The Environmental Impacts of Reuse

A Review

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Summary

The fear that human consumption is causing climate change, biodiversity loss, and mineral scarcity has recently prompted interest in reuse because of the intuitive belief that it reduces new production and waste. The environmental impacts of reuse have, however, received little attention—the benefits typically assumed rather than understood—and consequently the overall effects remain unclear. In this article, we structure the current work on the topic, reviewing the potential benefits and pitfalls described in the literature and providing a framework for future research.

Many products' use-phase energy requirements are decreasing. The relative importance of the embodied impacts from initial production is therefore growing and the prominence of reuse as an abatement strategy is likely to increase in the future. Many examples are found in the literature of beneficial reuse of standardized, unpowered products and components, and repairing an item is always found to be less energy intensive than new production. However, reusing a product does not guarantee an environmental benefit. Attention must be paid to restoring and upgrading old product efficiencies, minimizing overspecification in the new application, and considering whether more efficient, new products exist that would be more suitable. Cheap, reused goods can allow many consumers access to products they would otherwise have been unable to afford. Though socially valuable, these sales, which may help minimize landfill in the short term, can represent additional consumption rather than a net environmental benefit compared to the status quo.

Introduction

Reuse has become one of the well-known 3Rs—"reduce, reuse, recycle"—promoted by environmental agencies such as the U.S. Environmental Protection Agency (US EPA 2014) and the UK Waste and Resources Action Programme (WRAP) (WRAP 2014) and expressed as part of China's Circular Economy (Yuan et al. 2006). As policy makers look to incentivize greater reuse in the future, it is essential that the environmental impacts of reuse be better understood.

Reuse covers a range of activities from informal product exchanges between acquaintances, to the semiformal structure of car-boot sales and Internet exchanges such as eBay, to industrial reuse of products and components, often called remanufacturing. In this article, a broad definition is employed that covers most of the activities branded as reuse in the literature: It is a nondestructive process that finds a second or further use for end-of-first-life solid materials (products or components) without a change of state, excluding melting for metals, plastics and glasses, and pulping for paper. The further use of a product may be considered as product life extension. The spectrum from reuse to product life extension overlaps with the activity of product resale (Allwood et al. 2010a).

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Motivation: The Need to Reduce Production and Waste

The immense world-wide demand for products and materials means that human activities dominate the global flows of many elements (Klee and Graedel 2004), and that industry accounts for over one fifth of all anthropogenic carbon emissions (Allwood et al. 2012, based on International Energy Agency [IEA] data). The environmental impacts associated with our industrialized society are too numerous to study in detail here; however, Allwood and colleagues (2010b), in a white paper on material efficiency (delivering services with less material production), present a summary of the main impacts caused by the global demand for products: (1) climate change; (2) the exhaustion of resources (fossil fuels, water, land, ores, and biomass); and (3) other impacts such as toxic releases to the ecosystem, and—particularly in highly populated countries—concerns over land availability for landfill.

To avoid the potentially dangerous effects of climate change the Intergovernmental Panel on Climate Change (IPCC) has recommended a 40% to 70% cut in global carbon dioxide (CO_2) emissions from 2010 levels by 2050 (IPCC 2014). Allwood and colleagues (2010c, 2012) and Gutowski and colleagues (2013) have shown that there is limited scope for future efficiency improvements in material production; therefore, an absolute reduction in material production (achievable through strategies such as reuse) is likely to be required to make significant cuts to industrial emissions.

There are few instances of absolute global resource scarcity, but resource ore grades are declining over time (Phillips and Edwards 1976; Mudd 2009). This may cause higher material prices and more energy-intensive extraction because, for example, more grinding is required to liberate the diluted material of interest from the rock (Norgate and Jahanshahi 2011). As energy sources are typically fossil-fuel based, extraction from dilute ores is likely to further increase emissions (Gutowski et al. 2013). Material production is often water and land intensive. For example, cotton requires at least 7,000 liters (L) of water for every 1 kilogram (kg) of fibers produced (Well Dressed 2006). In recent decades, policies designed to increase cotton production in the Aral Sea area (once the fourth largest lake in the world) has caused water shortages (the lake shrinking by over 75%), dust storms, and salt contamination of agricultural land (Micklin 2007). If reuse could prevent materials from otherwise being sent to landfill, it may help alleviate water/land stress and the demands on the mining industry.

Material production often requires toxic chemicals that can cause environmental damage. For example, toxic red sludge is produced in the Bayer process (for refining aluminum ore), and sodium cyanide is used in gold extraction. In 2010, an accident at Hungary's Ajka alumina plant saw the release of red sludge onto adjacent agricultural land and into waterways, causing ten deaths and extensive loss of marine life (BBC 2010). Reusing existing materials may allow society and/or industry to bypass such hazardous processes.

Scope of This Review

This article presents an overarching review of the environmental impacts of reuse in each stage of a product's life cycle and its effects on the wider economy. In sections *Returning a Product . . .* and *Operating a Reused Product*, the literature on the energy required to restore a product at end of life (EOL) to a usable condition (equivalent to "[re]manufacture" in conventional life cycle assessments [LCAs]) and then operate a reused product (use phase) is reviewed. In the section *Reuse and the Production of New Goods*, this article reviews the economic and material-flow literature on reuse, challenging the belief that reusing an item displaces new products made from virgin materials.

This review will assist businesses in understanding the environmental impacts of their actions, policy makers in making informed decisions, and academics in researching numerous gaps in current knowledge, which are highlighted throughout this article. There are many metrics by which to measure environmental impacts. This article focuses on energy demand, the scale of which is a good indicator of other environmental impacts, such as CO_2 emissions (Ashby 2012). Some of the research reviewed is on existing reuse activities, and some is on prospective reuse activities; we make this distinction clear throughout the article. Many articles recommend design guidelines to make reuse easier in the future. The potential impacts of following these guidelines are also reviewed throughout.

Reuse Activities

In order to evaluate the environmental impacts of reuse, it is necessary to understand the different types of reuse that can occur.

Types of Reuse

Product reuse is already prominent in many economic sectors. For example, in the United States, 2.5 times as many electric motors are repaired as sold new, driven largely by reuse of large industrial motors (Nadal et al. 2002). Elsewhere, almost 5 times as many houses and 2.5 times as many cars are sold used as new (U.S. Census Bureau 2010) and, in Germany, ferrous food containers and plastic drink bottles are reused an average of at least 25 times (Tsiliyannis 2005). In contrast, component reuse, though widespread, is typically limited to small-scale activities. For example, according to Kay and Essex (2009), salvaged steel supplied only 1.5% of UK construction steel in 2007. The only prominent industry-wide examples of component reuse identified in the literature are the rerolling of steel plate dismantled from decommissioned ships in Asia (Tilwankar et al. 2008; Asolekar 2006), where the majority of discarded ships are broken, the retreading of truck tires, which in the late 1990s supplied 85% of the replacement market (Ferrer 1997b), and the reuse of small car parts, such as starters and alternators (Steinhilper et al. 2001; Steinhilper 2011).

Several researchers have proposed a framework for assessing the different physical methods of reuse. Allwood and colleagues (2010b) distinguish between longer-life products, product remanufacturing, and component reuse, suggesting a classification of the latter based on the structural changes undergone during reuse. In construction, Addis (2006) distinguishes between in situ building adaptation and reuse of reclaimed components, such as beams and hot water radiators, whereas Gorgolewski (2008) notes that sometimes whole buildings (particularly industrial buildings and warehouses) are relocated. In an analysis of metal component reuse, Cooper and Allwood (2012) differentiate between extensive and superficial reconditioning, and whether the component is reused in the same or different type of product. They cite several articles that describe the "cascading" of components to lower-value applications. For example, uncertainty about the origin of structural steel means it is not typically reused in another building, but as temporary shoring during construction (Gorgolewski et al. 2006). Cooper and Allwood (2012) also describe reuse in which a component's geometry is changed (e.g., the rerolling of ship plate) as "reforming". Allwood and colleagues (2010a) organize examples of reuse they have identified in the UK in a chart along two axes, one depicting the size of the reused item and another split into different types of reuse. In this article, we have extended this framework into table 1, including more reuse classifications and populated with examples of reuse we have identified in the literature.

