International Journal of Computer Integrated Manufacturing, Vol. 20, No. 8, December 2007, 773 – 780

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A review of research towards computer integrated demanufacturing for materials recovery

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The recovery of both toxic and non-toxic materials from billions of end-of-life electronics calls for efficient processes and exploration of opportunities for computer integrated demanufacturing for materials recovery. To date, recycling automation for selective disassembly has been limited by the proliferation of product designs, the difficulty of acquiring product feature and material content information, and the lack of integration of collection and demanufacturing processing. Product designs with standard modules and standard fasteners would improve the options for more automated disassembly. Making product structure and material composition information from a product design profile available will support planning models, Petri net algorithms and control models for demanufacturing, as well as integrated manufacturing and demanufacturing. Advances in imaging and materials identification techniques as well as more flexible technologies to separate materials may provide new opportunities for expert Petri net approaches for selective robotic disassembly. Linking end-of-life product service demand information will enhance scheduling for demand-driven demanufacturing. Nonetheless, the random arrival of so many different product sizes and design structures will require new approaches to designing reverse logistics networks and linking their activities. The present paper reviews the research to automate materials recovery planning and control, identifies challenges, and discusses directions for future research.

Keywords: Recycling; Disassembly; Computer integrated demanufacturing

1. Introduction

Computer integrated manufacturing seeks to coordinate design, planning, scheduling and control of manufacturing operations to improve price, customization, product development and delivery lead-times (Rogers *et al*. 1992). Extending this concept to electronics demanufacturing operations may reduce costs, enhance the development and processing of components, improve various material grades from billions of end-of-life electronics, and decrease environmental impact. The current product flow for electronics, illustrated in figure 1, shows that electronics may be disposed or demanufactured. Disposal may include landfilling or incineration.

Electronics recycling companies may demanufacture thousands of different incoming products to remanufacture them for resale, recover components for resale and/or separate materials for recycling. Research in remanufacturing, the complete disassembly, repair and re-assembly of products, serves to extend product life cycles (Bras and McIntosh 1999, Guide *et al*. 1999). However, low prices for new electronics and fast obsolescence limit opportunities for product and component resale of consumer electronics. Instead, companies are developing strategic initiatives to increase the sustainability of their resources (Preston 2001, Stevels 2002). Materials recovery is critical to recapturing nonrenewable resources (Graedel and Klee 2002). As the number of discarded electronics increases, recycling legislation is enacted, reuse options face obsolescence and price limits, data security concerns rise, and hazardous materials recovery is promoted, the potential demand for materials separation of billions of electronics warrants examination

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International Journal of Computer Integrated Manufacturing
ISSN 0951-192X print/ISSN 1362-3052 online © 2007 Taylor & Francis
http://www.tandf.co.uk/journals
DOI: 10.1080/09511920601079322

