Computers in Industry 65 (2014) 480–490

Contents lists available at ScienceDirect

Computers in Industry

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

Design process and data models to support the design of sustainable remanufactured products

Virginie Goepp [a,*], Peggy Zwolinski [b,1], Emmanuel Caillaud [c,2]

[a] INSA de Strasbourg – ICube, 24, Bld de la Victoire, 67084 Strasbourg Cedex, France
[b] INP Grenoble – GSCOP, 46, Avenue Félix Viallet, 38031 Grenoble Cedex, France
[c] Université de Strasbourg – ICube, 24, Bld de la Victoire, 67084 Strasbourg Cedex, France

ARTICLE INFO

Article history:
Received 15 January 2013
Received in revised form 23 January 2014
Accepted 5 February 2014

Keywords:
Modelling
Design process
Design for environment
Design for remanufacturing
Remanufacturing
Eco-design

ABSTRACT

The need for increased levels of reuse and remanufacturing is driving the need for sustainable design of remanufactured products. It is acknowledged that design for remanufacturing benefits the environment. However, it seldom integrates eco-design approaches as it requires 'life cycle thinking' with closed-loop life cycles. The objective of this paper is to support eco-design of remanufactured products with design process and data models structuring the activities to be performed and providing the support required. We consider the development of two activities in particular: definition of the target, and environmental analysis. The first activity exploits the concept of RPP (Remanufacturable Product Profile), building on the criteria that are crucial for a successful remanufactured product. The second one exploits the life cycle brick concept that associates each product component with a specific life cycle and related environmental impacts. The models proposed are exploited in a case study concerning the design of remanufactured truck gearboxes.

1. Introduction

In today's world, sustainable development has become not only an unavoidable social issue but also a major challenge in industry. Companies therefore organise themselves in ways which enable them to apply eco-design, that is design focused 'on the integration of environmental considerations into product development' [1]. Regulation policies and business considerations generally drive eco-design [2], along with environmentally conscious manufacturing and product recovery [3].

Environmental legislation is becoming increasingly stringent, particularly in Europe [4], as recent developments such as the WEEE (Waste Electronics and Electrical Equipment) and ELV (End of Life Vehicle) Directives [5,6] attest. The ELV Directive states that in 2015, 95% of a vehicle will have to be recoverable or reusable. According to [7], this directive drives the need for increased levels of reuse and remanufacturing.

Remanufacturing is an industrial process involving the conversion of worn-out products into products in a condition that is like new [8]. The process generally includes sorting, inspection, disassembly, cleaning, reprocessing and reassembly. Parts which cannot be refurbished to original quality are replaced, meaning the final remanufactured product will be a combination of new and reused parts. It is generally acknowledged that whether a product is suitable for remanufacturing or not largely depends upon decisions made during the design process. There are specific product properties that may have a positive or negative effect on particular steps in the remanufacturing process, such as disassembly or cleaning. Therefore, research in the remanufacturing field concerns either: (i) the logistics problem linked to putting this end-of-life strategy into practice (for a detailed review of these problems see [9]); or (ii) its integration into the design process also called design for remanufacturing (DfRem) consisting in increasing the remanufacturability of a product. According to [10], many researchers do not consider DfRem as a simple 'DfX', as it cannot be considered isolated. A more 'remanufacturable' product may actually have inferior cost effectiveness and environmental performance when compared to a less 'remanufacturable' product. However, even if it is acknowledged that remanufacturing can benefit the environment [11], the eco-design dimension and other 'life cycle thinking' are seldom taken into account [10]. In many publications, environmental benefits related to remanufacturing

* Corresponding author. Tel.: +33 03 88 14 47 00; fax: +33 03 88 14 47 99.
E-mail addresses: virginie.goepp@insa-strasbourg.fr, goepp_virginie@yahoo.fr (V. Goepp), peggy.zwolinski@g-scop.inpg.fr (P. Zwolinski), emmanuel.caillaud@unistra.fr (E. Caillaud).
[1] Tel.: +33 04 76 82 52 74.
[2] Tel.: +33 03 88 14 47 00; fax: +33 03 88 14 47 99.

0166-3615/$ – see front matter © 2014 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.compind.2014.02.002

strategies are highlighted, but many losses along the supply chain are neglected (even if they can balance the benefits!). There is not a clear framework shared between LCA practitioners to define a functional unit to compare a remanufactured product to a manufactured one. Therefore, a real effort has to be made to consider simultaneously the impact coming from the product, from the industrial remanufacturing processes, and from all processes along the supply chain.

