A comparison of manufacturing and remanufacturing energy intensities with application to diesel engine production

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ABSTRACT

Climate change reports and policies relating to end-of-use products, CO_2 emissions, and energy are causing manufacturers to examine their operations closely. Several reports have touted the economic and environmental benefits of remanufacturing, including claims of significant reductions in terms of energy and CO_2 emissions. However, large-scale remanufacturing of heavy equipment engine components has not been closely examined and no standard procedure exists to quantify the benefits of remanufacturing. A methodology is presented for determining the energy intensity and benefits of remanufacturing as compared to new manufacturing, and this is applied to a diesel engine example. These findings are used to estimate the embodied manufacturing/remanufacturing energy across multiple use cycles.

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1. Introduction

For several decades, researchers have been gathering a wealth of information on suspected causes of and recommendations for reversing climate change, which remains at the top of the global environmental agenda [1]. Public awareness of the causes and potential impacts of climate change is becoming pervasive. Demands for regulatory action to help quell the emissions of CO_2 and other greenhouse gases (GHG) are on the rise.

Within the industrial sector, manufacturing contributes a significant portion of GHG emitted globally. Manufacturing produces GHG emissions directly through onsite use of fossil fuels, as well as indirectly through resource and energy consumption to support operations. According to UNEP, in 2004, global CO_2 emissions were 28×10^{12} kg, primarily due to fossil fuel combustion. Nearly 20%, or about 5×10^{12} kg, was attributed to direct manufacturing and construction emissions [2]. Manufacturing end uses also produce indirect emissions, through electricity consumption. As actions are considered to reduce GHG, it should be noted that CO_2 emissions are largely proportional to energy consumption [3].

Fig. 1 shows the breakdown of U.S. energy consumption of manufacturing subsectors [4]. Primary metals processing is significant, and accounts for nearly 10% of overall manufacturing energy consumption. Vehicle and heavy equipment manufacturers create products from primary metals (e.g., steel and aluminum) in large quantities. Thus, they are responsible for CO_2 emissions from

plant operations (electricity and fossil-fuel use) and via the embodied carbon content of supplier-delivered materials.

Of course, the products of these manufacturers also produce significant CO_2 emissions during their use stage, when they consume large quantities of fossil fuels, as shown in Fig. 2. As is evident, the CO_2 emissions from the U.S. due to industrial end uses are slightly more than those from transportation end uses. However, the distribution of energy consumption (and CO_2 emissions) across the lifecycle stages is highly product dependent. For example, a diesel engine (components of which are considered in this paper) may produce 10 times the CO_2 over its operational life than during manufacturing and remanufacturing. This fact has driven many past efforts to improve engine efficiencies and reduce use stage GHG emissions. While the use stage of diesel engines has received much attention, it is believed that dramatic reductions in energy consumption due to manufacturing/remanufacturing activities are also achievable.

For many products, manufacturing energy is a small fraction of the total product lifecycle energy and as a result, has been largely overlooked. Consider the study of a generic automobile, which reported that the energy consumption for material production and manufacturing accounted for 14% of lifecycle energy, while use was responsible for about 85% [5]. With an average energy consumption of 133.7 GJ and an energy cost of $12.94 per GJ, the manufacturing energy cost is $1730. In contrast, fuel consumed throughout the life of the vehicle costs $7293, assuming a fuel economy of 10 L per 100 km, a fuel price of $0.379 per L (1995–2005), and a 192,000 km life [5,6]. Fuel economy has received much attention and remains a concern of the consumer, but there is much to be gained through renewed efforts to improve manufacturing energy efficiency.

Used product takeback is one way to conserve some of the energy expended in converting extracted materials into a new product. In the management of used products, recycling is better
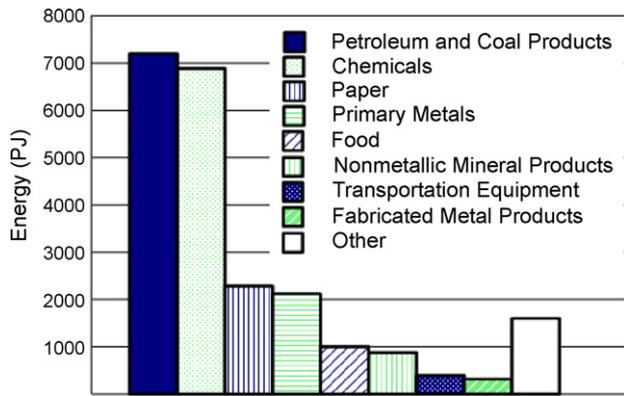
Fig. 1. Energy consumption for U.S. manufacturing subsectors [4].

than landfilling in that it recovers some material value and energy that has been invested via materials processing. However, both of these options are less desirable than remanufacturing. Remanufacturing has the ability to repair degraded components and put the product back into service, thus retaining the value of the extracted and refined material, as well as some fraction of the original manufactured value [7]. Remanufacturing includes disassembling, cleaning, refurbishing, replacing (as necessary), and reassembling parts to produce a "like new" product. In today's market, many products are remanufactured and reused, oftentimes without customer knowledge. For automotive and heavy equipment, engine and fuel system components are widely remanufactured. Drivetrain components and other systems are also remanufactured.