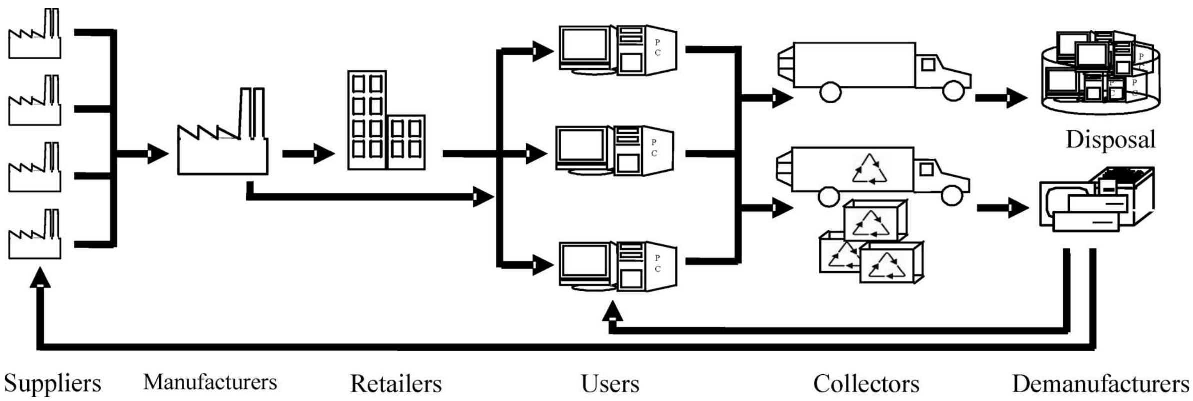

Figure 1. Current product flow.

of the potential for computer integrated demanufacturing for materials recycling. In the current paper, demanufacturing for materials recycling refers to pre-sorting and selective disassembly followed by size reduction and materials identification and separation. Operations may include shredding, grinding, magnetic, and density separation processes.

The remainder of the present paper is structured as follows. First, we review research to link design to demanufacturing and the technology to capture product design information. Next, we examine how product design information can improve demanufacturing planning, scheduling, and control. We close with a discussion of the systemic challenges to computer integrated demanufacturing and discuss important areas for future research.

2. Linking design to computer integrated demanufacturing

Opportunities to automate demanufacturing tasks for product or part reuse are enhanced if electronics designers employ modules, part commonality, and standard fasteners (Keoleian and Menerey 1994, Gu *et al.* 1997, Taleb *et al.* 1997, Stuart and Sommerville 1998, Westkamper *et al.* 1999, Lenox *et al.* 2000, Lewis *et al.* 2000, Sand *et al.* 2002, Anastas and Zimmerman 2003, Dobrescu and Reich 2003, Fujimoto *et al.* 2003, Okumura *et al.* 2003). Robotic systems for demanufacturing require the development of product design for automated disassembly, sensory systems, databases and control systems (Tang *et al.* 2002). To reduce the end-of-life processing challenges related to toxicity and emissions, design evaluation that considers environmentally weighted recyclability rather than simple weight basis calculations are recommended (Chen *et al.* 1994, Huisman *et al.* 2003).

Automating the product redesign task with recovery value, disassembly, and design modification algorithms may improve product recyclability (Dowie *et al.* 1995, Kroll *et al.* 1996, Pnueli and Zussman 1997, Viswanathan and Allada 2001, Rose *et al.* 2002). Sensitivity analysis is needed for design evaluations since demanufacturing choices may change based on product condition, the development of new automated demanufacturing technologies, commodity market fluctuations, and reverse logistics network design (Lee and Ishii 1997, Masanet *et al.* 2002, Krikke *et al.* 2003).

Currently, third-party demanufacturers do not receive product design information from other entities in the product supply chain illustrated in figure 1. A product environmental profile may include product structure, fasteners, material content and environmental attributes. Product design information to support computer integrated demanufacturing may be centralized in a company database as indicated in figure 2 or decentralized in a product life cycle unit that acquires and stores information throughout the product life cycle as shown in figure 3 (Scheidt and Zong 1994, Klausner *et al.* 1998, Seliger *et al.* 2001). Centralized product information management requires links between reverse supply chain entities. Product design data may aid demanufacturing planning for reuse and recycling (Spath 1994, Zeid *et al.* 1996, Grenchus *et al.* 1998, Kuo *et al.* 2000, Chung *et al.* 2003, Das *et al.* 2003, Peng *et al.* 2003).