As can be seen in table 1, few examples were found of small, consumer products being reused unless they could be directly relocated; for example, around 30% of the UK's discarded clothing is "relocated" through charity shops and sold on the international market (Well Dressed 2006). Similarly, the majority of reused cell phones are sold in the emerging markets of Africa and South America (Skerlos et al. 2003), and nearly 900,000 deregistered cars were exported out of the European Union (EU) in 2008, mainly to Africa (EP 2010). When significant refurbishment work is required, table 1 suggests that smaller products are generally not reused. For instance, in the UK it is cheaper to buy a new pair of trousers than repair a hole in the pocket (Well Dressed 2006). Because larger items tend to be owned by businesses, table 1 implies that items owned by businesses are more likely to be refurbished than products owned by individual consumers. Larger components can be cascaded to a different use (e.g., steel pipes can be reused as building piles) and reformed into a different geometry (e.g., ship plate rerolled into reinforcing bars). However, when whole products are reused, they tend not to be cascaded in function; rather, they are often sold to a less affluent customer (e.g., secondhand cars).

Of all the activities presented in table 1, remanufacturing has spawned the most literature. Lund (1984, 19) defines it as an industrial process where "worn-out products are restored to like-new condition" by deconstructing the product/subassembly, cleaning and refurbishing usable components, and reassembling with any new parts, if required. These labor-intensive processes mean that remanufacturing is typically restricted to the refurbishment of high-value subassemblies, such as cellular phones (Skerlos et al. 2003), photocopier modules (Kerr and Ryan 2001; King et al. 2006), industrial equipment components (Parker and Butler 2007; Butler 2009), some domestic appliances (Sundin and Bras 2005), and numerous car parts (Steinhilper et al. [2001] provides a list), including tires (Ferrer 1997b) and engines (Sutherland et al. 2008; Adler et al. 2007; Smith and Keoleian 2004). Lund and Hauser (2010) find that remanufactured products are typically priced between 45% and 65% of new product costs. No examples have been found of remanufactured subassemblies (engines, and so on) being used in the manufacture of a new product. Rather than being sold as new items, it appears that most existing remanufacturers provide one or more of three services: (1) supplying spare parts for existing products (Allwood et al. 2010b); (2) repairing products that have failed during manufacture or within warranty (Steinhilper 2011; Sundin and Bras 2005); and (3) repairing or upgrading expensive subassemblies within a valuable machine that might otherwise require complete replacement (e.g., repair of large truck and locomotive engines).

The Potential to Reuse Goods

A few researchers present benchmarks or systematic methods for evaluating maximum reuse rates. For products, Cooper and colleagues (2014) evaluate the current average life span of steel products (35 years) and present a framework in which to address product failure. Allwood and colleagues (2012) evaluate potential increases to the life span of steel and aluminum goods across construction, transport, industrial equipment, and metal products, finding that they can often be doubled. Umeda and colleagues (2006) and Östlin and colleagues (2009) present a framework that can be used to assess the maximum reuse rate for products based on the falling demand for older, obsolete products. For component reuse, Sherwood and colleagues (2000) analyze the waste streams of remanufacturing companies and report that most discarded parts are worn and unusable, suggesting that remanufacturing is efficient. This analysis, however, focuses only on existing remanufacturers. Cooper and Allwood (2012) present a global analysis on the potential to reuse steel and aluminum components, calculating that around 30% of current production of both metals could technically be reused with immediate and significant opportunity in the relocation of steel building components, particularly hot rolled structural steel beams.

For reuse to occur, there needs to be both a supply of used items and a demand for these goods. Both depend on business factors (e.g., access to used goods and labor prices) and physical factors (e.g., the physical condition of goods at EOL). Table 2 distills the lessons learned from the literature. Some of the physical factors can be designed for, such as durability and standardization. Implementing these strategies might be encouraged by a shift from consumer product ownership to leasing, incentivizing the owner (manufacturer) to refurbish their product. This may be done voluntarily or mandated as part of an extended producer responsibility policy, such as the German Einwegpfand on single-use glass bottles. This has been reported by many researchers, such as Ayres and colleagues (1997) and Nasr and Thurston (2006, 17), the latter arguing that "a product delivery model in which the product manufacturer has a

Table 1 Types of reuse

Business purchases, large items ⟷ Consumer purchases, small items

Reused for…	Reuse activity (applied to products or components)	Construction – buildings and infrastructure	Industrial equipment	Transport	Appliances	Paper and packaging	Textiles
…the same purpose: *products & components*	Relocation	Portal frame buildings, steel beams, purlins, or piles[1]	Large equipment such as rolling mills[1]	Used car sales for export[2], Reuse of alloy wheels[3]	Consumer electronics resold on eBay[4]	Shipping containers[1]	Clothing re-sold through charity shops[5]
	Remanufacturing: Re-fill		Liquid gas tanks[6]		Toner cartridges[7] Domestic propane tanks[25, 26]	Reusable drink containers[8] Refillable containers[6]	
	Remanufacturing: Module reuse/ replacement with or without upgrade	BP's North West Hutton oil rig: living quarters were reused onland[1]	Industrial food processing equipment[9] Air-conditioning units[10]	Swedish capped rail system, ReRail[11] Engine remanufacture – recovery (welding) of worn cylinder heads[12, 13]	Photocopier modules[14] Cell phones[15] Remanufacture of refrigerator compressors[16]		
	Remanufacturing: Remediation of component properties	Pre-cast concrete slabs reused in other buildings[17].	Re-grinding machine tools[10] Industrial electrical equipment, farm equipment, turbines[16]	Aircraft parts, railroad equipment[16] Retreading tires[18]	Lawn mowers[16], white goods[19]	*Toner removal from paper[A]*	
	Adaptive reuse	Buildings renovated or extended for a different purpose[1] Reused building foundations[20]	Gas pipe welded to form the supporting truss of the London 2012 Olympic stadium[1]	Discarded tires reused as footwear[21]	*Repurposing of smartphones[F]*		
	Cascade	Reuse of structural steel as shoring in construction[1] and of concrete for sea wave protection (Rip-Rap)[22]	Reuse of steel pipes as building piles[17]	Worn mainline rails are reused on branch-lines[1]	PC chips reused in toys[23]		
…a different purpose: *individual components*	Reform	Ship plate re-rolled into rebar[24]	*Large diameter steel pipe re-rolled into sheet[B], solid bonding of metal machining chips by extrusion[C]*	*Re-forming of car panels[D, E]*	*Re-forming of appliance panels[D, E]*		
	Typical materials:	Steel, aluminum, cement	Metals	Steel, aluminum, plastic	Steel, aluminum, plastic	Paper, steel, alum., plastic	Fabrics

Current reuse: 1. Allwood et al. (2010a) 2. EP (2010) 3. Cooper and Allwood (2012) 4. Clausen et al. (2010) 5. Well Dressed (2006) 6. Kelle and Silver (1989) 7. Ostlin and Ekholm (2007) 8. Mata and Costa (2001) 9. Butler (2009) 10. Parker and Butler (2007) 11. Rerail (2010) 12. Adler et al. (2007) 13. Venta et al. (1978) 14. Kerr and Ryan (2001) 15. Skerlos et al. (2003) 16. Bollinger et al. (1981) 17. Addis (2006) 18. Ferrer (1997b) 19. Sundin and Bras (2005) 20. Cooper et al. (2014) 21. BBC (2014) 22. FHWA (1989) 23. Geyer et al. (2007) 24. Tilwankar et al. (2008) 25. Ferrellgas (2015) 26. Oliver-Solà et al. (2009) *Prospective reuse: A. Leal et al. (2012) B. Cooper and Allwood (2012) C. Tekkaya et al. (2009) D. Takano et al. (2008) E. Tekkaya et al. (nd) F. Zink et al. (2014)*