On an industry-wide basis, the monetary benefits of remanufacturing have been documented [8,9]. It has also been reported that automotive remanufacturing alone could save an annual energy equivalent of five nuclear power plants [10,11]. Industry-wide remanufacturing energy savings, or the difference between original and remanufacturing energy consumption, have been reported to be approximately 85% [12]. In addition, research issues related to expanding remanufacturing operations have been studied. Zhang et al. [13] introduced a method to optimize the disassembly sequence of electrical equipment based on operational costs. Seliger et al. [14] investigated the remanufacturing of mobile phones, including the development and assessment of remanufacturing plans under such uncertainties as product quantity and quality. Williams and Shu [15] analyzed remanufacturing facility waste streams to develop metrics for product design evaluation that minimize remanufacturing waste.

While many industry-wide studies of remanufacturing have been undertaken, little work has focused on the difference between manufacturing and remanufacturing in terms of CO_2 emissions or energy consumption attributed to specific products. In this paper, the energy benefits of remanufacturing are presented for the major components of a large diesel engine. The broader implications of large-scale remanufacturing are then examined
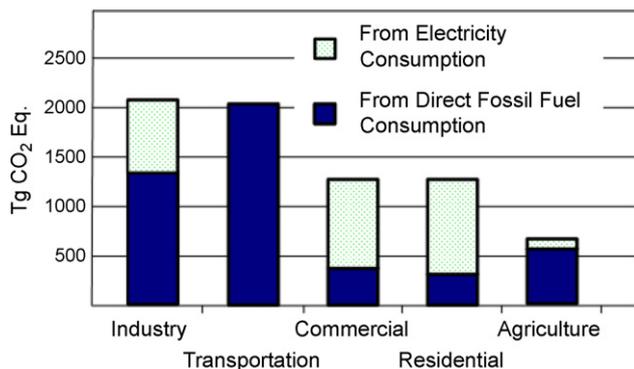
across multiple product use cycles. It is concluded that product remanufacturing is a promising corporate strategy to reduce energy consumption and decrease CO_2 emissions.

2. Environmental performance of manufacturing and remanufacturing

Environmental impacts due to product manufacturing are beginning to receive increased attention from companies. Manufacturing contributes heavily to such environmental lifecycle measures as energy, materials use, and water consumption. However, unlike manufacturing, the environmental performance of remanufacturing has not been well quantified. The focus of this study was the original manufacture and remanufacture of diesel engine components. The remanufacturing facility that was studied receives large shipments of used diesel engines. The engine subsystems are disassembled, cleaned, and inspected. A component (or core) that cannot be refurbished satisfactorily based on inspection is recycled; otherwise, it is remanufactured using welding, machining, and other salvage operations. The primary cores of interest for this study were engine blocks, cylinder heads, crankshafts, connecting rods, and pistons. The last step in the remanufacturing process is to reassemble the components to produce a like-new diesel engine, with "virgin," or newly manufactured, components serving as replacements for the non-remanufacturable cores.

Diesel engine components are primarily composed of strong, durable materials such as cast iron and steel. Table 1 synthesizes the findings of Boustead and Hancock [16] that examined the energy consumption of a variety of products made from these materials (aluminum is also shown for reference). These results encompass the cradle-to-gate energy requirements of generic manufactured products, including transportation. It should be noted that Boustead and Hancock used data from the U.S. and Europe and was compiled in the 1970s. The table also shows predicted remanufacturing energy requirements using data from Adler et al. [17].

The values for remanufacturing energy in the table were obtained from measurements taken in the engine remanufacturing facility for the remanufacturing processes under study. These measurements were the production flow rate (components per hour) and workstation energy consumption (MJ per hour). Mass flow rate was determined from the production flow rate, and was then divided into the energy flow rate to estimate the specific energy associated with remanufacturing.

The original manufacturing of the same components was characterized in a similar fashion, and the resulting specific energies compared favorably to the Boustead and Hancock values shown in the table. The energy benefit of remanufacturing can be expressed through the ratio of remanufacturing energy to original manufacturing energy. These ratios ranged between 2% and 25%. Recovered components that were subjected to harsh conditions, e.g., cylinder heads, have a higher probability of large wear levels and/or structural failure, and therefore have higher relative remanufacturing energy requirements than those subjected to less severe conditions, e.g., pistons and connecting rods.