A significant challenge in computer integrated demanufacturing is obtaining information about the product design and the current state of the recycling network. Product disposition decisions in computer integrated demanufacturing require assessment of the product structure and materials, the current location and quantity of inventory, and the status of operating capacity of the demanufacturing facility(s). Product knowledge may be acquired through a product information system (Scheidt and Zong 1994, Klausner *et al.* 1998, Seliger *et al.* 2001), a barcode (Rogers and Tibben-Lembke 1999, Baumgarten *et al.* 2003, Thomas 2003), a radio frequency identification (RFID) tag (Rogers and Tibben-Lembke 1999, Thomas 2003), sensor (Scheidt and Zong 1994, Seliger *et al.* 2001), symbols (Rios *et al.*

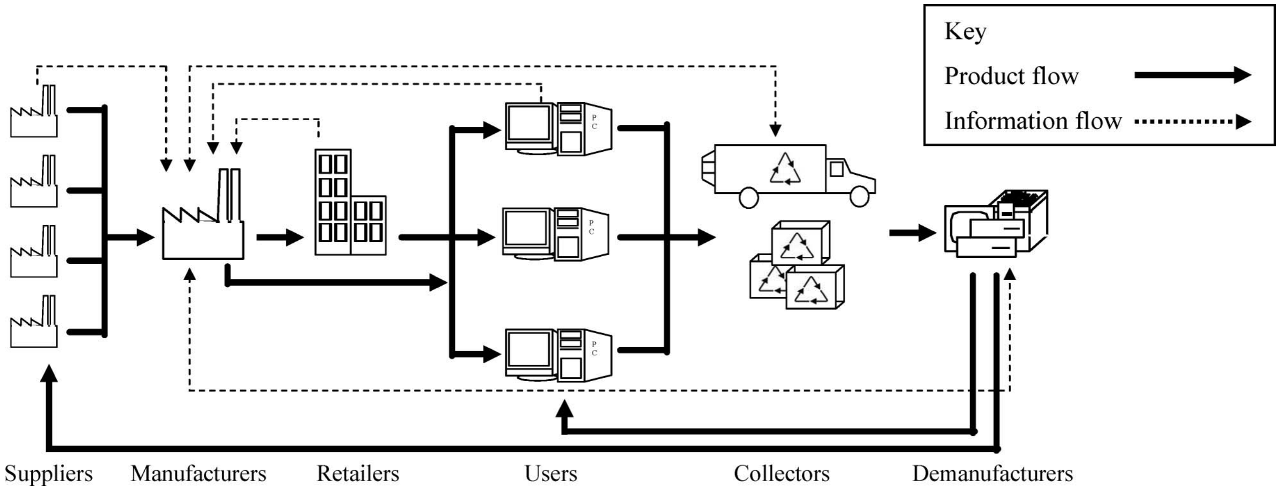

Figure 2. Future centralized information flow for product environmental profile.

