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Authors

Helu, Moneer
Vijayaraghavan, Athulan
Dornfeld, David

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Evaluating the relationship between use phase environmental impacts and manufacturing process precision

M. Helu [a,*], A. Vijayaraghavan [b], D. Dornfeld (1)[a]

[a] Laboratory for Manufacturing and Sustainability, University of California, Berkeley, USA
[b] System Insights Inc., Berkeley, CA, USA

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ABSTRACT

The environmental impact of most consumer products is dominated by their use phase. However, these impacts tend to be driven by the manufacture of the product's components since components fabricated with higher precision typically allow the product to operate at higher efficiencies. This paper investigates the relationship between precision and life cycle environmental impacts by extending the traditional LCA methodology to evaluate the impact of manufacturing process precision on the functional performance of a product during its use phase. The implications of this relationship to manufacturing decision-making are also discussed as sustainability concerns may support the use of higher precision processes.

1. Introduction

Life cycle studies of products tend to focus on the use phase for several reasons including the assumed long life of components, the ease of implementation of strategies to reduce use phase impacts, and a general lack of expertise with other life cycle stages. Previous literature, though, has shown that the manufacturing phase can have a substantial effect on the environmental impact of a product particularly when flows beyond electrical energy are considered [1]. This is especially true since manufacturing decisions can have a direct effect on a product's use phase impacts. For example, increasing the manufacturing precision of a product generally leads to longer service life and greater operational efficiency. An example of this trend can be seen in Fig. 1, which shows the historical power density of engines manufactured by Daimler, a German automotive manufacturer; the increased slope is from the increase in tolerances and precision that have been achieved in the manufacture of powertrain components over time [2].

The potential effects of manufacturing on the use phase show that a manufacturer should focus on a product's entire life cycle to reduce impacts instead of only on areas of legal responsibility [3]. As manufacturers become increasingly responsible for the environmental performance of products throughout their life cycle, it is vital to know how manufacturing decisions can affect a product's environmental impact across all life cycle stages [4,5]. So, it is important to evaluate if the manufacturing process affects the use phase environmental performance of products since this can potentially have a significant effect on the product's life cycle, especially if the product's environmental impacts are dominated by its use phase. This paper seeks to explore the relationship between manufacturing process precision and the life cycle environmental impacts of a consumer product and how this relationship may affect manufacturing decision-making.

2. Related work

Much of the literature on the life cycle impacts of manufacturing have focused on characterizing and reducing the environmental impact of manufacturing processes, equipment, supply chains, and facilities, and have provided extensive and important knowledge in understanding the manufacturing phase of the product life cycle [1]. More recent research has started to consider the implications of manufacturing decisions on the entire product life cycle. For example, Hauschild et al. [6] discusses the need to balance trade-offs in the operational performance and environmental impact of any design or manufacturing decision. Duflou et al. [7] provides a specific product example where the use of composite structures in an automobile is evaluated across all life cycle stages to determine its ability to reduce overall environmental impact. Other work has developed strategies using product design to address environmental impacts in later life cycle stages including Kara et al. [8], who provide a methodology to estimate the life cycle impacts during the concept design stage, Umeda et al. [9], who discuss a modularized framework to evaluate the life cycle impacts of different product design options, and Lucchetta and Bariani [10], who use a multi-objective analysis to take into account performance requirements when reducing the environmental impact of injection molded parts. This paper builds upon these previous approaches by extending the life cycle analysis (LCA) methodology to evaluate the effect of manufacturing process precision on the use phase of a product.

3. Effect of manufacturing precision on operational efficiency

Manufacturing precision can have a strong effect on the operational efficiency of many consumer products such as an

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* Corresponding author.
E-mail address: mhelu@berkeley.edu (M. Helu).

