Journal of Cleaner Production 51 (2013) 34–46

Contents lists available at SciVerse ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Evaluation of green maintenance initiatives in design and development of mechanical systems using an integrated approach

V.N. Ajukumar*, O.P. Gandhi

Industrial Tribology, Machine Dynamics and Maintenance Engineering Centre, Indian Institute of Technology, New Delhi 110016, India

ARTICLE INFO

Article history:
Received 20 April 2012
Received in revised form
4 January 2013
Accepted 7 January 2013
Available online 29 January 2013

Keywords:
Design for environment
Green maintenance
Multi-criteria decision making
Green product design
Digraph

ABSTRACT

The growing public concern on global environmental degradation is forcing many industries to undertake environmentally conscious policies for product design, manufacturing, service and end-of-life activities. Maintenance is a critical activity carried out in the use phase of the product life cycle to prolong system availability. The increasing amount of repairs and maintenance of machinery has become a burden on the environment. Therefore, green maintenance driven product design and maintenance actions are critically important; and organizations are now looking for methods and tools to assess the sustainability aspects of their design and operation. This paper presents an objective approach to evaluate green maintenance aspects of mechanical systems at its design stage and rank the design alternatives. It takes into consideration the green maintenance requirements, environment conscious attributes and their interrelationships. The evaluation problem is formulated as a multi-attribute decision-making model and solved using analytical hierarchy process (AHP) and the technique for order preference by similarity to ideal solution (TOPSIS) approach. The proposed approach starts with applying AHP method to evaluate the importance of green maintenance requirements during maintenance. Then the relationships between the requirements and design characteristics are established and the TOPSIS method is adopted to rank the design alternatives.

1. Introduction

Maintenance is a desirable activity in plant operation and it is the most efficient way to retain or restore the system to a desired level of performance. In addition to fulfilling the requirements of equipment inspection, lubrication and repair, it has an added responsibility of plant protection, pollution prevention, personnel safety and waste disposal. The increasing requirements of maintenance in the unproductive use phase of the product life cycle of mechanical systems produce significant impact on the environment; as defective parts, used oils, grease and cleaning agents are discarded into the environment. In this context, the designers and practising maintenance personnel are facing the challenge in responding: how to do the necessary maintenance, with minimum negative environmental impact? Moreover, various environmental regulations/policies have put pressures on the organizations to service, repair and dispose of their equipment in an environmentally friendly manner. Green maintenance enabled design of equipment and sustainable maintenance practices emerge as a solution to the problem.

Green maintenance is an attempt to make maintenance more environmentally benign by eliminating all waste streams associated with maintenance. Its activities involve the integration of product design issues with issues of maintenance planning and execution aimed at minimizing negative environmental effect; while at the same time ensuring health and safety of the personnel involved. This demand for understanding the green maintenance requirements during operation phase of maintenance and how these can be mapped onto design characteristics at the design stage. The challenge is to alter conventional design process to anticipate and assess environmental impacts during maintenance and to incorporate the green considerations systematically and effectively. This is significant as the environmental impact of maintenance associated with equipment is primarily decided at the design stage and secondarily, by the policies and steps followed during the operation phase of maintenance. Designers must therefore, be aware of the interrelationships between process and product design issues, and incorporate green aspects into design for eco-friendly maintenance, in addition to the conventional design variables.

* Corresponding author. Tel.: +91 9495925959.
E-mail address: vnaju@yahoo.com (V.N. Ajukumar).

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http://dx.doi.org/10.1016/j.jclepro.2013.01.010

Researchers have tried to minimize the negative impact of products on the environment by focusing on design for environment (DFE), as design is the process in which the most factors of the product life cycle are determined. Santos-Reyes and Lawlor-Wright (2001) described a structured approach to DFE for addressing the problem of integrating green concerns at an early product design phase. The approach suggested eco-principles and the measures of eco-performance that can be useful to choose alternative options for improving and quantifying product environmental performance. Madu et al. (2002) introduced a step-by-step approach for environmentally conscious design. Kuo et al. (2006) presented a green fuzzy design analysis (GFDA) to evaluate product design alternatives based on environmental consideration using fuzzy logic.

Efforts have also been made to analyze the environmental impact using various approaches during the stages of manufacturing, servicing and disposal. Life-cycle assessment (LCA) is one such approach, which identifies the environmental burden that arises from a product at its various stages of life cycle (Ishi, 1995). Hundal (1998) carried out the detailed analysis of various aspects of life cycle to be considered at the product development process. It was revealed that consideration of eco-design and waste prevention at the design stage is useful for successful development of the product. Yang (2007) developed an LCA based sustainable product design for eco-design support and for product LCA analysis at early design stages, using which the designers can compare material and energy consumptions, and to assess environmental impacts of different end-of-life treatment options.