Table 2 Enablers and barriers to reuse

	Enablers	*Barriers*
Physical factors	Physical durability[1] Standardized components[1] Mature technology and design[1,2,3] Modularity allowing upgrade and repair[1,4] Reversible joints allowing easy disassembly[1]	Degradation (wear, corrosion, fatigue, fracture, etc.)[1,5] The technology is obsolete by end of life (e.g., computers and cell phones)[1,6] Old components incompatible with new designs (bespoke products)[1] Components that are irretrievable (e.g., steel rebar in building foundations)[1,7]
Business factors	Cheap labor[2] Lower capital costs than new production[2] Low scrap prices[2,8] Knowledge of technical properties at end of life[1] Ability to protect a brand name and intellectual property [4] Vertically integrated companies[4*]	Legislation (banning old products and health and safety concerns favoring demolition over deconstruction)[1] Cheap imports and expensive labor[2] Customers likely prefer new product when remanufactured product price exceeds 70% of a new product[9] Dispersed (poor infrastructure) reverse supply chain[10*] Obsolescence (aesthetics and fashion)[1] In construction, time pressure from land owners can favor demolition over slow deconstruction[4] Tax policies that favor demolition and rebuild over refurbishment[11] Planned obsolescence [See below]

*Srivastava (2007) provides a review of "green supply-chain management" including the issue of reverse logistics for reuse/remanufacturing.
1: Cooper and Allwood (2012); 2: Bollinger and colleagues (1981); 3: Stahel (1982); 4: Allwood and colleagues (2010b); 5: Ferrer (1997b); 6: Ferrer (1997a); 7: Geyer and Jackson (2004); 8: Allwood and colleagues (2010a); 9: Ortegon and colleagues (2014); 10: Ferrer and Ayres (2000); 11: Power (2008).

leading role in the entire product life cycle . . . promotes a greater interest in more efficient material use and reuse." Parker and Butler (2007) describe business-to-business examples of this model, including Rolls Royce's "power by the hour" jet engines. However, Intlekofer and colleagues (2010) analyze the effect of product leasing on household appliance and computer sales, finding that it can actually reduce product life spans because consumers expect relatively new equipment.

The idea that producers might deliberately curtail the life of products in order to increase new product sales was popularized in Packard's critique of consumerist culture, The Waste Makers (Packard 1960). As outlined by Guiltinan (2009), this "planned obsolescence" can take various forms, including limiting functional life, designing for limited repair, choosing aesthetics that age, and designing for functional enhancement making existing products appear inferior. Such behavior is expected to be more prevalent in less competitive markets (Waldman 2003), more saturated markets (Guiltinan 2009), and in more technologically dynamic industries (Bayus 1998). These actions inhibit the use of long-life products, but also result in a lot of EOL units that could represent a resource for those pursuing component reuse.

Returning a Product at End of Life to a Usable State or Location

The environmental impact of reusing an item depends on the actions taken at product EOL. In order to determine the environmental merit of reuse, these actions are best understood relative to an alternative nonreuse scenario. The impacts are therefore the net effect of "additional processes" required to reuse the item, and "avoided processes" that would have been required to make the product from new materials and to deal with the old product waste.

If a product is not reused, then three options exist at EOL: landfill, incineration, and recycling. In the United States in 2012, 54% of municipal waste was discarded in landfills, 12% was incinerated with energy recovery, and the remaining 35% was recycled, of which one quarter was composted (US EPA 2012).

Landfills are not only causing space concerns in densely populated nations (prompting landfill taxes in Europe), but also contaminating surrounding water courses with toxic chemicals (e.g., lead and mercury) from discarded products such as computers (Christenson and Cozzarelli 2003). Incineration of waste (e.g., old car tires) can be used as an effective heat source (e.g., in the cement industry) and reduces the depletion of primary energy sources. However, burning the waste is often inefficient, with moisture needing to be removed and combustion incomplete (Ashby 2012). Burning also causes CO_2 emissions and potentially toxic fumes and residues. Options for disposing of the resulting ash include landfilling and use in bricks and aggregates (Mendes et al. 2004). Many materials are regularly recycled, but this is often an energy-intensive process. Further, recycling (and landfill) of many products used in the developed world takes place in the developing world.

These nations are often ill-equipped to handle toxic materials (Skerlos et al. 2003). Premalatha and colleagues (2014, 1601) report "gross pollution of air, soil and waterways" in many places in the developing world where recycling of electronic waste is occurring. They report manual dismantling of cathode ray tubes, cyanide salt leaching of circuit boards to recover gold, and open burning of cables to recover copper and of circuit boards to separate components and recover solder.

Relocation or Direct Resale

For items that can be directly reused, the energy demands are likely to be negligible if resold locally or approximately equal to the transport impacts if relocated. Most studies typically ignore transport impacts or assume them to be comparable to the nonreuse scenario. Researchers do, however, often include transport when considering the reuse of small, reinforced products (such as reusable packaging) that must be collected from dispersed locations. This results in the inefficient use of heavy goods vehicles. Reusable packaging (e.g., glass bottles) has been studied by many researchers (Hannon 1973; Van Doorsselaer and Lox 1999; Mata and Costa 2001; Levi et al. 2011; among others). Hannon (1973) studies reusable and disposable soft drink, beer, and milk containers, where the distance between the end user and distribution/refilling center is 230 miles (370 kilometers [km]). He finds that reusable bottles require only one third of the energy of their throwaway counterparts. Levi and colleagues (2011) consider varying transport distances in their LCA of disposable and reusable grocery packaging, finding that a "crossover distance" exists: When the distance between the end users and the distribution center is shorter than this, the benefits of avoiding new production make reuse beneficial. When the distance is longer, then the emissions from inefficiently transporting reusable packaging dominate. The calculated crossover distance was 1,200 km, suggesting that reusable packaging is advantageous for all but sparsely populated areas.

Larger components usually represent greater residual value than smaller ones because they can be cascaded to a less demanding function or oversized in the new application. For example, in the absence of a material specification, steel beams are reused under the conservative assumption that they were made from the lowest structural steel grade (Lazarus 2003). This can, however, lead to larger foundations and supporting structures being required to support oversized beams. Astle (2008) postulates that oversizing reused beams by as little as one third leads to greater energy requirements and carbon emissions than recycling the beams. This is because the shortfall in scrap returning to the steel supply chain has to be supplied using new steel (primary) production, which is 3 times more energy and carbon intensive than recycling. In order to prevent oversizing and encourage reuse, the actual specification of the steel can be determined using mechanical tests on "coupons" of material (Gorgolewski et al. 2006), though this may be currently prohibitively expensive. Gorgolewski and colleagues (2006) recommend stamping structural steel with a permanent barcode representing the grade. More generally, Gray and Charter (2007) recommend labeling components in a product with a radiofrequency identification, a concept explored further by Saar and Thomas (2003). A critical future development is to either retain a product's/component's original specifications or to develop cheap testing methods that determine the specifications before reuse.

Remanufacturing

The best indication of average remanufacturing energy requirements comes from Bollinger and colleagues (1981). They collate data from surveys sent to 258 North American remanufacturing companies. Respondents revealed the direct energy (fuels and electricity) needed to remanufacture their products and the mass of new components bought to replace worn parts. The surveys are from over 30 years ago, but remain the most comprehensive analysis of the industry to date. Bollinger's broad findings, discussed below, are consistent with more recent analyses on the remanufacture of specific products, such as diesel engines (Adler et al. 2007) and electric motors (Gutowski et al. 2011).

The data presented by Bollinger and colleagues suggest average energy savings of approximately 80% compared to new production. However, the savings appear to be very sensitive to the product being remanufactured. For example, Kerr and Ryan (2001) found savings between 27% and 68% for photocopier remanufacture. Figure 1 summarizes the calculated energy savings presented in the literature.

As an illustration of a remanufacturing process, Boustani and colleagues (2010b) describe the physical processes needed to retread a car tire: (1) buffing of the old tires (shaving off the remaining tread); (2) adding the new tread; (3) the applied tread and the casing are wrapped around a rubber envelope and a vacuum is generated; and (4) the new tire is cured at approximately 300°F. Remanufacturing requires some energy and materials, but saves more from avoiding new product manufacture. In the case of retreaded tires, Ferrer (1997b) reports that it takes, on average, 26l of oil to produce a new passenger car tire, but only 9l to remanufacture one.

Most of the energy required to remanufacture a product is embodied in replacement parts. Bollinger and colleagues' survey suggests that, on average, around 20% of all parts received by the remanufacturer are discarded, with reused material accounting for 85% of the final product mass. Consistently, Boustani and colleagues (2010b) report that 10% to 20% of a retreaded tire is new material, and Adler and colleagues (2007) find that 70% of the energy required to remanufacture engine cylinder heads is embodied in new parts. Material savings can be increased if the original product is more modular so that only the "failed" material needs to be replaced. For example, Kerr and Ryan (2001) found that energy savings on a Xerox remanufacturing line more than doubled as a result of design changes that made the original product more modular.