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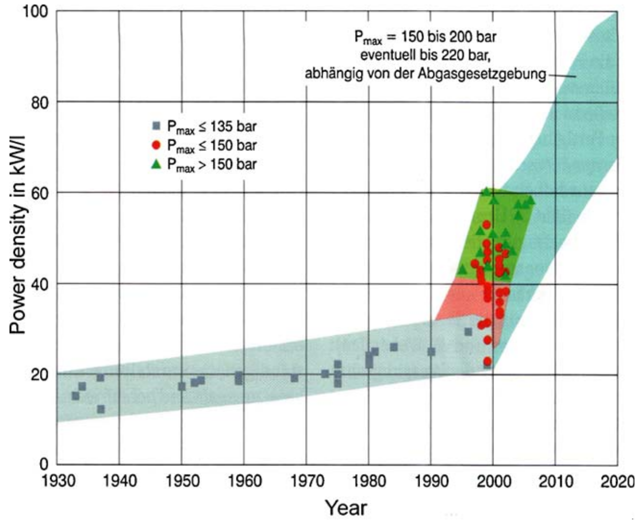

Fig. 1. Change in power density due to increased precision for Daimler diesel engines [2].

automobile. The operational efficiency of an automobile can be generally measured based on its fuel economy, which is strongly influenced by the construction of the powertrain where tight tolerances and high quality surfaces in the camshaft and crankshaft bearings are required to ensure relatively low losses. Tight tolerances are also required between the piston, piston ring, and cylinder surfaces to enable the use of lower viscosity oils that reduce frictional losses in the engine. The drivetrain is another component of automobiles that is vital to fuel economy.

The efficiency of gear systems has recently become an important research area as the automotive industry has sought ways to improve fleet fuel economies and reduce pollutant emissions to meet increasingly stringent regulations [11]. Recent work has shown that the efficiency of gear systems is due to several factors including the surface roughness of the mating surfaces, assembly errors (e.g. shaft misalignments), and other manufacturing errors (e.g. form errors). Fig. 2 shows the influence of RMS surface roughness (labeled S in Fig. 2 instead of the traditional R_q as used in this paper) on gear efficiency for a helical gear pair modeled after the final drive reduction of a standard automotive manual transmission drivetrain. Similar work has shown an even greater dependence on the surface roughness of the mating surfaces for hypoid gear pairs, which are found in automotive differentials [12]. Because the vast majority of environmental impacts of an automobile occur during the use phase [13], the impact of increased manufacturing precision through better surface finish on the final drive reduction of an automotive manual transmission drivetrain presents the ideal case study for this investigation.

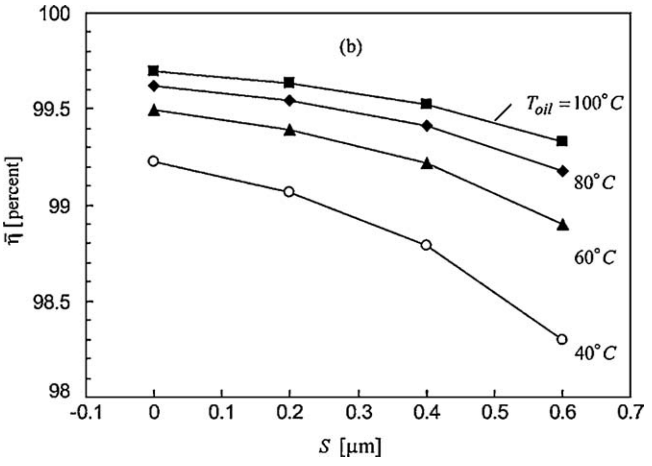

Fig. 2. Relationship between gear mesh efficiency, η, and RMS surface roughness, S, for different inlet lubricant temperatures, T_{oil}, for a helical gear pair modeled after a final drive reduction [11].

