ARTICLE IN PRESS

Resources, Conservation & Recycling xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

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

Full length article

Adaptive remanufacturing for multiple lifecycles: A case study in office furniture

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ARTICLE INFO

Keywords:
Circular economy
Closed-loop supply chain
Remanufacturing
Multiple lifecycle
Adaptive remanufacturing

ABSTRACT

Remanufacturing has achieved viability in a diversity of industrial markets as a means to both maintain the value of products and minimize waste. From carpet tiling to manufacturing robots, a wide range of goods have presently established supply and consumer networks that support remanufacturing, and thus offer a point of entry into a more circular industrial economy. Based on this performance, it is reasonable to expect that remanufacturing can in some cases be made an iterative endeavor; that existing networks may be leveraged to create additional lifecycles for previously remanufactured goods at net environmental and economic gain over virgin production. This case study identifies and explores factors of Davies Office, Inc. (Davies) remanufacturing processes for office furniture that affect the economic and environmental practicality of creating multiple remanufacturing cycles. Specifically, we use Life Cycle Assessment (LCA) to estimate the impacts of multiple remanufacturing cycles and how these are affected by "adaptive remanufacturing," a neologism to describe the use of an end-of-life (EOL) product core to create a similar, but non-identical product. LCA results suggest that adaptive remanufacturing is both an environmentally preferable and economically viable business strategy. Specifically, the ability to update, reconfigure, and customize previously obsolete products to meet present market demands enables lifecycle extension beyond what is achievable with traditional remanufacturing. In this, the study posits that such adaptive remanufacturing techniques not only expand the potential environmental benefits of remanufacturing, but enhances the long-term economic viability of remanufacturing in durable product markets.

1. Introduction

1.1. Remanufacturing

As resource scarcity, energy costs, and supply chain management emerge as important factors in the sustainability of modern manufacturing, steps must be taken to challenge the linearity of "take-make-waste" production models. In response to this need, remanufacturing of products through the isolation of used product cores, addition of new materials, and subsequent reconstruction of finished goods is becoming both a significant market player and a major focus of research (Yang et al., 2011). Broadly, remanufacturing involves returning a previously used product to a level of form and function effectively equivalent to when that product was new. In some cases, remanufacturing can upgrade a product to condition beyond its original state by, for example, correcting for original product design flaws or adding functional or aesthetic enhancements not present in the original product. Several studies demonstrate that remanufacturing operations consistently achieve energy savings (Sahni et al., 2010), cost savings (Abbey et al., 2015), and increased material efficiency (Gamage et al., 2008) relative to new products. Previous analyses of Davies Office Furniture by the National Center for Remanufacturing and Resource Recovery (NC3R) outline such savings and estimate resultant environmental benefits in the specific case of office furniture (NC3R, 2005).

The fundamental premise of remanufacturing is that it extends the life of a good in the product stream, maintaining its value (Bakker et al., 2014). With durable goods such as office furniture, this lifespan extension provides the opportunity to create additional lifecycles by remanufacturing a single product multiple times. However, this requires a reliable supply of virgin and previously remanufactured products whose durability and characteristics are such that the investment of further time, energy, and materials into their restoration remains both economically and environmentally preferable to virgin production. Assessment of this viability has uncertainty, as both environmental impacts and economic performance fluctuate with a number of variables. A study on the lifecycle environmental impacts of remanufacturing

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http://dx.doi.org/10.1016/j.resconrec.2017.07.028
Received 9 January 2017; Received in revised form 3 July 2017; Accepted 18 July 2017
0921-3449/

laser printer toner cartridges (Hilton, 2011) suggests that environmental impacts of multiple remanufacturing cycles increase with each additional cycle in comparison to the immediately preceding series. However, as each cycle is still less harmful than virgin production, net environmental benefit grows for a finite number of lifecycles. Krystofik et al. (2014) draw similar conclusions for refilling (i.e. remanufacturing) inkjet cartridges, but consider that transportation between end user and refilling service provider (i.e., remanufacturer) introduces considerable variability in actual environmental benefit.

Economically, remanufacturing as a hybrid component of primary manufacturing is known to be a profit-boosting strategy that can both reduce material costs and create complimentary revenue streams (Ayres et al., 1997; Chen and Chang, 2012). While remanufacturing cannot exist without virgin OEM production within incumbent economic structures, profitability in a remanufacturing-focused business model, like Davies, can be supported through cost-minimizing coordination of end-of-life (EOL) product collection and remanufacturing activities (Geyer et al., 2007). However, it is necessary to consider that like all products, office furniture has a finite degree of durability, and that as condition degrades with subsequent lifecycles, the material and energy intensity of remanufacturing—and thus the environmental and economic costs—may increase (Gallo et al., 2012).