Component failures often occur on the surface (wear, corrosion, and so on). Remanufacturers may choose to: (1) replace the component; (2) remove the damaged surface (e.g.,

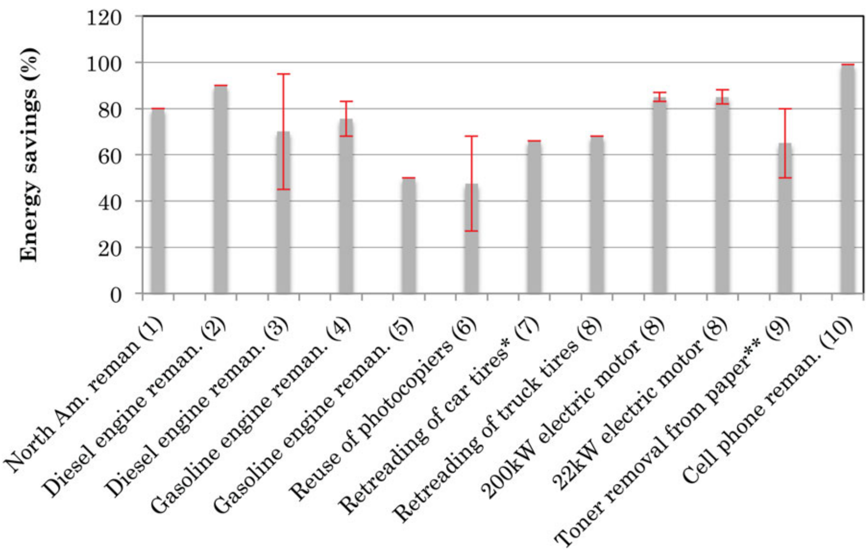

Figure 1 Energy savings in remanufacturing. Accounting for direct energy (fuels) and embodied energy (material production), excluding the use phase. The error bars indicate a range of presented values. *Oil savings (oil used as a fuel and constituent of rubber); **carbon emission reduction. 1: Bollinger and colleagues (1981); 2: Sutherland and colleagues (2008); 3: Adler and colleagues (2007); 4: Smith and Keoleian (2004); 5: Venta and Wolsky (1978); 6: Kerr and Ryan (2001) 7: Ferrer (1997b); 8: Gutowski and colleagues (2011); 9: Leal-Ayala (2012); 10: Skerlos and colleagues (2003).

reboring engine cylinders and using a larger piston); (3) replace the surface with a sacrificial component (e.g., sacrificial engine cylinder liners; Krill and Thurston [2005]); or (4) repair the surface using additive "surface engineering" techniques (Xu 2004). Energy-intensive material deposition processes exist for metals (e.g., thermal spraying for thick coatings and chemical and physical vapor deposition for thinner coatings) that may be used to repair damaged surfaces. There is evidence that these are being used to remanufacture some products. For example, the Center for Remanufacturing in Rochester, New York remanufactures expensive marine shafts where the corrosion-protective coating has failed: The original coating is first removed using a lathe, an abcite coating is then applied using thermal spraying techniques, and the shaft is machined to the desired diameter and surface finish (RIT 2013). Gutowski and colleagues (2001) state that similar processes are used to remanufacture some engine components and there is evidence that they could be used to remanufacture worn ball bearings (Kelsey et al. 2014), among other metal components (Yao et al. 2012). Surface remediation of used paper (removing the toner from the used sheets) has also been shown by Leal-Ayala and colleagues (2012) to be almost commercially viable. The technology uses a short pulse laser to ablate the toner and Leal-Ayala (2012) calculates emissions reductions of 50% to 80% over recycling.

Energy requirements can be very low when no new components are needed. For example, during phone remanufacture, energy is only required for sorting (driving a conveyor belt), battery testing/reconditioning, and software updating (standard personal computer [PC] usage). These requirements amount to less than 1% of the total energy in material production and manufacturing of a new phone (Skerlos et al. 2003). On average, the direct energy (fuels and electricity) used by remanufacturers is 4% to 5% of the energy required in new production (Bollinger et al. 1981), and is mainly used to clean components, often by ultrasonic cleaning or immersing in heated (salt) baths. This may be because most products and components that are currently reused are in a relatively good condition, and require little refurbishment; several researchers have recognized that variation in the energy needed to remanufacture a part is dependent on the degradation of the component at EOL. Fatigued or worn components (such as some cylinder heads) may be refurbished by welding and grinding operations, but require greater energy inputs than those subjected to less-severe conditions, such as pistons and connecting rods (Sutherland et al. 2008).

Adler and colleagues (2007) were the only researchers listed in figure 1 able to report energy requirements directly from facility and process energy measurements. They compared the original manufacture and remanufacture of Caterpillar engine components, recording that the remanufacturing process energy requirements were 41% to 55% of original manufacturing. In the case of 100% reusable material, the energy requirements dropped to 5% to 25% of original manufacturing. Other researchers have had to infer energy requirements from knowledge of the remanufacturing process. Such inferences are common in LCAs and have been used, for example, by Venta and Wolsky (1978) to calculate energy savings for gasoline engine remanufacture based on economic input-output data. In Gutowski and colleagues' (2011) analysis of motor rewinding, they only include the energy required to produce the copper and paint for the new windings and outer case, respectively, ignoring the energy needed to "burn-out" the old coils, testing, and varnishing, owing to lack of available data. If the direct energy

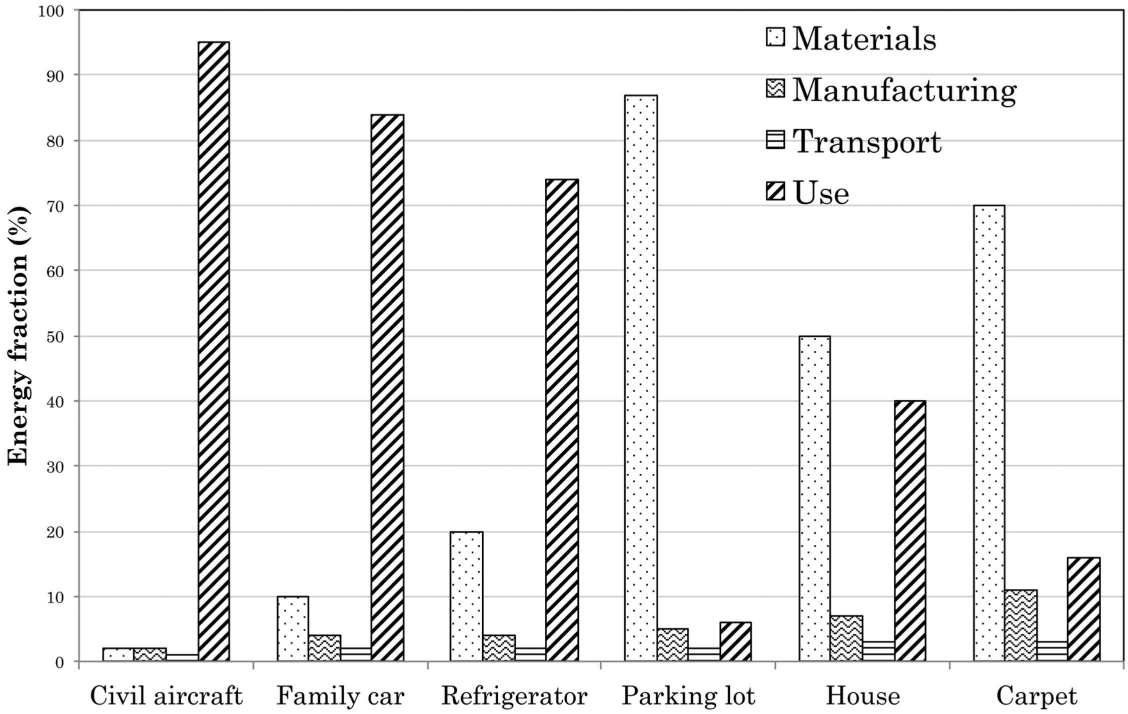

Figure 2 Life cycle contributions for different products (data from Ashby [2012]).

of remanufacturing remains low (4% to 5% of new production as found by Bollinger and colleagues), then such inferences are acceptable; however, if greater reuse leads to the use of more energy-intensive additive and subtractive processes (as discussed above), then there will be a need for more rigorous studies that measure the energy required to perform remanufacturing operations.