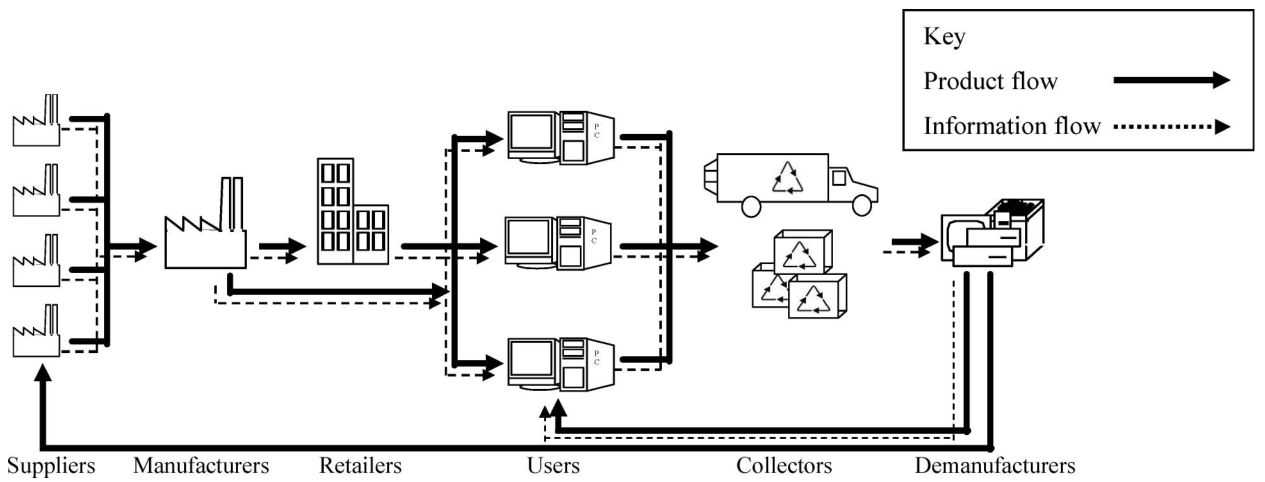

Figure 3. Future decentralized information flow for product environmental profile in which information is embedded in the product.

2003), prior experience with the product or experimental tests. The challenge with a product information system is that the forward supply chain for electronics is a complex web of many different subcontractors. The product material information approach requires capturing and coordinating information from many different component manufacturers and preserving the link between this information and the product in a way that is accessible to third-party recyclers many years later (Scheidt and Zong 1994, Klausner 1998, Seliger *et al.* 2001). A further complicating factor is that the product may undergo upgrades and repairs throughout its useful product life cycle that change the product structure and material content information (Scheidt and Zong 1994, Klausner 1998, Seliger *et al.* 2001). A bar code or sensor may suffer damage during product use. On the other hand, product labels need to be evaluated for materials recycling compatibility (Suoss *et al.* 1999). Prior experience with the product depends on a resident expert. Finally, physical testing requires time, labour or robotics, and equipment-intensive tests to determine the current product structure and material composition of each end-of-life product arrival. Important research questions include how much information to acquire through what means to demanufacture a variety of products.

3. Research to integrate production planning for manufacturing and demanufacturing

Design for demanufacturing initiatives enhance efforts to integrate manufacturing and demanufacturing planning.

Integrated production planning for the product life cycle stages, manufacturing and recycling, is modelled in (Clegg *et al.* 1995, Hoshino *et al.* 1995, Spengler *et al.* 1997, Sandborn and Murphy 1999, Stuart *et al.* 1999). Westkamper *et al.* (1999) recommend integrating disassembly with excess assembly capacity. Disassembly is reviewed extensively in (Srinivasan *et al.* 1997, Zhang *et al.* 1997, O'Shea *et al.* 1998, Gungor and Gupta 1999, Lee *et al.* 2001, Lambert 2003). Disassembly analysis seeks the depth that maximizes the ratio of the value of the disassembled components to the disassembly cost (Viswanathan and Allada 2001). Integrating manufacturing and demanufacturing operations calls for demand-driven disassembly planning approaches such as those presented in (Taleb and Gupta 1997, Kongar and Gupta 2002, Lambert and Gupta 2002). An interesting challenge is to develop methods for computer integrated manufacturing and demanufacturing (CIMD).

4. Demanufacturing planning and scheduling research

Demanufacturing planning for disassembly, remanufacturing, materials recovery, and/or disposal is modelled in (Johnson and Wang 1995, Gupta and McLean 1996, Johnson and Wang 1998, Krikke *et al.* 1998, Lambert 1999, Gupta and Veerakamolmal 2001, Ploog and Spengler 2002, Lu and Stuart 2003, Lu *et al.* 2004, Spengler *et al.* 2003). Kanai *et al.* (1999) discuss an information modelling system to link disassembly, shredding and material sorting decisions.

Sodhi and Reimer (2003) introduce separate discrete optimization models for planning collection, mechanical processing, and smelting operations. Nagurney and Toyasak (2005) develop a model to link these decisions to the prices and material shipments between end-of-life electronics sources, recyclers, processors, and suppliers for deterministic scenarios. Future extensions for this framework are to consider random quantities and qualities of end-of-life electronics as well as random demands by suppliers.