Masui et al. (2003) presented a methodology for applying Quality Function Deployment (QFD) for environmentally conscious design in the early stage of product development. Watkins et al. (1995) developed the EcoSys system that integrates design information and expert system to perform environmental impact analyses during product design and manufacturing processes. As sustainability assessment principles, strategies and tools are on the rise, it is a challenge to integrate systems and sustainability perspectives into product design, manufacturing and delivering decisions (Wage, 2007). Fukushige et al. (2012) developed a representational scheme using which the life-cycle scenarios can be represented and the designer can easily derive requirements for product and process design to take care of later processes of life-cycle design. Recently, Anand and Wani (2010) presented an evaluation procedure for product life-cycle design at the conceptual stage in terms of life-cycle design index.

It is clear from the above that although maintenance being a significant contributor in prolonging the use phase of product life, particularly with mechanical systems, yet its role on negative environmental impact has not been adequately addressed. Existence of strong gap between green maintenance requirements and existing design practices is another matter to be taken care of. However, there are not many effective tools available either in assessing how the design can be altered in bringing and accommodating sustainability aspects in maintenance. Therefore, it is required to provide designers with appropriate tools to analyze and predict the impact at the early stages of the design. Such an assessment will help in devising design modifications and proposing maintenance policies/strategies catering to the design. This paper presents an approach that integrates AHP and TOPSIS to assist designers in identifying and incorporating green maintenance requirements with design characteristics, and help to achieve an effective evaluation of the final design. AHP will be used to evaluate the priority indices of the required green maintenance requirements. These green maintenance requirements are then correlated with the design characteristics to highlight the critical design features that must be included in the equipment design. The interrelationships among the design characteristics are also analyzed using graph theoretic techniques. On the other hand, TOPSIS will be used to evaluate the best design alternative by taking into consideration the extent to which each alternative is capable of meeting the green maintenance requirements. The paper is organized as follows. The green maintenance aspects, its issues, challenges and enabling features are explained briefly in Section 2. A brief description regarding the integrated approach of AHP and TOPSIS is presented in Section 3. An example is included to illustrate the application of the methodology in Section 4. Finally, Section 5 summarizes the results of this paper.

2. Green maintenance – features and characteristics

This section discusses the impact of maintenance on environment and the issues involved in incorporating environmentally benign features during design and operation. It also elaborates the features of green maintenance and identification of environment conscious attributes facilitating sustainable maintenance.

2.1. Maintenance and its impact on environment

Products impact the environment at various stages of its life cycle including during maintenance. Fig. 1 represents the stages in a product life cycle, starting from design to end-of-life activities. The environmental impact of the product at major stages of life cycle (EI_{lc}) is expressed by Sy and Mascle (2011) as

$$EI_{lc} = EI_{mat} + EI_{manuf} + EI_{use} + EI_{eol} \quad (1)$$

where EI_{mat}, EI_{manuf}, EI_{use} and EI_{eol} are, the environmental impact of the material needed to produce the component, the impact

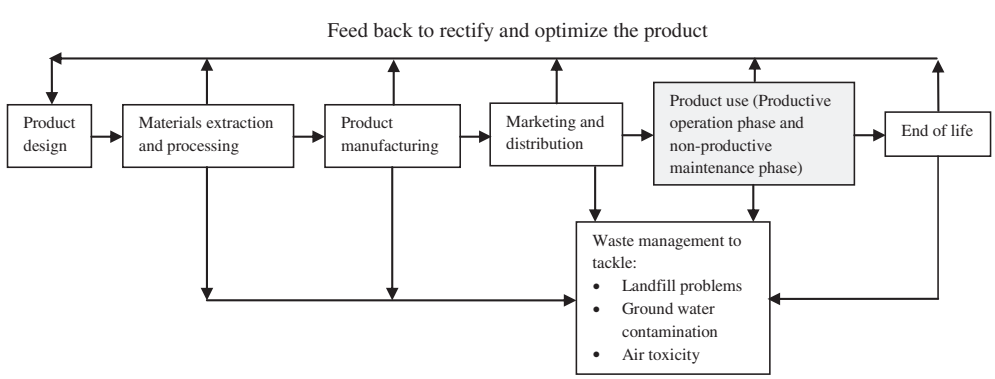

Fig. 1. Life-cycle stages of a product.