Adapting, Cascading, and Reforming

Environmentally motivated research on adapting products is dominated by case studies on modifying building structures. Gorgolewski and colleagues (2006) present several case studies in which a building's steel frame has been either retained or extended including, for example, the addition and removal of floors and frame reinforcement. Milford (2010) collates data on Gorgolewski and colleagues' case studies, calculating the emissions avoided by adapting, rather than rebuilding, these structures. For example, Milford considers Parkwood in Oshawa, which required the adaptation of an old office complex into a new residential complex. Ninety percent of the original steel frame was retained, reusing 350 tonnes (t) of steel and saving 269 t of CO_2-eq (CO_2 equivalents). Elsewhere, Zink and colleagues (2014) consider "repurposing" a smart phone for use as an in-car parking meter, finding it would save between 23% and 55% of the CO_2 emissions associated with primary production of a new parking meter.

No literature has been found on the environmental impact of cascading components through different applications. The immediate impacts are, however, likely to be those associated with transport (e.g., transporting worn mainline rails to branch line routes). The transport impacts are likely to be small compared to the impacts of new production, but there is a danger that, as described in the section *Relocation or Direct Resale*, significant oversizing in the new application could lead to increased primary production of the material or displacement of lower impact materials, such as timber in the case of steel reuse. The most prominent example of reforming found in the literature was Indian rerolling of ship plate into rebar. Tilwankar and colleagues (2008) calculate that this process (ship breaking, transportation to mills, and then rerolling) saves 60% of the energy and CO_2 emissions needed to make rebar using virgin steel.

Operating a Reused Product

The environmental impact of reusing a product or component depends not only on the processes used to return a good to a useful state or location, but also the impacts of using the item for a second time. The contribution of many products' use phase to its life cycle impacts has already been quantified in the LCA literature (see figure 2). For "unpowered" products (such as the carpet or parking lot), the life cycle will be dominated by embodied impacts and then the use-phase efficiency of the reused product is not such a concern; we can safely assume that reusing such an item has a lower impact than discarding it to landfill and producing a new product. In contrast, for many "powered" products, such as white goods, the use-phase energy requirements dwarf those in initial production, the benefits of reusing these products being largely determined by any discrepancy between the use-phase efficiencies of the reused product

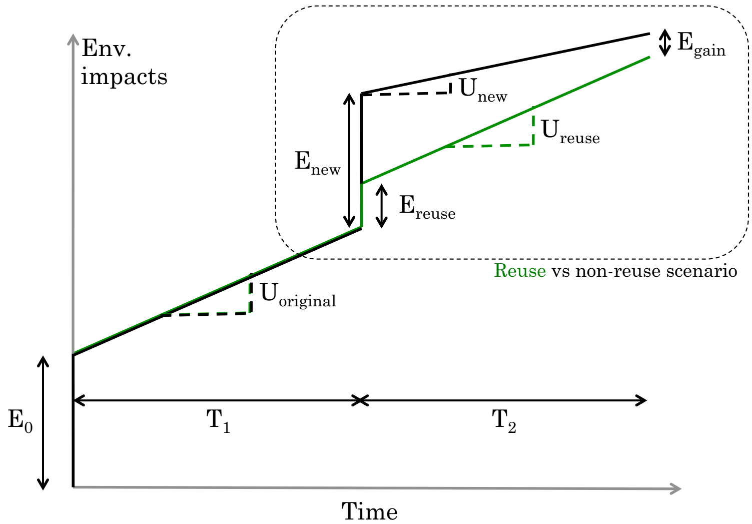

Figure 3 Environmental impact of product replacement versus reuse.

and a new equivalent (see figure 3). The same applies to the reuse of some critical components within a powered product. For example, the rolling resistance of a retreaded tire has a direct effect on the fuel efficiency of the vehicle (a case examined by Gutowski et al. [2011]).

In the literature, the efficiency of a reused or new (equivalent) product is often described with reference to the original (reused) product efficiency when it was first sold. The efficiency of the reused or new, equivalent product could be better than, equal to, or worse than this original efficiency, as summarized in table 3.

Efficiency of Reused Products

Very little data have been collected on the efficiency of reused products. Nadal and colleagues' handbook on energy-efficient motor systems contains a rare example of collated measured data on the efficiency of remanufactured products (Nadal et al. 2002). For products that are simply relocated without extensive repair (such as a secondhand fridge purchased on eBay), then the efficiency will be equal to that at the end of the product's first life span. Regular maintenance may enable original efficiencies to be maintained (Ortegon et al. 2014); otherwise, efficiencies can decrease. For example, Kim and colleagues (2003, 2006) point out that for a refrigerator, degassing of insulation foam, dirty coils, and worn-out gaskets can cause energy requirements to increase by 60% over the life span of the fridge. Remanufacturers typically distance themselves from such simple reuse and define their practices as returning a product to a "like-new" condition, with a warranty to match (Ijomah et al. 2007). This definition has been accepted by British Standards (BS 2010). There is also evidence that some remanufacturers upgrade their products to higher efficiency standards than when the products were first made. Bollinger and colleagues find that the majority of firms perform some sort of technological updating (Bollinger et al. 1981). More recently, several researchers echo Parker and Butler's (2007, 3) sentiment that remanufacturers upgrade "products from old to current [energy efficiency] standards," such as Blazek and colleagues (1998) and Linton and Johnston (2000) with respect to telecommunications equipment, Atasu and colleagues (2010) with respect to photocopiers, and Galbreth and colleagues (2013) for fast-moving consumer goods.

Several practical case studies have been reported in the literature, including studies on retrofitting buildings (Brown et al. 2014; Harvey 2013), repairing and upgrading various steel products (Cooper et al. 2014), and the remanufacture of electric motors (Nadal et al. 2002; Easa 2003), print cartridges (Hewlett Packard 2008), tires (Boustani et al. 2010b), and wind turbines (Ortegon et al. 2014). Their findings can be summarized as:

- *Efficiency drops during remanufacturing:* In theory, many products can be restored to their original efficiency. To do so, remanufacturers must typically ensure that they: (1) avoid practices that degrade efficiency and (2) conduct appropriate testing before and after remanufacturing to ensure quality. For example, when rewinding an electric motor, baking the stator loosens the old windings. High temperatures will speed up the process, but can damage the magnetic properties of the core and distort the motor. Nadal and colleagues (2002) and Easa (2003) both review multiple studies that have measured the efficiency of rewound motors (for motors less than 150 horsepower) finding an average decrease in full load efficiency of 1% compared to original specifications. Elsewhere, Hewlett Packard (2008) report that a new printer cartridge has a 1% misprint rate, whereas a remanufactured cartridge has a 12% misprint rate. A Michelin tire report also suggests that retreaded tires have a 7% to 9% higher rolling resistance than new equivalents (Boustani et al. 2010b). It should be noted that these last two reports were produced by original equipment manufacturers that

Table 3 Use-phase efficiency of reused products

	. . . lower than the original efficiency of the reused product	*. . . the same as the original efficiency of the reused product*	*. . . higher than the original efficiency of the reused product*
Efficiency of the reused product is . . .	Item deteriorated during first life span, potentially owing to wear and tear (e.g., unrestored refrigerator[1])	Item did not deteriorate during first use (e.g., steel beams[2]) or was restored during reuse (e.g., some remanufactured products[3])	The item has been upgraded during reuse (e.g., retro-fitted building[4] or upgraded photocopiers[5] and engines[6])
Efficiency of the new equivalent product is . . .	Lower (relative) energy prices may decrease the economic incentive for efficiency (e.g., cars and trucks were less efficient in early 2000s than late 1980s[7])* New products may be powered whereas the original was not (e.g., new snow blowers vs. old snow shovels[8])	There has not been a significant change in technology or the use-phase impacts are small enough to be ignored (e.g., steel beams[2])	New, more efficient technology and/or efficiency standards (e.g., refrigerators owing to energy standards[9])

*Component level savings that do occur (e.g., improved engines and motors) may be eradicated by increasing the product service (e.g., bigger vehicles or white goods).
1: Kim and colleagues (2003, 2006); 2: Cooper (2013); 3: Parker and Butler (2007); 4: Harvey (2013); 5: Atasu and Wassenhove (2010); 6: Claimed by DEI (2013); 7: US EPA (2008); 8: Gutowski and colleagues (2011); 9: Meyers and colleagues (2003).

may compete with remanufacturers. No detailed studies have been found on the fuel efficiency of remanufactured engines or other car parts. Research on this topic would be a valuable addition to the literature given the size of the market for remanufactured car parts.