1.2. Closed-loop supply chain

Contemporary manufacturing industries increasingly look to the concept of a circular economy as a means to reduce waste, avoid costs, and improve environmental footprints at the institutional level (Schulte, 2013). Central to this concept is the notion of a closed-loop supply chain; resource networks and processes that enable materials from products otherwise designated as waste to be utilized in a valuable manner (Guide et al., 2003). Within the context of office furniture, original equipment manufacturers (OEMs) are known to participate, to a degree, in circular planning through material recycling. Steelcase™ office panel systems are advertised to contain 46% recycled material and 71% EOL recyclable material (Steelcase, 2014). However, the Steelcase company does not itself engage directly in remanufacturing activities, relying instead on the acquisition of secondary material from an independent recycler. Thus, while the OEM supply chain incorporates a circular element, it is still primarily open-loop, as the majority of its material is derived from primary sources, and at least 29% of material components are disposed of at EOL stages (with the actual material recovery ratio likely falling below the full potential 71%).

In contrast, businesses such as Davies Office are well positioned to benefit from a more complete closed-loop model. Davies' primary raw material supply consists of finished, EOL office furniture products, a large portion of which would be sent to landfill disposal if not remanufactured. By creating additional lifecycles for material that would be otherwise discarded, Davies avoids the generation of nearly two tons of landfill waste for every hundred remanufactured office panels (NC3R, 2005). This diversion of otherwise wasted material to a value-added form is fundamental to the sustainable closed-loop supply chain approach (Winkler, 2011). Further, Davies' incoming office furniture cores are sourced from business-sector enterprises wherein finished products have reached the end of usable life through either condition degradation, business relocation or closure, or style preference change. Interestingly, this same sector of consumers makes up the customer population for Davies' products. In these respects, Davies currently embodies the circular economy model in two major ways: [1] its operations create valuable goods from waste products conventionally perceived to be of low value (Lacy and Rutqvist, 2015; Winkler, 2011) and [2] its logistics channels are structured to simultaneously minimize waste opportunities and maintain both a viable resource stream and consistent customer base (Savaskan et al., 2004).

1.3. Market adaptability

The examples mentioned in section 1.1 (Hilton, Krystofik et al., Ayres et al.)—and, indeed, much of the literature concerning multiple remanufacturing cycles—consider scenarios wherein either products are of relatively stable design or remanufacturing is conducted by OEMs who are able to dictate and anticipate changes in design. It is important to consider, however, that within the context of office furniture, third-party (non-OEM) remanufacturers have neither of these advantages; preferred styles in office furniture evolve rapidly with consumer demands, and remanufacturers only have access to product designs that already exist. As a result, remanufacturers must be able to account for and respond to changing design preferences if economic viability is to be maintained (Gu et al., 2004). In other words, because market preferences change rapidly, the original style and/or function of EOL office furniture products may already be obsolete, and thus noncompetitive, by the time of remanufacturing; remanufacturers are therefore challenged to create products that are *better* than their as-manufactured condition to achieve fitness for the current market. For example, while Davies has recognized a shift in customer preferences towards office divider panels that are shorter than years past, most incoming cores are still full-height. Davies restores some of these to their original condition—at full height—but also recognizes the opportunity to create products better suited to shifting preferences by reducing height and adding features more conducive to open work environments. From the customer perspective, this process, called "indexing," makes the product *better* for current markets than when it was as new, and thus more competitive with virgin products. Aziz et al. (2016) refer to this consideration as "designing for upgradability," and assert that an optimal strategy must maintain effective functional equivalence with the current virgin product market to preserve the economic viability of remanufacturing.

1.4. Multiple remanufacturing cycles

In light of these concepts, creating multiple remanufacturing cycles presents challenges that can potentially confound the determination of environmental impacts and, in some cases, limit profitability to a point of impracticality. One such challenge is that the virgin production supply chain, a linear, one-way model designed to sell as much virgin office furniture as possible, supports only an initial remanufacturing cycle by providing EOL products. Sustaining *multiple* remanufacturing cycles, however, requires a reverse supply stream of previously remanufactured products. Chen et al. (2015) illustrate that the consistency of such a supply stream is wrought with uncertainty; even if a reliable supply stream is identified, the variability of product type and condition within that stream is likely to be high. This is an essential consideration with respect to both material and energy intensities. As Gallo et al. (2012) highlight, wear, and thus required material and energy inputs for replacement or repair, increase with each additional lifecycle. As a result, additional lifecycles may also increase the degree of core fallout and the need to replace parts with virgin materials, corresponding to an increase in costs and environmental impacts. In addition, traditional systems that restore products to their original form may be hurt by variations in incoming product type that disrupt the consistency of product availability, thereby requiring virgin material integration to make up for potential supply deficits of suitable cores.

Given these realities, it seems a physical inevitability that creating additional remanufacturing cycles will at some point result in a high enough energy and material impact that virgin production is actually preferable to extending product life any further. With respect to office furniture, welding and powder coating are the most significant contributors to CED in virgin production (Dietz, 2005). Likewise, previous analyses suggest Davies' most common remanufacturing activities are cutting, welding, powder coating, and reupholstering associated with design reconfiguration (NC3R, 2005). Beyond in-house manufacturing