Extreme E-waste generated from successful Operations Management? More focus on Design for Repair for Extension of Life

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Abstract

This paper identifies how research in the field of Operations Management (OM) has been extremely successful in reducing costs for the manufacturing of electrical and electronic equipment by focusing on design for assembly and manufacturing. The downside is the generation of extreme amounts of e-waste. Based on a literature survey, 2251 kg of e-waste and on case study, this research identifies the need to extend product lifetimes to drive down e-waste. The study concludes that more research is needed on designs for disassembly, repair, refurbishment, and remanufacturing to meet future requirements for reduction of e-waste, and greater support from legislation.

Keywords: extreme e-waste, design for repair, modularization.

Introduction:

Operations Management (OM) has been extremely successful in manufacturing domestic goods such as electrical and electronic equipment, and that success has resulted in a remarkable cost reduction (Baldé et al., 2017). New and improved methods for manufacturing have produced affordable electrical and electronic equipment for domestic tasks such as cleaning, washing, preparing and preserving food, for educating and being entertained. The huge reduction of cost can be attributed to the development of a variety of new materials and much more efficient manufacturing methods like the Design for Manufacturability (Bralla, 1999), the development of assembly processes into Design for Assembly (Boothroyd & Alting, 1992), and later Lean Assembly (Baudin, 2002). These efficient methods have dramatically reduced costs on electrical and electronic equipment. Even though King and Burgess (2006) identified a 40% increase in the price of washing machines from the 1980s to the 1990s they also noted that the repair cost increased by 165% over this period. A personal observation from one of the authors of this paper affirms his first washing machine cost 750 Euro in 1986 and his latest, larger, and more modern machine purchased in 2017 was just 400 Euro.

While the development of advanced manufacturing methods has been extremely successful in manufacturing a large variety of products at low cost, this efficiency has created an unanticipated challenge. Products are easy to manufacture but very difficult to disassemble and to repair. Electrical and electronic products most often serve a short lifetime and are discarded despite their continuing functionality (Parajuly, 2017). The result is that globally, enormous volumes of electrical and electronic equipment waste (WEEE) are generated (Baldé et al., 2017; EU 2017; Parajuly, 2017). WEEE embodies, in fact, one of the fastest growing waste streams in the EU, with 9 million tons generated in 2005 and more than 12 million tons expected by 2020 (EU, 2018). The EU has taken initiatives to reduce WEEE through the Extended Producer Responsibility initiative (European Commission, 2014), in which producers shoulder the responsibility for collecting or taking back used goods for their eventual recycling.

In 2010, Stephen Childe, chief editor of the journal Production Planning & Control, announced a need for more studies of *"How can we manage the repair of more used products?"* (Childe, 2010). This paper argues that research emphasizing the reduction of e-waste falls short in traditional OM literature studies. Most scholarly attention is devoted to manufacturing, cost reduction, efficiency, and to service but there is very little on repair, reduction, or the growing challenges of e-waste.

Because traditional OM research focuses primarily on cost reduction in manufacturing and ease of assembly, less attention is given to future agenda such as longevity, disassembly, service, and repair. Hence, this paper strives to explore:
Where does operations management literature focus on reducing e-waste, and how can electrical and electronic equipment be developed for service and repair through modularization to extend product lifetime and to reduce e-waste?

In its focus on e-waste, the paper is structured as follows. First, a literature survey investigates to what extent OM literature explores improving manufacturing through a focus on cost, efficiency, lean methods, and assembly. Secondly, we look at how OM literature focuses on e-waste, disassembly, and repair. Then we introduce the methodology and a case study, and finally, we present our analyses and discussion before recommending future operations management research.

Methodology and case description

This study uses the definition by the United Nations (UN) Global e-waste monitor (Baldé et al., 2017). The UN e-waste monitor divides e-waste into six different categories. However, because e-waste is a rather broad field, this study focuses on their category 5, which covers small equipment, typical vacuum cleaners, microwaves, toasters, electric kettles, electric shavers, and so forth. E-waste from temperature exchangers such as refrigerators, freezers, air conditioners, and large equipment like washing machines, dryers, dishwashers, and other small IT and telecommunication equipment are left out.

The empirical study is based on 2251 kg (1505 items) of small household appliances of e-waste from a typical Danish municipal recycling centre. Luminaries constituted the highest volume of e-waste with 88,8 Kg (129 items). However, because vacuum cleaners constituted a complete product and by far the highest weight, 233,52 kg (46 items) of the sample, a deeper investigation of vacuum cleaners was selected; other e-waste is not included in this research. 13 randomly chosen vacuum cleaners have been systematically investigated for their common malfunctions, disassembly, and requirements for repair.