- *Efficiency upgrades:* For some products, the component that determines the efficiency of the product may be replaced and upgraded independently of the rest of the product. The replaced component or subassembly may be nonphysical. For example, Cooper and colleagues (2014) present evidence of steel rolling mills that are renovated (either in situ or as part of a relocation) by upgrading the control system. On the other hand, the components can be physical. For example, by retrofitting ventilation systems and replacing windows, buildings are now routinely upgraded to higher use-phase efficiencies. Harvey (2013) has collated data on building energy requirements pre- and postretrofit, finding that retrofits often improve energy efficiency by at least a factor of three. Pandey and Thurston (2009) introduced the concept of an *effective age* for remanufactured products (emphasizing the age of the critical subsystems rather than the product as a whole). The effective age is an intuitive means of conveying the technology present in a remanufactured product (Ortegon et al. [2014] use it when considering the technology present in a remanufactured wind turbine), but determining the criticality of each subsystem may be subjective.
- *Impact on reuse's environmental merit:* Most studies do not consider reusing a product with a lower use-phase efficiency than its original specification. In this respect, they are favorable to reuse. On the other hand, most quantitative analyses also ignore the possibility of upgrading reused products to current efficiency standards. This is, at times, sensible because, as noted by Gutowski and colleagues (2011, 4546), efficiency improvements are sometimes not "incremental but radical, with major transformations in the product architecture." The main exceptions to the above assumptions are studies on the benefits of building renovation versus replacement. For example, Brown and colleagues (2014) calculate that, because of improved use-phase efficiency, the emissions payback time for retrofitting most buildings is only around 3 years. Elsewhere, only Gutowski and colleagues (2011) consider efficiency drops during remanufacture, calculating that the efficiency drops in motor rewinding are likely to make buying new, in terms of energy use, favorable. They also calculate that a change of only 0.025 miles per gallon during remanufacture of a diesel engine is likely to have the same effect.

The efficiency of a repurposed product (adaptive reuse) could be better than, equal to, or worse than the original efficiency given that it depends on the new function and operating conditions.

Efficiency of New Products

The efficiency of many "powered" products has improved in recent years, driven by innovation and legislation on energy efficiency. For example, Meyers and colleagues (2003) find that U.S. regulations on domestic appliances (since the late 1980s) resulted in annual energy savings of 0.75 exajoules by the year 2000. They project that in 2020 regulations will have reduced residential CO_2 emissions by 8% to 9% compared to levels expected without any standards. Table 4 shows the efficiency improvements of some common products used in the literature.

Environmental studies on the use-phase impacts of product reuse analyze the trade-off between saving the embodied energy

Table 4 Historic use-phase energy improvements used in the literature on reuse

Product	*Time period*	*Efficiency improvement (%)*	*Reference*
Car	Theoretical annual improvement	+3.2	Skelton and Allwood (2013)
Refrigerator	1947–1974	–530	Gutowski and colleagues (2011)
	1974–2008	+76	
Dishwasher	1981–2008	+45	Boustani and colleagues (2010a)
Clothes washer	1981–2008	+70	
Refrigerator	1981–2008	+62	
Clothes washer	1981–2003	+88	AHAM (2005) cited in Bole (2006)
Cell phone, LCD monitor, CD player	Theoretical 1991–2001	Variable but nominal +20	Rose and Stevels (2001)

Note: LCD = liquid crystal display; CD = compact disc.

associated with new production and taking advantage of the latest efficiency improvements. Figure 3 depicts this trade-off, showing the total environmental impact of two scenarios, one in which a product is replaced with a modern equivalent and another where it is reused. Manufacturing new products requires energy, represented in figure 3 as a step in the line graph (E_{new}). Reusing a product (remanufacture, and so on) may also require energy and is represented as a smaller step in the graph (E_{reuse}). Once manufactured the new and reused products may operate at different efficiencies, represented in figure 3 with different line gradients after the replacement/reuse step (U_{new} and U_{reuse}). The "E_{gain}" presented in figure 3 is therefore a function of the relative embodied and use-phase energy requirements and their improvements over time.

Studies that examine this trade-off fall into two broad categories. (1) Studies that assume product life spans are fixed and that the second life span of a reused product is equal to its first ($T_1 = T_2$ in figure 3). This is a reasonable assumption for remanufactured products at least, which are often sold with a warranty equivalent to new products (Ijomah 2002; Parker and Butler 2007). Studies in this category include Gutowski and colleagues (2011) with respect to furniture and clothing reuse as well as tire, prime mover (internal combustion engine and electric motor), and domestic product remanufacture; Boustani and colleagues (2010a) and Truttmann and Rechberger (2006) for white goods, Sahni and colleagues (2010) for personal computers, and Rose and Stevels (2001) for consumer electronics. (2) Studies that calculate optimum product life spans in order to minimize environmental impacts ($E_{reuse} \rightarrow 0$ and T_1 does not have to be equal to T_2 in figure 3). Studies in this category include Kiatkittipong and colleagues (2008) for electronic goods, Bole (2006) for residential clothes washers, Kim and colleagues (2003) for cars, Kim and colleagues (2006) for fridges, De Kleine and colleagues (2011) for air-conditioning (AC) units, and Skelton and Allwood (2013) for cars, planes, office buildings, and washing machines. Summarizing the lessons learned from these studies:

- *Should products be reused?* Products with a high use-phase energy requirement and improving efficiencies over time have low optimal life spans (from an environmental perspective) and should not be reused. This is because the emissions associated with powered products, which require an energy source, are dominated by the energy requirements in use (Gutowski et al. 2011). As a result, improvements in use-phase energy mean that frequent replacement with new products causes the lowest energy requirements and emissions. Studies on optimal life spans suggest that such products should often be replaced more frequently than they already are. Skelton and Allwood (2013) find that the optimum life spans for a car and an airplane are only 10 and 12 years, respectively, whereas average current life spans are 14 and 25 years, respectively. De Kleine and colleagues (2011) find that AC units should have been replaced up to 12 times since 1985. Kim and colleagues (2006) consider refrigerator replacement between 1985 and 2020, calculating that (depending on the model year) the optimum product life span was as low as 2 years. Conversely, products with low use-phase energy requirements and low use-phase efficiency improvements should be reused. Gutowski and colleagues (2011) find that products such as clothing and furniture should be reused. Consistently, studies on optimal life spans indicate that such products are currently discarded too early. For example, total CO_2 emissions associated with a building structure is dominated by the production phase; Skelton and Allwood (2013) find the actual life span of a typical office building (60 years) is less than half the optimal life span (135 years).
- Can new products be less efficient than old equivalents? Most literature claims that new products are at least as efficient as older goods. This appears to be true for products with high use-phase energy requirements that are now (or have recently been) subject to environmental legislation (e.g., refrigerators). This has not always been the

