of the current sustainability indicators from the literature (He et al., 2018a; Jain, 2005; Khan et al., 2004; Krajnc and Glavic, 2003), this paper proposes a general product sustainability indicator model for mechanical product in the manufacturing industry. The product sustainability assessment is a comprehensive evaluation with energy, environmental, resource, technical, and economic indicators.

(1) Energy indicator

Energy indicator includes energy efficiency, energy usage, clean energy usage rate, and energy consumption as well. The product consumes large amounts of energy in its life cycle, so it is necessary to improve energy efficiency, energy usage, and make use of clean energy as much as possible.

(2) Environmental Indicator

Environmental indicator aims to reduce ecological environment destruction in the product life cycle. It mainly considers environment-related indicators in the product life cycle, including exhaust gas emissions, waste water emissions, and solid waste emissions.

(3) Resource indicator

Resource indicator mainly considers the material resources and equipment resources in the product life cycle. Main evaluation indicators include material resource, equipment usage, equipment resource, material utilization ratio, equipment efficiency, and equipment failure rate.

(4) Technical indicator

Technical indicator reflects the product's reliability, precision, and product configuration. It is the primary problem to examine the basic technical properties describing the basic functions of the product to meet the technical indicator, such as reliability and precision of the product when evaluating the technical performance of the product. The product configuration could be always a factor for product technical innovation.

(5) Economic indicator

The economic indicator mainly includes the cost and the recyclable rate. The economic indicator of this paper does not only refer to the general cost of the product, but also the social environment impact in its life cycle.

The product sustainability assessment is an overall consideration with multiple levels and multiple indicators. Thus, the product sustainability indicators for product sustainability assessment are required in the evaluation process, as shown in Fig. 1.

3. Product sustainability assessment based on graph theory

The product sustainability assessment is a comprehensive evaluation process with the consideration of the product's energy, environmental, resource, technical and economic indicators, which is a multi-level and multi-indicator evaluation process with respect to the entire product life cycle. Because of the complex relationships among various levels and indicators, it is subjectively difficult to obtain reasonable and accurate hierarchical indicators and a judgment matrix to build up a clear hierarchical evaluation system. For example, all of three evaluation indicators: reliability, energy efficiency and product configuration, have impacts on the sustainability assessment of a product. But these evaluation indicators could be interlaced, rather than mutually independent. Morever, they may generate cycle control, which makes it difficult to build up a clear hierarchical evaluation system.

In this paper, the directed graph is used to establish a reasonable