Energy, and associated GHG emissions, was invested in the original creation of the recovered cores, and the remanufacturing of these components allows this embodied energy to be retained. Thus, the use of remanufactured components for a six-cylinder diesel engine can potentially avoid the extra 16,250 MJ of energy

Fig. 2. U.S. CO_2 emissions allocated to end uses [3].

Table 1
Comparison of energy intensity estimates for manufacturing and remanufacturing

Material	Extraction/refining (MJ/kg)	Casting/manufacturing (MJ/kg)	Remanufacturing (MJ/kg)
Aluminum	240	16	0.32–4.0
Cast iron	22	28	0.56–7.0
Steel	24	17	0.34–4.3

Table 2
Embodied energy of various engine components

Component	Casting/manufacturing (MJ)	Remanufacturing (MJ)
Engine block (cast iron)	9970	600
Cylinder head (cast iron)	4445	1110
Crankshaft (steel)	2800	110
6 connecting rods (steel)	330	10
6 pistons (steel)	555	20
Total energy required	18100	1850
Avoided energy with remanufacture		16250

that would be required to create new components rather than remanufactured cores (Table 2).

Of course, to realize the potential energy benefits of remanufacturing relative to manufacturing, the cores recovered via disassembly must be remanufacturable. The actual benefits of remanufacturing, in terms of energy consumption, are highly sensitive to several factors. This sensitivity is examined in the next section.

3. Assessing benefits of remanufacturing

The previous section explored the potential dramatic benefits of remanufacturing over manufacturing in terms of energy savings (study showed greater than 90% energy savings). However, to realize these potential benefits a few challenges must be addressed. For example, it was frequently noted in the examination of the engine remanufacturing facility that newly manufactured components were needed to "make up" for damaged cores. The observed core remanufacturability efficiency ranged from 50% to 90% (depending on the component); this is the efficiency with which a manufactured core actually is remanufactured at some future point in time. The losses of cores can be attributed to:

- Nonsalvageable, heavily damaged components;
- Inadequate remanufacturing procedures or equipment to return a component to like-new condition; and
- Systemic losses of cores, e.g., cores that are never recovered.

These barriers to achieving higher remanufacturability efficiencies are daunting, but not insurmountable. Product development teams addressing remanufacturing issues must create robust designs so that cores can be remanufactured and reused in newer products. Manufacturing engineers must develop competitive technologies for remanufacturing used components. Finally, lifecycle managers must provide a systems perspective to address recovery challenges and target components for redesign to facilitate remanufacturing.

Several design strategies can be employed to assist in improving core remanufacturability efficiency. Component assemblies can be designed to promote removal, repair, and replacement. Cores requiring frequent replacement can be designed to perform over multiple use cycles with periodic refurbishment. Also, based on material properties and part geometries, nonsalvageable cores can be designed to serve different functions. For example, a worn loader bucket can be used as a source of steel plate.

In making decisions about product design and recovery system changes to be implemented, the relative benefits of the alternatives must be quantified. Specifically, an accurate accounting of energy benefits, and concomitant GHG emissions, is needed to support decisions related to the planning and implementation of any change. Product development teams therefore need decision support tools that can assist them in minimizing lifecycle energy and CO_2 releases.

To illustrate how a design team can quantify the benefits of product and recovery system changes to facilitate decision making, a method is described below to analyze energy consumption. This method considers original manufacturing energy (E_M), remanu-
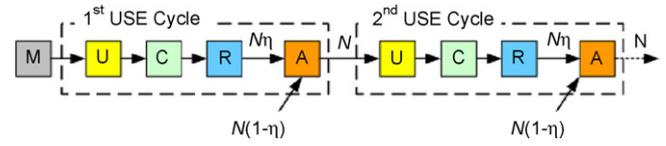

Fig. 3. Flow of components over multiple use cycles.

facturing energy (E_R), and the core remanufacturability efficiency (η). Let us assume that the number of cores within a system is N. If N engines are in use, for example, then N engine block cores are in the system. Fig. 3 shows the flow of new and recovered cores for manufacturing (M) and several use (U), collection (C), remanufacturing (R), and assembly (A) cycles. Following each remanufacturing step, core losses are made up with $N(1 - \eta)$ virgin cores.

Energy requirements can be calculated assuming that the manufacturing and remanufacturing energies remain constant, and that the system core remanufacturability efficiency also stays the same. The cumulative energy can be calculated as a function of the number of use cycles, and the manufacturing/remanufacturing energy per use can also be determined. The manufacturing energy for the batch of new parts is

$$E_1 = NE_M. \tag{1}$$

In general, the cumulative energy consumed by the N cores in the system after k use cycles is

$$E_k = NE_M(k - (k - 1)\eta) + NE_R(k - 1)\eta. \tag{2}$$

The predicted energies for this method are illustrated in Fig. 4 for several core remanufacturability efficiencies.