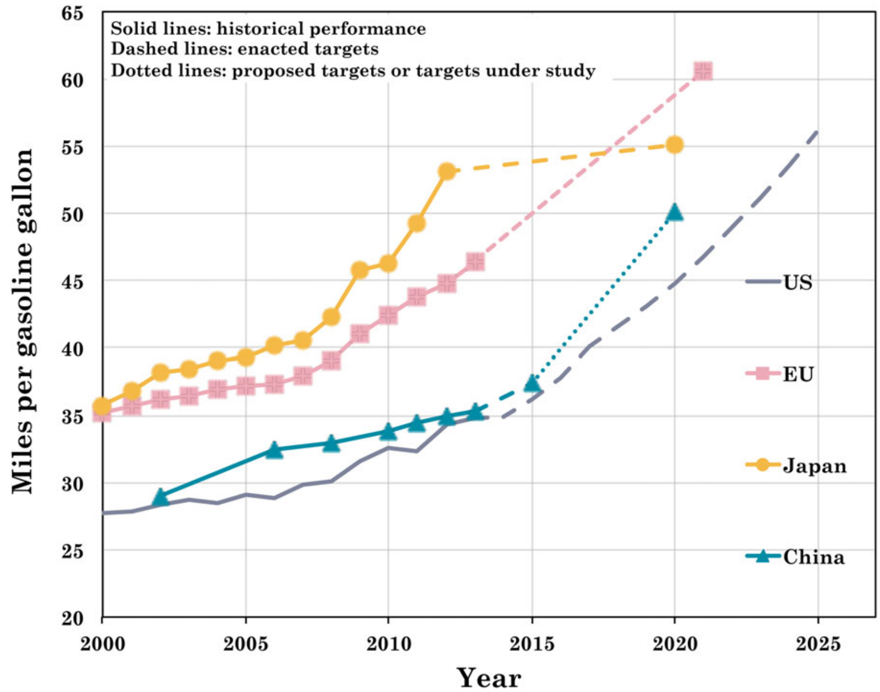

Figure 4 Passenger vehicle efficiency standards, data from ICCT (2013).

case, however, with, for instance, both passenger cars and trucks being less efficient in the early 2000s than the late 1980s (US EPA 2008), and refrigerators less efficient in the 1970s than the 1940s (Gutowski et al. 2011). These energy-intensive consumer products have been subject to increasingly strict energy performance standards in recent years; however, elsewhere in the home new products have been "powering up." Gutowski and colleagues (2011) note that leaf blowers, snow blowers, and power tools have replaced rakes, snow shovels, and hammers. As these powered tools develop in the future, new versions are likely to become more efficient, rendering reuse of old powered models more energy intensive than buying new (unless upgrades can be incorporated as part of reusing them). However, the initial switch to powering previously manual items is a shift toward increasing use-phase emissions for these products. These new tools may reduce human toil, but from an environmental perspective, convincing consumers to reuse nonpowered items could be doubly environmentally beneficial, saving on both embodied and use-phase impacts.

Designing for Reuse

A product with an unchanging design, such as a steel beam, is best suited for reuse. For powered products, with changing efficiencies, the environmental merits of reuse are likely to change. This was illustrated by Gutowski and colleagues (2011), who performed retrospective LCAs on reusing versus buying new refrigerators, finding that reuse would have been environmentally beneficial in the 1960s, but in no decade since. A prediction of future new product efficiencies is needed in order for a designer to understand the environmental merits of reusing his or her product in the future. The designer can then perform a product specific calculation on the trade-off presented in figure 3. Predicting efficiency improvements can be aided when preemptive legislation has already been enacted forcing manufacturers along a roadmap toward lower use-phase efficiencies. This is most likely in well-regulated industries. For example, figure 4 presents either enacted or proposed target efficiencies for passenger cars and light commercial vehicles in several countries. Similarly, Borg and Kelly (2011) collate data from the UK's Department for Environment, Food and Rural Affairs, calculating likely efficiency improvements by 2020 for several domestic products (washing machines, electric ovens, and so on). If product efficiencies are unlikely to change, then the designer may choose to make his or her product more durable. If an upgrade would be required to maintain a high efficiency, he or she may be able to redesign the product to make it more modular. If he or she is working in a fast moving industry (such as information technology [IT]), where the product is likely to become obsolete, then designing for effective component reuse or recycling (e.g., designing for disassembly) may be the best choice. Table 5 presents a suggested classification of these design options.

Design strategies that increase the reusability of a product or component (greater durability, modularity, or standardization) will often require the use of additional material and so increase the initial impacts in production. This has been recognized by Okumura and colleagues (2003) and examined by Skelton and Allwood (2013). They model the life cycle emissions associated with a product that takes account of embodied energy, use-phase

Table 5 Proposed framework for evaluating design for reuse options

	Design for...	Design principles...
Recycling	Lightweight design & design for recycling	Minimize bending moments Limited range of materials and coatings used
Technological change and efficiency improvements (Obsolescence)	Component reuse	Easy to disassemble and standardized components and joints
	Sub-assembly upgrade	Modularity and easy disassembly
Life extension	Simple repair	Durability and easy access to worn components

efficiency, and life span. They find that "built-in redundancy" that increases the product's embodied emissions by 10% can only be justified if it already fails before two thirds of its optimal life. For example, Skelton and Allwood (2013) calculate that additional embodied emissions may be justified to increase a washing machine's life span (actual life: 6 years; optimal life: 21 years) or office block (actual: 50 years; optimal: 135 years), but not a car (actual: 13 years; optimal: 10 years) or an airplane (actual: 25 years; optimal: 12 years). The environmental case for increasing the overall reusability of a product is therefore dependent on the rate of new product efficiency improvements, which are often unknown.

Reuse and the Production of New Goods

The studies reviewed so far have focused on the energy needed to reuse (and operate) an old product versus making it from new (primary) materials. For any calculated savings to translate directly into a global reduction in energy use requires the sale of a reused product to displace the sale of a new product made from primary material. The following subsections review the literature examining these two requirements respectively.

Rebound Effects: Does Reusing Reduce Producing?

Very little research has been done attempting to deduce the degree to which reusing a product displaces new production. Evidence of the belief (or fear) that reuse does displace some new product sales is the restrictions many nations place on the import of used goods in order to protect native manufacturers. Many nations have imposed bans, licensing requirements, or high tariffs (Navaretti et al. 2000); for example, on clothing imports in South Africa (Thomas 2003) and car imports in Latin America (Pelletiere and Reinert 2002). At a company level, Guide and Li (2010) present evidence that firms may be apprehensive of reusing their own products for fear of displacing new product sales, often termed "demand cannibalization." They cite a telecommunications company that scrapped US$800 million worth of returned equipment based on the fear that reusing it would displace their new product range. The above evidence from governments and original equipment manufacturers, however, does not confirm that reused goods displace new sales on a one-to-one basis nor does it reveal the potentially complex dynamics between the sales of new and reused products.

The academic literature on new product displacement consists of behavioral tests and surveys on consumer willingness to purchase new and reused products (Ovchinnikov et al. 2014; Ovchinnikov 2011; Guide and Li 2010; Farrant et al. 2010) and analytical studies that attempt to maximize utility functions based on rational consumer practices (Thomas 2003; Yokoo 2009; Thomas 2010; Scitovsky 1994; Fox 1957). The behavioral studies conclude that reuse can displace new product sales, but that it is not on a one-to-one basis. For example, Farrant and colleagues (2010) use surveys to assess the extent to which shoppers in secondhand clothing stores are only purchasing additional items that they would not consider buying at a new product price. They find that for every 100 garments that are reused, one could expect to see a decrease in new clothing sales of between 60 and 85 garments. Ovchinnikov and colleagues (2014) use results from a survey judging respondents' willingness to pay for a new and refurbished cell phone to conclude that nearly three quarters of the sales could come from new equivalents, but that this would drop if the phone company used the profits from reused sales to lower the price of new equivalents. Guide and Li (2010) use data on eBay bidding of new and reused products to infer the additional market (first-time buyers) created by a lower reuse price. They are only able to compare two products, making their results at best indicative, but they find that few people bid on both types of products, suggesting little new product displacement.

Studies that use economic utility models to predict the displacement of new products have often found that the sale of reused products could be subject to a rebound effect. Rebound effects (reviewed by economist Saunders [1992] and industrial ecologist Hertwich [2005]) are where improvements in economic efficiency (providing a cheaper good or service) lead to either a direct rebound, increasing the demand for that good or service, or an indirect rebound, where the money saved is spent elsewhere in the economy (the Khazzoom–Brookes postulate), stimulating economic growth and resource use. With respect to reuse, several researchers have postulated that it allows first-time buyers the opportunity to own products that they would otherwise have done without (Thomas 2003; Skerlos et al. 2003). This may be considered a positive social result, but the effect is not to displace new production and reduce its environmental impacts. On the contrary, some researchers have argued that reuse may stimulate new production by allowing the seller of a used item the economic opportunity to replace their goods early (Scitovsky 1994; Fox 1957; Thomas 2003), effectively making consumer products "liquid assets" (Fox 1957).