4. Case study: automotive drivetrain

Our case study looked at the relationship between the surface finish of the final drive reduction of an automotive manual transmission drivetrain and its use phase impacts. The vehicle for the case study was modeled after a Honda Civic, a representative fuel-efficient sedan currently on the market. The modeled vehicle had a mass (without passengers) of 1193 kg [14]; a frontal area, A_r, of 2 m^2; a drag coefficient, C_d, of 0.30; and a rolling resistance coefficient, C_{rr}, of 0.013 [15]. The functional load of the vehicle was assumed to be 1.2 passengers who each weigh 71.2 kg and carry 7 kg of luggage, and the fuel tank was assumed to be 55% filled [7]. The functional life of the drivetrain components was assumed to be 130,000 km, which is at the lower range of the expected lifetime of most vehicle transmissions that are maintained at standard levels.

The drivetrain components of the modeled vehicle were grouped into three parts to simplify analysis: transmission, final drive reduction, and differential. The efficiency of both the transmission and drive axle was assumed to be 95% [15]. The drive axle is composed of the final drive reduction, differential, and the axles that transmit torque from the transmission to the tires. This analysis assumed that the axles were reasonably stiff, solid components so that the losses in the drive axle occurred equally in the final drive reduction and differential. The powertrain of the modeled vehicle was conservatively assumed to have an efficiency of 30%.

Since this analysis was concerned with the change in life cycle environmental impacts, the functional unit was a final drive reduction. To enable comparison across both the manufacturing and use phase, the metrics for this analysis were primary energy (PE) to represent resource consumption and global warming potential (GWP) emissions to represent environmental impacts. This analysis focused on electricity and gasoline usage as the sources of PE demand and GWP emissions in the manufacturing and use phases, respectively.

4.1. Manufacturing phase

The gear manufacturing process chain is relatively complex with several options available to the manufacturer at each fabrication stage. However, it is assumed that the main process chain would be unchanged and that only gear finishing would need to be altered to produce gears with improved surface finish. Karpuschewski et al. [16] provides an excellent review of different abrasive gear finishing processes; this analysis applies general grinding processes for gear finishing.

Malkin and Guo [17] describe a general empirical relationship that relates the achieved average height surface roughness, R_a, of a grinding process to the specific volumetric removal rate, Q'_w, and the grinding wheel speed, v_s:

$$R_a = R_1\left(\frac{Q'_w}{v_s}\right)^x, \tag{1}$$

where R_1 and x are experimentally determined constants and $0.15 < x < 0.60$. If the working width of the grinding wheel remains constant, then a relative change in Q'_w is equivalent to a relative change in the volumetric removal rate, Q_w. So, assuming that all other aspects of the grinding process remain constant, the volumetric removal rate needed to achieve a lower R_a relative to a defined gear finishing process can be estimated as follows:

$$Q_{w2} = Q_{w1}\left(\frac{R_{a2}}{R_{a1}}\right)^{1/x}. \tag{2}$$

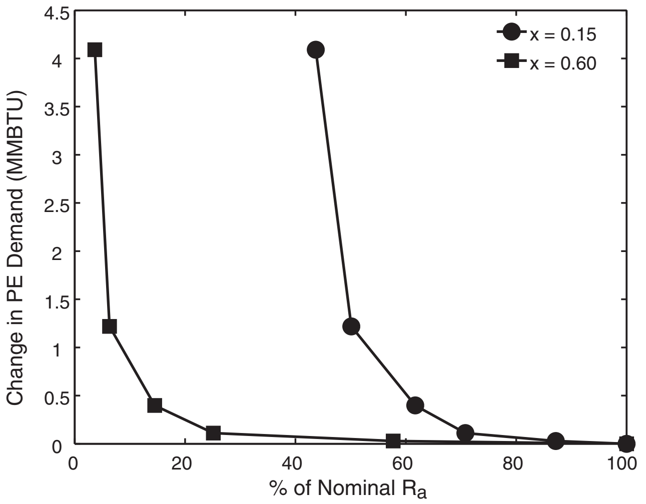

Fig. 3. Change in PE demand during the manufacturing phase due to decreased surface roughness. *x* is an experimentally determined constant that describes the relationship between the specific volumetric removal rate of the grinding process and the achieved average height surface roughness.