For this illustration, let us assume that original manufacturing uses 10 units of energy and remanufacturing consumes 2.5 units of energy. The system is assumed to have a requirement of $N = 100$ cores. The figure demonstrates the potential energy benefits achievable through remanufacturability efficiency improvements.

To reduce the use-stage energy impact of a product, cast iron is often replaced with aluminum (density ratio is 2.91). Assume such a design change was pursued for the cast iron cylinder head. The energy to extract and process material and manufacture a cast iron head is 10.2 GJ, and remanufacturing requires 1.11 GJ. For the same size aluminum head, the manufacturing and remanufacturing energies are 23.0 GJ and 0.36 GJ. However, such a design change may require a greater volume of aluminum, e.g., 50% more [18]. For this cylinder head illustration, this would increase the manufacturing and remanufacturing energy use to 33.5 GJ and 0.52 GJ.

Fig. 5 shows the energy per use for several use cycles at a core remanufacturability efficiency of 50% for the two materials. Cast iron appears to be superior to aluminum. In fact, further analysis found the larger aluminum heads would need a core remanufacturability efficiency of 99% for eight use cycles to achieve lower manufacturing energy per use. It must be noted that the energy
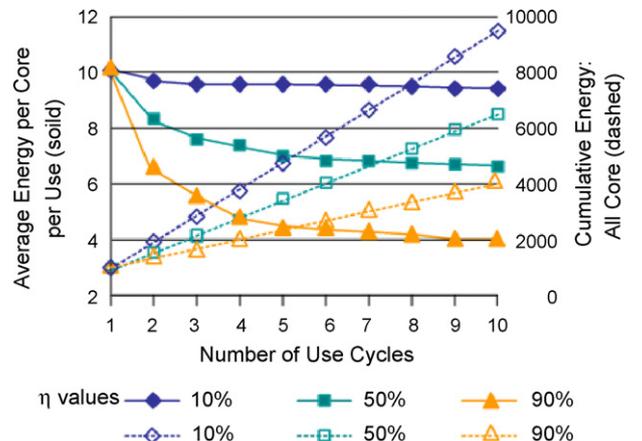

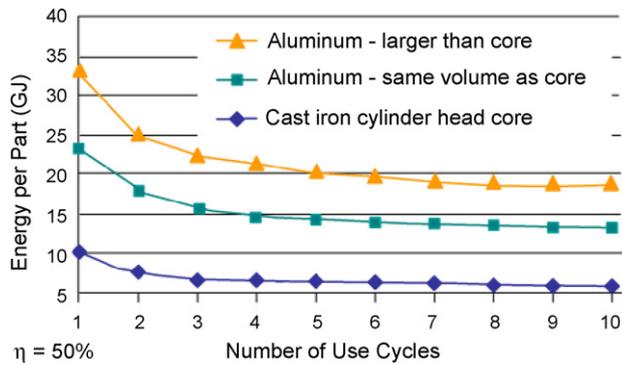**Fig. 4.** Average and cumulative energies for several remanufacturability efficiencies.

Fig. 5. Simulated energy intensity reductions through additional use cycles.

values for new component manufacturing are likely inflated, since it was assumed that components are created from virgin material. Of course, the model can be used to evaluate different energy assumptions and as part of an overall lifecycle energy analysis.

Previous redesign efforts have focused on weight reduction to reduce use stage environmental impacts. In some applications, lighter materials present wear and fatigue issues that can lead to increased failure rates, indirectly increasing product environmental impacts. Moreover, existing design analysis methods are generally focused on a single-use lifecycle for new products. With increased component longevity, accounting for impacts over multiple use cycles and evaluation of manufacturing and remanufacturing environmental impacts is necessary.

4. Summary and conclusions

The benefits of remanufacturing relative to manufacturing for diesel engine production have been examined. A model was developed for manufacturing/remanufacturing energy requirements per use cycle for a given number of cores and use cycles. The model was used to evaluate the sensitivity of manufacturing energy to changes in design and core remanufacturability efficiency. Model results showed that increases in core remanufacturability efficiency could significantly reduce energy consumption (and GHG emissions) per part over multiple use cycles. The model suggests that the traditional focus on only the use stage for material selection may oversimplify the problem. For some applications, energy savings achieved during use may not overcome other lifecycle energy losses, even when considering multiple use cycles.

Avoided GHG emissions attributed to remanufacturing are due to less raw materials and materials processing and fewer

manufacturing operations. Enterprise strategies and product designs are needed to capture the benefits of remanufacturing, and reduce costs, energy, and waste.

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