Recent attempts to analytically model the rebound effect for reuse include Thomas (2003). She finds that the only scenario in which reuse can fully replace new product sales is when the secondhand price is zero and the value customers place on the newness of the product is low. These conditions for "perfect substitution" are largely contradictory: If the value on "newness" is low, it is likely that the secondhand price will be above zero.

Table 6 Environmental impacts of production

Material	Primary production: Primary energy (Ep) MJ/kg	Primary production: Carbon dioxide kg CO_2/kg	Water usage L/kg	Secondary production: Primary energy (Es) MJ/kg	Secondary production: Carbon dioxide kgCO_2/kg	Recycled content (r%)
Dominant materials for industrial energy demand and carbon emissions						
Steel[b]	31–34	1.9–2.1	37–111	7.7–9.5	0.47–0.57	40–44
Aluminum	200–220	11–13	495–1,490	22–30	1.9–1.3	41–45
Paper and cardboard	49–54	1.1–1.2	500–1,500	18–21	0.72–0.8	70–74
Plastic[c]	77–85	2.6–2.9	38–114	45–55	2.7–3.0	8.0–9.5
Concrete	1.0–1.3	0.09–0.12	1.7–5.1	0.7–0.8	0.063–0.07	12.5–15.0[a]
Additional materials dominant in U.S. municipal waste						
Textiles—cotton	44–48	2.4–2.7	7,400–8,200	N/A	N/A	N/A
Textiles—wool	51–56	3.2–3.5	160,000–180,000	N/A	N/A	N/A
Wood[d]	8.8–10.9	0.36–0.94	500–750	N/A	N/A	N/A
Glass[e]	10–11	0.7–0.8	14.0–20.5	7.4–9	0.44–0.54	22–26

Source: All data compiled from Ashby (2012).
[a] Aggregate.
[b] Low alloy steel.
[c] Polyethylene (PE).
[d] Hard and softwoods, excluding plywood.
[e] Soda-lime glass.
MJ/kg = megajoules per kilogram; kg CO_2/kg = kilograms carbon dioxide per kilogram; L/kg = liters per kilogram; N/A = not applicable.

Thomas therefore concludes that one of the few scenarios that would result in perfect substitution is the reuse of valuable items that are otherwise being left unused in storage or being thrown away. Products with a steady long-term value, such as furniture, may fall into this category. Thomas (2010) applies her utility model from Thomas (2003) to the reuse of books, finding that, when the used goods market is small, a general rule is that the fractional decrease in sales of new goods is approximately equal to the ratio of the used to new good price.

The above studies suggest that, although reusing goods can displace new production, it is typically less than one to one. The reuse rebound effect requires greater research and is critical to understanding the holistic benefits of reuse. By drawing an analogy with the more studied rebound effect caused by cheaper energy, we may cautiously hypothesize that reuse is more likely to displace new production in the developed, rather than developing, world. Previous research has found that the direct energy rebound in developed countries is relatively low (Greening et al. 2000) compared to developing countries (Antal and van den Bergh 2014; Roy 2000). Given steel stocks' saturation, despite rising prosperity, in developed nations (Müller et al. 2011), it is possible that steel reuse in these countries will directly displace new steel production. Zink and colleagues (2014) argue that repurposing (adaptive reuse) may allow the reuser to target final applications with a high "displacement potential." It must be emphasized, however, that a reuse specific study on rebound effects is the only way to establish real trends.

Rebound considerations need to be included in LCAs of product reuse. Thomas (2010) does this in a stylized analysis of book reuse, and a few other researchers have acknowledged that the savings implied by their reused product versus new product analyses will likely be reduced by the rebound effect, notably Skerlos and colleagues (2003) and Schischke and colleagues (2003) for cell phone and PC remanufacture, respectively. A report by the UK's Waste and Resources Action Programme, in which a formal LCA methodology for assessing reuse is presented, also acknowledges "information on the propensity of a [reused] item to replace an alternate item or service should be gathered and used" (James 2011, 13).

Does Reusing a Product or Component Prevent Primary Material Production?

If selling reused products displaces new product sales, it will also displace the production of new material. New materials can, however, be produced from either natural resources, such as metal ores (primary production), or from recycling scrap (secondary production). With this is mind, how should the "saved" impacts of new material production be calculated? Table 6 presents the energy requirements and CO_2 emissions associated with primary and secondary production, along with recycled contents, for several key materials: the five materials whose production dominates global industrial energy demand (IEA 2008), and the three materials that dominate municipal waste destined for landfill in the United States (US EPA 2012).

For materials with negligible recycling, such as textiles, the new product would have to be made from natural resources (primary production). Many materials, though, such as metals, are produced from both primary and secondary scrap sources (r% recycled content). The impact of making materials for the new product (E) may then be *attributed* proportionally to primary (E_p) and secondary production (E_s), as shown by equation (1).

$$E = (E_s \times r) + (E_p \times (1 - r)) \quad (1)$$

When the *consequences* of reusing a product on the material supply chain are taken into account, the comparison between the reuse and nonreuse scenario can be further complicated. By enlarging the scope of the analyses, and assuming one-to-one displacement of new products by reused items, it is apparent that the energy savings associated with reuse are then dependent on whether or not the product would have been landfilled or recycled:

- *Product would have been landfilled:* Reusing the product saves the energy and other impacts of primary production because the material would otherwise have been lost. This assumes that reusing the item does not affect the recycling of other products.
- *Product would have been recycled*: The savings approach those of avoiding secondary production. This is because, even in the absence of reuse, the material in the product would have been recycled, contributing to the flow of material now being displaced. It should be noted, however, that reusing material might not displace recycled material on a one-to-one basis. For example, during recycling, some primary material might have to be added to the melt to correct for alloy composition.

In Allwood and colleagues' (2010c) material flow analysis, they assume a one-to-one displacement of new products by reused items and calculate that a 92% diversion of scrap away from recycling and into reuse would allow steel industry emissions to be halved by 2050. They do not assess the viability of achieving this percentage, but Milford and colleagues (2013) determine the theoretical maximum steel reuse rates for different product categories, none of which are above 30%. As discussed in the section *Rebound Effects: Does Reusing Reduce Producing?*, the underlying assumption that reused products perfectly displace new items may often be incorrect. In circumstances where reuse stimulates new production, primary and secondary production might increase.

Conclusions

Many prominent consumer goods (refrigerators, cars, and so on) are becoming increasingly efficient. As these products' use-phase impacts further decline (potentially plateauing) and consumers become more affluent, perhaps coming to own several of the same product (such as a freezer in both the basement and kitchen), the relative importance of the embodied impacts will become more significant. Longer term, therefore, the importance of reuse as an abatement strategy is likely to grow.

The case studies recorded in the literature indicate that the energy and materials needed to return a product or component at EOL to a usable condition or location are typically minimal compared with new production. There are some immediate opportunities, posing few technical challenges, to reuse energy-intensive unpowered products, such as structural steel, packaging, and furniture. If the product is powered, the environmental impact of the use phase is often dominant. In this case, it is important that short-lived products are fully restored to their original efficiencies. For longer-lived products, there is the possibility that more-efficient, new products now exist, and unless an upgrade to modern efficiency levels is possible, it may be better to replace the old product and pursue reuse of its components. When new product efficiency trends can be predicted with some confidence, it appears that designers can justify adding material in the production stage (increasing durability, standardization, or modularity) to facilitate reuse at EOL.

Reusing an item does not guarantee environmental benefits. Whereas numerous studies have shown that, under the right circumstances, the life cycle energy of a reused product may be lower than that of a new product, for this to translate into a real reduction in environmental impacts, sales (or gifts or continued use) of reused products must displace sales of new products. This reflects the extent to which the reused products are utilized by consumers who would otherwise buy new, displacing new sales, or from consumers who would not buy new, which does not displace new sales. Based on the limited research conducted so far, it appears unlikely that, without regulatory pressures, an increase in the reuse of products will translate to an equal decrease in the sale of new products.

In order to encourage reuse, policy makers should first ensure that existing legislation does not present disincentives. For example, Power (2008) notes that the UK charges a value-added tax on refurbishments, but not new-build construction projects. Government could stimulate demand and an effective supply of reused products by mandating some reuse in their purchasing and construction decisions. In academia, further research is needed in order to understand how reuse could maximize the displacement of new products.

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