To generate a deeper understanding of the complexity of repair, service, and extension of product life for vacuum cleaners, a single case study, inspired by Eisenhardt (1989), Voss et al. (2002) and Yin (2014), has been conducted at one of the few remaining repair shops for electrical equipment in Denmark.

Literature review

As described in the introduction, this research has identified that the traditional OM literature connected to the EurOMA community has a high focus on cost reduction and efficiency. Table 1 below illustrates this focus through an investigation of five journals central to the field of OM: *Production Planning & Control* (PPC), *Journal of Manufacturing Technology Management* (JMTM), *Journal of Operations Management* (JOM), *Production and Operations Management Journal* (POM), and *International Journal of Operations and Production Management* (IJOPM). All five journals are normally represented at EurOMA conferences. Table 1 details research of *cost, efficiency, Lean* methodology, *service*, and other factors that are often investigated within OM literature. These keywords were employed to search "everywhere/anywhere" in the five journals.

Table 1: Focus areas from five OM journals

Jour-nal	*Cost*	*Efficient (cy)*	*Lean*	*Assemble*	*Service*	*Modulari (s)zation*	*Repair*	*E-waste*	*WEEE*	*Disassem ble*
PPC	1716	1085	2216	630	1303	24	287	289	11	31
JMTM	1353	1082	347	302	980	27	177	407	6	26
JOM	1166	933	214	253	1166	105	153	140	3	16
POM	1355	863	92	142	1098	10	118	160	19	21
IJOPM	2028	1515	497	353	1705	42	263	598	4	17

Surprisingly, the very successful manufacturing of electrical and electronics equipment seems to have a dark side, which is the generation of massive amounts of e-waste. According to the UN (Baldé et al., 2017), rich countries generate much more e-waste when compared to poor countries. For instance, countries like Norway and the United Kingdom generate the highest quantity of e-waste per inhabitant in Europe (respectively 28.5 kg/inh and 24,9 kg/inh), whereas countries like Albania, Bulgaria, and Romania generate only 7.1 kg/inh, 11.1 kg/inh and 11.6 kg/inh respectively of e-waste pr year. Although environmental issues and sustainability are on the agenda all over the world, the subject of this study demonstrates only a minor focus in traditional OM literature. Table 1 illustrates how terms such as *repair, disassemble, E-waste,* and *WEEE* appear to a minor degree when searching "everywhere/anywhere" in the five OM journals and when comparing to the first mentioned search terms.

<u>Design for manufacturing/assembly vs. design for disassembly and repair</u>

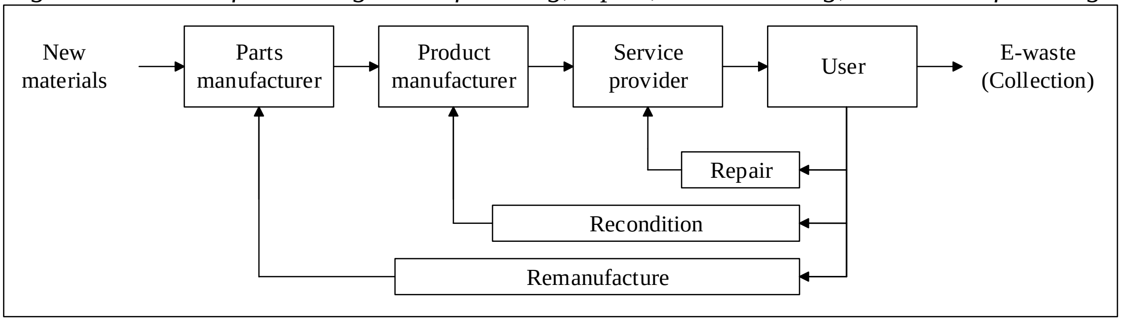
As illustrated in Table 1, the terms "assemble," "disassemble," and "repair" are a focus of this study. Other subject areas, such as "design for manufacturing" and "design for assembly" have been on the OM agenda for many years. Within the electronic industry, Boothroyd and Knight (1993) developed software for Design for Manufacturing and Assemble as early as 1980 to meet requirements from concurrent engineering and to support new organizational structures where designers and manufacturing engineers worked together in their development of new products. Boothroyd and Alting (1992) were concerned about environmental protection, occupational health, and resource utilization. Therefore, the models for Design for Disassembly were developed (Boothroyd and Alting, 1992) and even a whole life-cycle design concept was developed by Alting (1991).