While manufacturing and disassembly scheduling for product and part reuse may seek to optimize traditional metrics related to product demand due dates (Lee *et al.* 2001, Neuedorf *et al.* 2001, Tang *et al.* 2001, Ranky *et al.* 2003), scheduling for materials recovery may focus instead on timely processing of random arrivals. A demanufacturing centre may have little control over the arrival rate of truckloads with end-of-life products. Therefore, supply-based demanufacturing scheduling strategies were developed to reduce the staging space requirements for highly variable receipts in (Stuart and Christina 2003).

Examples of procedures which automatically generate demanufacturing sequences require the product computer-aided design (CAD) file as well as the product bill of materials, part mating data, material content, and the value of recovered materials (Gungor and Gupta 1998, Srinivasan *et al.* 1999, Srinivasan and Gadh 2000, Dini *et al.* 2001, Erdos *et al.* 2001, Das *et al.* 2003). For example, if product topology, mating and precedence relations are available for a product, a disassembly Petri net can be used to generate an optimal disassembly plan (Zussman and Zhou 1999, Zha and Lim 2000). Zha and Lim (2000) and Singh *et al.* (2003) discuss disassembly Petri net complexity problems with respect to the size of the net and propose expert Petri net models to reduce complexity. Singh *et al.* (2003) show how to generate a low-level expert Petri net for robotic disassembly sequencing for a given product design and its corresponding input and output arcs and disassembly transition costs. Tang *et al.* (2001) develop Petri net algorithms for an integrated flexible demanufacturing system. Ranky *et al.* (2003) present demanufacturing control software that uses design inputs such as disassembly task precedence and processing time. This body of research demonstrates the feasibility of linking design to computer integrated demanufacturing to improve planning, scheduling and control.

5. Directions for future research

Many challenges remain, owing to lack of collection infrastructure, supply chain links for information management, and adequate demanufacturing technology. Directions for future research are discussed in each of these areas.

Multiples types of collection methods and random return rates characterize reverse logistics for end-of-life electronics (Scholz-Reiter *et al.* 1999, Lonn *et al.* 2002). Collection methods include curbside pick-up, permanent drop-off centres, special event drop-off sites, and shipment collection (Jung 1998, Glazebrook and Beling 1999, Butler and Hooper 2000, Hainault *et al.* 2000, The Associated Press 2000, Macauley *et al.* 2001). Returns forecasting is complicated by variability in the quantity, types and conditions of end-of-life products (Marx-Gomez *et al.* 2000, Stuart *et al.* 1998). The design of reverse logistics networks has focused on the location allocation problem to reduce demanufacturing facility start-up and transportation costs (Fleischmann *et al.* 1997, Listes and Dekker 2005). New research to integrate product related design with reverse logistics network design indicates that the former most directly impacts energy and waste while the latter most significantly impacts systemic costs (Krikke *et al.* 2003).

An important extension for future research is the integration of reverse logistics routing with flexible reconfigurable disassembly facilities (Sommer-Dittrich *et al.* 2003). Manufacturers seek a reliable supply and quality of recovered products and materials, such as plastics (Sharfman *et al.* 2001, Boks and Tempelman

1998, Dillon 1999, Dillon and Aqua 2000). Research to integrate collection with automated manufacturing, remanufacturing, and recycling systems may improve overall supply chain efficiency. However, global transportation impacts should be included in analysing the environmental impacts of remanufacturing and recycling enterprises (Skerlos *et al.* 2003).

Varying collection rates often result in small batch sizes of similar products at product take-back centres, which increase the system requirements for perception technology, material handling equipment flexibility and set-up time to adjust jigs, fixtures and tools for different batches. Even if collection is managed with web-based decision support systems (Bhargava and Tettelbach 1997, Electronic Industries Alliance 2003, Environmental Health Center 2003), the diversity of products collected from residential sources is high due to technology obsolescence. For example, 1800 different cell phone models are registered with the European Telecommunications Standards Institute (Saar 2004). When other types of electronics are added to the list of models that may be collected for end-of-life processing, the number of models grows by orders of magnitude.