According to [12–14], eco-design success is linked to: (i) consideration of the environmental issues at the very beginning of the product development process; (ii) the effective application of tools and environmental design principles, rules and standards; and (iii) the availability of the information required in cross-functional teamwork. A way to foster these aspects is to provide a reference eco-design process and data models. The objective of this paper is therefore to develop such models for sustainable design of remanufactured products by instantiating and completing the reference model of the eco-design process in general, proposed in [15].

The paper is structured as follows. Section 2 describes the design process model of sustainable remanufactured products that we propose, based on the analysis of the model of Goepp, Rose and Caillaud [15]. Section 3 details the complementary data models formalising the data required to perform the activities of the process model. Both models are built following the enterprise modelling principles of the ISO 19439 standard for enterprise [16] with respect to the ISO 14062 technical report [17] and exploiting the knowledge of DfRem. Section 4 illustrates the exploitation of these models in the case of the sustainable design of a remanufactured truck gearbox. In Section 5, we draw some conclusions and outline directions for further research.

2. Design process model for sustainable remanufactured products

2.1. Principle of eco-design process reference modelling

The reference eco-design process model developed in [15] follows the ISO 19439 standard for enterprise modelling [16]. It is a business process model, that is, a model of: *a partially ordered set of enterprise activities that can be executed to achieve some desired end-result in pursuit of a given objective of an enterprise or a part of an enterprise* [16]. This model is built on the ISO TR 14062 standard [17] and related bibliography aimed at operationalising this standard. Thus, eco-design is regulated, within the ISO framework, under the banner of the ISO 14000 series. The global purpose of the ISO TR 14062 standard [17] is to govern the integration of environmental aspects into product design and development. As the design of a sustainable remanufactured product can be considered as the design of a product integrating environmental aspects, the reference eco-design process model fits our research concern.

Moreover, the activity modelling is done at a partial level, also called the reference level that captures characteristics common to many enterprises within or across one or more industrial sectors. Such models enable modelling process efficiency by allowing their reuse in a 'plug-and-play' manner rather than developing the models from scratch. From this point of view they can be exploited here. The sustainable remanufactured product design process can be built through instantiation of the eco-design reference model, which we present in the next section.

2.2. Eco-design process reference model

The backbone of the eco-design reference model is the six-stage typical model of product design and development proposed in [17]:

(1) Planning;
(2) Conceptual design;
(3) Detailed design;
(4) Testing/prototype;
(5) Production/launch on the market;
(6) Product review.

These stages are considered as six sub-processes of the eco-design reference model proposed. The sub-processes, modelled in the form of an UML activity diagram, are performed one after the other from the planning stage up to the product review, through conceptual and detailed design.

In order to build the design process model for sustainable remanufactured products, we propose to analyse these six models in order to identify the activities that are specific to sustainable remanufactured product design. These models are then instantiated by exploiting existing knowledge and work stemming from the DfRem field.

In this way, the model proposed enables us both to integrate the eco-design aspect into the design of remanufacturing products, and to pinpoint the design rules and standard of the remanufacturing field that can be applied. This is only a partial model for companies interested in sustainable remanufactured product design, as it still requires adaptation to each particular enterprise entity. However, the model proposed provides a shared view of the design process. This is essential to foster cross-functional teamwork [18] and to avoid the 'green wall' effect [19] caused by the separation of 'environmental divisions' and conventional structures. Thus, the proposed model promotes relational flows within and outside the company and the creation of a new network of actors.

2.3. From eco-design process model to sustainable remanufactured product model

2.3.1. Planning the sub-process

The objective of this sub-process is to work out the complete definition of the requirements (difference between what already exists and what should exist after design). It is structured around three basic activities (see Fig. 1):

- *Define the target:* this activity requires a prior feasibility study and repeated cross-checking with the company's strategy until the two match;
- *Perform an environmental analysis*: this activity requires one to choose an environmental analysis approach and identify a reference product;
- *Formulate the environmental requirements:* this is a synthesis of the environmental analysis.

To help the definition of the requirements for sustainable remanufactured products, two specific approaches related to the field of remanufacturable products are considered: (i) the first one using the concept of remanufactured product profiles (RPP) and (ii) the second one using a specific life cycle model and remanufacturing parameter to perform a LCA (Life Cycle Assessment) for remanufactured products. The idea is first to validate the economic viability and then to assess the environmental viability of the remanufactured product. In this way, the remanufacturing strategy can be validated from two points of view and a particular focus can be chosen to improve the main impacting elements of the system.

Use of RPP during the feasibility study: The first concept considered in the eco-design of remanufactured products is that of Remanufacturable Product Profiles (RPPs). RPPs have been drawn up by Lopez et al. [20], who extracted the factors affecting