In disassembling mechanical systems, Cappelli et al. (2007) designed a method for an optimal disassembly sequence, and Nahas et al. (2014) generated solutions in the selection of machines and buffers in unreliable assembly/disassembly manufacturing networks.

Few literature reviews have been made to identity taxonomies of assembly and disassembly (Hatcher et al., 2011; Ghandi and Masehian, 2015). However, in a comprehensive review of assembly and disassembly path planning, Ghandi and Masehian (2015) identified studies where surveys and reviews were related to two main subproblems, including: 1) Assembly/Disassembly Sequence Planning, and 2) Assembly/Disassembly Line Balancing. However, no comprehensive studies are identified in relation to 3) Assembly/Disassembly Path Planning (ADPP), even though the ADPP was identified to play an important role in the design process of products as invaluable tools for deploying concurrent engineering, end-of-life processing, maintenance, and repair.

Figure 1 illustrates a workflow in the extension of a product's lifetime by its repairing, reconditioning, or remanufacturing. The figure is inspired by King et al. (2006) and studies at the Ellen MacArthur Foundation (2016). The two studies emphasize the reuse and extension of a product's lifetime. Figure 1 illustrates how the repair constitutes a first step carried out by a service provider. Reconditioning is more complicated and involves much more work than repairing; it is expected that major components may be at the point of failure and will need to be rebuilt or replaced in the reconditioning process (King et al., 2006). The "remanufacture" illustrated in Figure 1 will, like refurbishment, require that parts be disassembled and then overhauled before they can be reused in new products. It is important to note that the energy required for remanufacturing is only 20-25% of the energy needed to manufacture new parts (King et al., 2006). This finding is also supported by Parajuly (2017) who identified that material losses and energy consumption can be far much lower if products are repaired or reconditioned.

Figure 1. Material flow through manufacturing, repair, reconditioning, and remanufacturing



<u>Modularization of service and of products to extend lifetime</u>

Modularization has traditionally been used to meet customer demand where different products could be manufactured from a base of modules (Starr, 1965 & 2010). The concept of modularization then moved from the field of manufacturing to other parts of OM such as service. For instance, Voss and Hsuan (2009) made a study of how modularization could be used to structure a variety of different services on cruise ships. De Blok et al. (2010) studied how modular care and service packages could be developed to support independent living for the elderly in a Dutch context. Petersen et al. (2016) pursued how modularization might be utilized in the maintenance of large offshore wind power farms to meet the requirement for constantly reorganizing and rescheduling maintenance in a harsh and fluctuating environment that depends on the weather.

Multiple studies illustrate that electrical and electronic equipment are easy to manufacture and assemble but call for modularization to ease disassembly and repair (Bogue, 2007). Therefore, ideas from modularization will contribute in this study to steps of repair, refurbishment, and remanufacturing (Figure 1) and to identify how modularization can be used as a concept to extend the lifetime of products which will reduce e-waste.

<u>Legislation as a support for repair and reduction of e-waste?</u>

In decreasing the volume of e-waste, legislation can be an important parameter to encourage more repair, refurbishment, and remanufacturing and, in that way, to force original equipment manufacturers (OEMs) to extend the lifetime of manufactured products. Several movements in the US, from farmers owning tractors to owners of smartphones and printers, have fought for the "Right to Repair." For instance, the State of New York enacted a "Fair Repair Act" (2015) to compel OEMs to give the same diagnostic, repair, and remote communication capabilities that are available to their own repair and engineering staff. Similar legislation in the EU (Regulation (EC) No 595/2009) has made customers' repair and maintenance of cars much easier. Through the EU legislation, OEM car manufacturers have been forced give free access to maintenance and repair guides. Costs for maintenance and repair of cars have been driven down in the EU as individual and free repair shops have become competitive compared to the authorized repair shops closely connected with OEMs. The EU Extended Producer Responsibility (EPR) (European Commission, 2014) initiative where the producers take over the responsibility for collecting or taking back used goods may also encourage disassembly and remanufacturing activities.

Findings

The empirical findings are in this study are based on eight randomly chosen varieties of small household appliances that offer examples of e-waste. These appliances are typical of products found in a Danish municipal recycling centre. In all, 2251 kg (1505 items) have been investigated.