Product information management has not developed such that equipment end-of-life processors can easily access product design and material content information (White *et al.* 2003). Even if barcodes and product tags are placed on products at time of manufacture, the end-of-life processing system must be able to access and read them (Saar and Thomas 2003). Furthermore, random product conditions may occur including damage, rust, dust, oil, missing or added components which also cause difficulties in designing robust automated disassembly systems (Boks and Tempelman 1998, Steinhilper 1998). Despite these challenges, Gungor and Gupta (1999) point out that disassembly labour, time, cost and human exposure to hazardous materials are important motivating factors to automate disassembly operations.

Hula *et al.* (2003) show that end-of-life processing solutions with both economic and environmental objectives are very sensitive to labour costs. Important strategic planning questions to evaluate are the transportation, overhead, energy, labour and processing costs and benefits of an extended network of recycling companies carrying out different recycling tasks versus bringing different recycling tasks into one facility (Mann 1996). Cost accounting that represents economies of scale for processing multiple products in a reverse logistics network is needed to extend deterministic optimization models to multi-product scenarios (Krikke *et al.* 1999). Similar to remanufacturing, inventory control and holding costs need to be analysed for materials recovery operations (Teunter *et al.* 2000). Research is needed to integrate decision making for collection, pre-sorting and processing to optimize the material recovery system (Murphy *et al.* 2001).

6. Conclusions

As billions of end-of-life electronics are retired, the need for efficient component and materials recovery is escalating. When the end-of-life electronics are organized by common materials and/or structures, there is potential for automated processing. Yet, only a limited level of automation has been realized in electronics recycling to recover ferrous metals and some non-ferrous metals. Clearly, product design and redesign that employ standard modules and standard fasteners may enhance opportunities for computer integrated demanufacturing.

Tools to advance computer integrated demanufacturing are reviewed in the present paper. While these tools include disassembly Petri net algorithms, their adoption has been hampered by the lack of available end-of-life product feature information such as the computer aided design file, topology, mating and precedence relations and material content. Important to computer integrated demanufacturing are product design information management, planning and scheduling.

Product design information management may be centralized or decentralized. In either case, up-to-date product design and material content information needs to be easily accessible to demanufacturers. For example, even if barcodes and product tags are attached to products at time of manufacture, their information may require revision during the product lifetime and the demanufacturer must be able to access and read them.

Another important end-of-life product information management challenge is the management of new product, used product and end-of-life product service demand. Demand-driven selective disassembly planning will require advances in reserve supply chain information sharing. In addition to developing and implementing product information systems, computer integrated demanufacturing processes will require information from the collection networks, product receipts inventory and forecasts, work-in-process inventory, operating capacity, finished goods accumulation to fill orders and part and material demand forecasts.

Future scheduling for automated demanufacturing requires careful thought regarding where in the reverse supply network to sort products to combat widely varying product sizes and design features. Automated scheduling for materials recovery may call for automated materials identification earlier in the reverse supply network. An important gap in the research is reverse logistics network design to organize various products for automated recovery of parts and materials.

Since expert Petri net approaches for selective robotic disassembly require task precedence relationships and processing times, advances may include new approaches to integrating imaging and materials identification techniques as well as new processing technologies to separate materials. For example, future material recovery systems may seek to identify high concentrations of desirable materials for removal with destructive automated disassembly techniques. Planning and scheduling to determine when to remove which types of materials in what concentrations will require demand and inventory information links for the reverse supply network. Future research to automate product demanufacturing will require creative solutions to identify common product structures and flexible separation techniques.

Acknowledgement

This research was supported by National Science Foundation grants DMII-0049074 and BES-0124761. Any opinions, findings and conclusions or recommendations expressed in this paper are those of the author and do not necessarily reflect the views of the National Science Foundation.

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