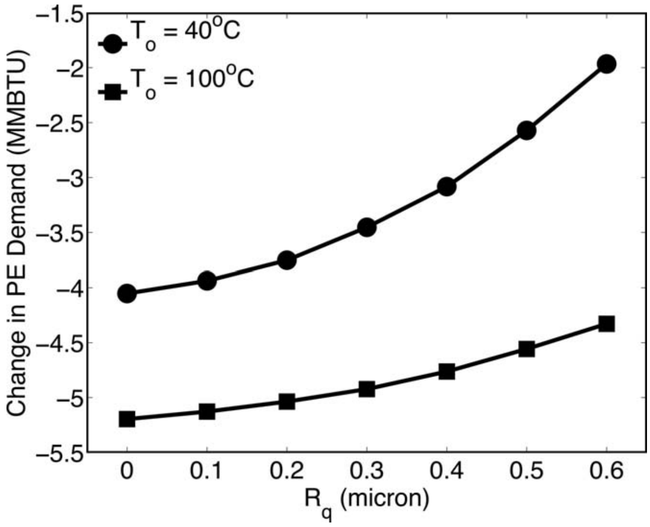

Fig. 4. Relationship between RMS surface roughness, R_q, of the final drive reduction and the change in PE demand relative to a standard finished final drive reduction during the use phase for two lubricant temperatures, T_o.

Gutowski et al. [18] assigns a specific energy requirement of 200,000 J/cm^3 to a representative grinding process with process rate $\sim 10^{-2}$ cm^3/s. This representative grinding process was assumed to also be reflective of standard automotive gear finishing applications. The results of Gutowski et al. [18] and Eq. (2) were used to estimate the increased specific energy required to decrease the surface roughness of the final drive reduction relative to the representative gear finishing process. To determine the energy required, the volume of material removed was estimated by first calculating the surface area of the modeled helical gear pair in Fig. 2 ($\sim$21,055 mm^2). The depth of cut was then assumed to be 1 mm for the gear finishing process; this estimate provides an upper bound to the manufacturing energy usage since finish processes generally have lower depths of cut. PE demand and GWP emissions were then determined assuming a Michigan electricity mix (7015.2 Btu/kW h and 0.7131 kg CO_2-eq/kW h, respectively [19]). Fig. 3 shows the resulting change in PE demand for a corresponding decrease in R_a. GWP emissions follow a similar trend to PE demand over the range 0–425 kg CO_2-eq.

Fig. 3 shows that decreasing the R_a of the gears in the final drive reduction to 20–60% of that achieved for standard automotive gear finishing can be accomplished for less than 0.5 MMBtu PE per final drive reduction. The energy required to further decrease R_a increases significantly since the processing rates are less than 10^{-5} cm^3/s, which is unlikely with standard grinding processes. However, these smaller R_a values could be attained with other abrasive processes such as lapping or superfinishing, which would likely require less PE.

4.2. Use phase

The fuel consumption of a vehicle is dependent on the power that the powertrain must deliver to meet the commanded acceleration while powering any accessories (e.g. air conditioning) and overcoming losses in the drivetrain and engine. Because this analysis considered only changes to the drivetrain efficiency, the power required for any accessories and frictional losses in the engine were neglected since neither would be affected. So, the change in fuel power due to a change in drivetrain efficiency, ΔP_{fuel}, is as follows:

$$\Delta P_{\text{fuel}} = \frac{P_{\text{tractive}}}{\eta_e \eta_t \eta_d}\left(\frac{1}{\eta_{f2}} - \frac{1}{\eta_{f1}}\right), \tag{3}$$

where P_{tractive} is the power that must be provided to overcome tractive losses and accelerate the vehicle, η_e is the engine efficiency, η_t is the transmission efficiency, η_d is the differential efficiency, and η_{f1} and η_{f2} are the final drive reduction efficiencies of interest. A vehicle must overcome road grade or climbing resistance, rolling resistance, and aerodynamic drag in order to accelerate. Thus, P_{tractive} can be estimated as follows:

$$P_{\text{tractive}} = v(ma + mg\sin\theta + mgC_{rr} + \tfrac{1}{2}\rho_{\text{air}} v^2 A_r C_d), \tag{4}$$

where v is the velocity of the vehicle, m is the mass of the vehicle and load, a is the commanded acceleration of the vehicle, g is the acceleration due to gravity, θ is the road grade, and $\rho_{\text{air}} = 1.225$ kg/m^3 is the density of air at 15 °C and 101.32 kPa, which are standard conditions for vehicle performance calculations [15].

The U.S. EPA Federal Test Procedure 75 (or FTP-75) emissions driving cycle was used to represent a standard driving scenario for this analysis. FTP-75 is a common transient cycle used for dynamometer testing and covers 17.77 km in 1874 s for an average speed of 34.12 km/h [20]. Using FTP-75, Eqs. (3) and (4), and the efficiencies from Fig. 2, the decrease in fuel requirements was calculated for each R_q of the gear pair in the final drive reduction. The resulting decrease in energy that must be provided by the fuel was then determined by integrating the decrease in fuel power over time. All deceleration events were removed from this calculation, though, since a deceleration event does not require power from the engine. Modern engines are operated to fully combust fuel, and so the PE demand and GWP emissions were determined assuming that the fuel source was regular, unleaded gasoline (1184.8 Btu/MJ used fuel and 0.0948 kg CO_2-eq/MJ used fuel, respectively [21]). Fig. 4 shows the resulting change in PE demand corresponding to a particular value of R_q. GWP emissions follow a similar trend to PE demand over a range of −400 to −150 kg CO_2-eq.

Fig. 4 shows that decreasing R_q lowers PE demand relative to a standard finished final drive reduction from 2 to 5 MMBtu in the use phase depending on the lubricant temperature in the final drive reduction, T_o. We saw earlier that a 20–60% reduction in R_a increases PE demand in the manufacturing phase by less than 0.5 MMBtu. Comparing these analyses indicates that improving the manufacturing precision of the final drive reduction can provide a substantial reduction in the life cycle impacts of an automobile. Since the final drive reduction is one of several gear pairs in a vehicle, the impact of manufacturing precision on the entire vehicle drivetrain could be much greater. Furthermore, the increased manufacturing precision of the final drive reduction may also increase the service life of the component itself, which would provide further reduction in the life cycle impacts of an automobile.

5. Conclusions

This analysis has shown that a relationship exists between the manufactured precision of a product and its environmental impacts over its entire life cycle. In the case of automotive drivetrain components, this relationship was found to be positive. However, it may not be true for every product and is largely dependent on the intended function of the product. Ultimately, if a manufacturer is concerned with environmental impact when considering a process or system design, then he should improve the manufacturing precision if the resources required for the improvement are less than the potential benefit of the improvement in the use phase of the manufactured product.

Measuring the impacts of each life cycle stage is vital to ensure dependable results. The analysis presented in this paper was quite broad and requires more precise measurement to be effectively used in manufacturing decision-making for automotive drivetrain components. Future work will seek to improve the measurement of the impacts of each life cycle stage so that a causal relationship between manufacturing precision and environmental impacts may be developed for this and other consumer products. The potential impact of other manufacturing considerations should also be explored and an LCC analysis should be completed to ensure economic sustainability.

The approach presented in this paper should enable manufacturers to evaluate the impact of process precision and other manufacturing considerations on the functional performance of a product during it use phase. Such an effort not only offers the manufacturer easy-to-attain quantitative insight into both the precision and impact of their design, but also allows the manufacturer to be better positioned to control the environmental performance of a product throughout its lifecycle. As this performance has increasingly become the manufacturer's responsibility, these types of tools will be important to ensure continued competiveness.

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