Based on counts, the top five e-waste products identified were lamps/lights (129), vacuum cleaners (46), switches (40), mixers (37), and remote controllers (36). Because vacuum cleaners constituted a complete product and by far the highest weight, 233,52 kg (46 items) compared to lamps/lights (129 items) 88.8 kg of the sample, a deeper investigation of vacuum cleaners was selected and other examples of e-waste are not included in this paper.

13 vacuum cleaners were randomly chosen and systematically investigated for malfunctions and methods for disassembly. When testing the 13 vacuum cleaners, 10 were still able to function. With some of the vacuum cleaners, the click systems for the hose were damaged which may have resulted in their disposal. More than half of the

vacuum cleaners had a bad smell (from pet or other foul odors) and the smell factor may have generated the vacuum's disposal.

When disassembling the vacuum cleaners, we identified how parts were designed for manufacturing and assembly. Click systems, crews, and glue were used to ease assembly but made the vacuums difficult to disassemble for service, repair, reconditioning, or to remove parts for remanufacturing. The task of disassembly was challenging. For instance, screws for assembly were often hidden behind buttons or were inaccessible due to being sunken. Screws of different kinds were utilized in the same product, and special screwdrivers were needed. Snap fits were tricky to open and easily resulted in unintentional damage to the vacuum cleaner. Challenges to repair consequently lead to the vacuum being discarded and creating additional e-waste. However, in one case, the whole dust compartment was developed as a module which could easily be taken out for service.

Table 2: Summary of findings from dismantling

Tools used	Hammer, slotted screwdriver, Philips screwdriver # 2, Torx screw driver, wrench, pliers, spanner, drilled tamper proof screwdriver, chisel
Accessibility	Sunken screws, hidden screws, hidden snap fits
Glue	In few instances, glue could be warmed for dismantling; however, in most cases glue led to destruction when dismantling
Snap fits	From easy to disassemble to snap fits that became damaged when dismantling
Screws	From 4 screws and up to 40 screws for one product From the same kind of screws and up to 8 different screws in one product
Modules	In one product the dust compartment was made into a module

Findings from a case study of repair shops

To support our findings, interviews were conducted in one of the two remaining Danish repair shops for vacuum cleaners in the island/region of Fyn in Denmark. Twenty years ago, more than ten repair shops could be found in the same island/region. All but two repair shops have closed. The findings in this section is based on interviews with employees having 35 years of experience from the field of selling and repairing vacuum cleaners of all kinds.

Several details emerged from our interviews. Very cheap vacuum cleaners (60 Euro), often marketed and sold on the internet, spoiled the whole repair business. These cheap vacuum cleaners may have similar features to more expensive versions (such as an automatic wire coiling system, a HEPA filter, and an equivalent appearance). Hence, customers were not able to observe the vacuum's low quality when ordering from the internet. Poor performance of the low-quality vacuum cleaners meant they were discarded within their first two years; products were made to optimize costs and to keep prices low. The wire coiling systems could earlier be disassembled for exchange of the wire. However, most often the whole coiling system needed to be exchanged or the coiling systems cannot be repaired; hence, the whole vacuum cleaner must be scrapped. Housing for some of the vacuum cleaners were made not from normal polypropylene but from very bad polymer materials that would rot or crumble within a few years. In earlier models, carbon brushes in the electric motor could be exchanged. But in the lower quality cleaners, the whole motor—including carbon brushes, holders, springs, and so forth—are most often glued or welded together and therefore must be exchanged. Repairs of such low-quality machines are cost prohibitive when compared to buying a new vacuum. A new vacuum cleaner could be purchased for 130 Euro while in some instances a repair shop would need 175 Euro to replace a motor. Often, the small click systems that connect hoses in the vacuum cleaner will break. However, repair shops are not always able to buy such small click systems, requiring them to sell a whole new hose system for 40 Euro if the click systems break. These common malfunctions cause vacuum cleaners to be scrapped all too early and thus to generate more e-waste.

Analysis and discussion

OM has been extremely successful in reducing costs for electrical and electronic equipment. As illustrated in this paper, a minor increase of 40% was identified for washing machines from the 1980s and 1990s (King et al., 2006), but at the same time an increase of 165% in repair costs occurred. A personal observation from one of the authors of this paper affirms a 46% cost reduction over 31 years from his first washing machine to his latest, larger, and more modern machine purchased in 2017. An intentional focus on design for assembly and for manufacturing has been an important factor in decreasing these costs. However, globalization and, consequently, access to cheap labor may also have contributed to reduction in costs even though inflation has taken place over more than three decades. The reduction in cost for electronics and electrical equipment has led to much higher consumption and consequently to the generation of much more e-waste. Richer European countries generate 3 to 4 times more e-waste than poorer European countries (Baldé et al., 2017). Future research agendas from the field of circular economy may therefore put pressure on the field of traditional OM where the expertise in handling logistics and supply chains can be important knowledge in future handling of parts for repair, refurbishment, and even remanufacturing as illustrated in Figure 1.

According to our survey (illustrated in Table 1), the traditional OM literature has published roughly 20 times more research papers that focus on design for assembly than on design for disassembly (Table 1). However, our research on disassembling domestic vacuum cleaners illustrates how difficult we found the process because screws were hidden or of different kinds, or click systems were badly made and could be destroyed through the disassembling process. Our study also revealed how parts could be glued together and required heating or parts could be easily destroyed during the disassembling process. We also found how polymer parts were stamped with a mark, PP, to explain the materials. These stamps could be expanded to identify needed screwdrivers or spanners in places where proper actions for disassembling the product should be made. As illustrated in the literature review models for Design for Disassembly developed nearly 30 years ago (e.g., Boothroyd and Alting, 1992; Alting, 1991), methods for disassembling mechanical systems have been developed (Cappelli et al., 2007). Even taxonomies for both assembly and disassembly have been studied (Hatcher et al., 2011; Ghandi and Masehian, 2015). However, this research has illustrated the need for more research, for innovation, and for the development of particular fasteners that are easy to use both when assembling and disassembling parts for repair, refurbishment, or remanufacturing. The ultimate goal is to generate much less e-waste and unnecessary losses (Parajuly, 2017).

This study has also identified how movements like the "Right to Repair" can influence legislation (e.g. Fair Repair Act, 2015) and how political decisions in the EU can make repair of cars easier (EU, Regulation (EC) No 595/2009) and may attempt to reduce waste and e-waste form legislation by establishing extended producer responsibility (EPR) (EU, 2014). Legislation could serve as an appropriate first action to be able to repair, later refurbish and finally disassemble for remanufacturing to minimize e-waste. This study has revealed that to extend the lifetime of electrical and electronic products and to minimize e-waste and to promote repair, refurbishment, and remanufacturing there is a need for support from legislation within this field.

Figure 1 illustrates a simplified flow of materials from manufacturing a product to its end of life as waste. A full flow of materials when repairing, refurbishing, and remanufacturing of parts is much more complex and shows the importance of how experts from the field of OM are needed in handling the logistics and supply chain for parts and modules. A reduction of e-waste will be required in the future, so much more OM research on handing the logistics for repair, refurbishment, and remanufacturing will also be required.

Conclusion, contribution and implications

Based on a literature study, a survey of small and light e-waste from a typical Danish recycling center, and on a case study in one of the few remaining repair shops for vacuum cleaners, this study concludes:

- E-waste is one of the fastest growing waste streams in Europe. E-waste is expected to grow even more over the next decade. Richer countries generate much more e-waste than poorer countries.
- OM has been very successful in cost reduction and the OM research has mainly emphasized efficiency, Lean methodologies, Design for Manufacturing, Design for Assembly, and service. At present, OM literature has had little focus on Design for Disassembly or on e-waste.
- The empirical part of this study has identified a need for much more studies to develop Design for Disassembly and Design for Repair to meet the trends from the circular economy where our future focus will be on extending product lifetime through repair, refurbishment, and remanufacturing with the goal of reducing e-waste and losses. Modularization has been identified as a concept that can make repair and refurbishment easier.
- Movements in the US are focusing on the "Right to Repair." This seems to influence legislation. Both in the US and in the EU, legislation is putting OEMs under pressure for free access to information for repair. EU legislation has extended producer responsibility (EPR) where reverse systems must be considered after end of life. To reduce future volumes of e-waste, more distinct legislation will be needed in relation to repair, refurbishment, and remanufacturing to reduce the amounts of e-waste and losses.

This paper is a first step in our research focusing on the reduction of e-waste. The study contributes to the relatively few studies in field of traditional OM research by exploring design for disassembly to support repair and the extension of product lifetimes. So far, the field of OM has been extremely successful in reducing cost through the design for assembly and design for manufacturing. Because agendas in the future will focus much more on reduction of e-waste and on waste in general, many more studies will be needed on designs for disassembly, repair, refurbishment, and design for remanufacturing.

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