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Comparative life cycle assessment of manufactured and remanufactured loading machines in China

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ABSTRACT

Remanufacturing is the industrial process of returning used or worn-out products to a new functional state and has been developed in China within the framework of the circular economy. Due to the recent mass production and use of construction machinery in China, there will be a huge remanufacturing potential in coming years. In this paper we take the loading machine as a case study, and use life cycle analysis to compare the environmental impacts and cost of a manufactured loading machine (S1) with its remanufactured counterparts under two return-back scenarios: remanufacturing at the original factory (S2) and at regional dealers (S3). A life distribution model was used to estimate loading machine scrappage. The results showed that climate change effects in S1, S2 and S3 were 4.4 t, 1.3 t, 0.92 t CO_2-eq respectively. The financial cost in S2 and S3 was 48% and 35% respectively of the cost in S1. S3 achieves an efficient closed-loop and had the best environment and economic benefits. Carbon reduction resulting from remanufacturing is expected to peak in 2020 and 2039, and if the recycling rate is increased from 25% to 60%, the maximum CO_2-eq reduction will increase by 351 million tons. Remanufacturing should play a vital role in urban carbon reduction strategies, and enterprises are capable of implementing remanufacturing through technical innovation. The quantitative environmental and economic analysis also enables remanufacturers and consumers in the market to make informed decisions.

1. Introduction

The manufacturing of HDOR (heavy-duty and off-road) machinery has experienced explosive growth in China since the 1990s, and the industry has recently entered a new stage of technological innovation, transformation, and upgrading (Zhou et al., 2012; Off-Highway Research, 2016). A loading machine is a type of HDOR machine mostly used to load materials such as asphalt, demolition debris, dirt, gravel, raw minerals, and so on, and has played an important role in China's huge construction projects in recent years. China will soon enter a peak period of discarding worn out construction machinery, and although official statistics are lacking, a preliminary user survey suggests that most end-of-life machines are dismantled and sold as scrap to steel plants. Recently the price of scrap steel has fallen to less than 1 yuan RMB/kg, meaning that there are minimal economic benefits for scrap sale when transportation and dismantling fees are deducted. As a result, many end-of-life loading machines are illegally dumped, resulting in significant resource waste and land pollution.

Remanufacturing is an industrial process of returning used or worn-out products to an "as new" functional state (Tan et al., 2014). Compared to recycling, remanufacturing is a relatively high level treatment process for end-of-life products, because a greater part of the value added during original fabrication, including labor, energy, and equipment expenditures, is preserved while adding a second life to the product (Liu et al., 2014; Smith and Keoleian, 2004). As a result, remanufacturing is an effective way to implement green manufacturing by repairing degraded components and putting the product back into service, thus retaining the value of the extracted and refined materials (Liu et al., 2016). The United States is currently the largest remanufacturer in the world, with the value of remanufactured production growing by 15% per year (U.S. International Trade Commission (USITC, 2012), and the American and European HDOR remanufacturing markets were estimated to be worth $7717 million and $4827 million respectively in 2015 (Parker et al., 2015). These figures indicate that there is a huge potential for the HDOR remanufacturing industry in China, where machines often operate under extremely severe working conditions (Zhou et al., 2012). China's HDOR remanufacturing is currently still at the initial stage but is developing quickly (Xu, 2010; Xu et al., 2013, 2015).

Price and environmental issues typically constitute positive

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motivations for customers to purchase a remanufactured product (Beatriz et al., 2014). For remanufacturers, environmental regulations have an extremely important influence on their ability to compete with new machines, and about 36% of HDOR equipment remanufacturers have reported that high transportation costs affect their competitive position, while 31% cited environmental regulations (U.S. International Trade Commission(USITC, 2012). Although loading machine remanufacturing is technologically feasible, the overall environmental and economic performances of remanufacturing have been unclear, so effective government support is still lacking. As a result, there is an obvious need to perform a quantitative analysis of the environmental and economic performances of remanufacturing to provide accurate information for customers, suppliers and regulators.

Life cycle assessment (LCA) is a scientific and technical tool to assess the requirements and impacts of technologies, processes and products in order to determine their capacity to consume resources and contribute to pollution (Guinée et al., 2011; McKone et al., 2011; Michalek et al., 2011). It allows the environmental impacts of remanufactured products to be comprehensively evaluated by comparing their production to the manufacturing processes of new products (Plevin et al., 2014). As a framework to evaluate emissions inventories and their impacts in complex systems (Michalek et al., 2011), LCA follows internationally accepted methods (ISO 14040:2006 and ISO 14044:2006), making it more useful to decision makers and other stakeholders, for example, customers, researchers and industrialists (Mckone et al., 2011; Cluzel et al., 2013; Gao et al., 2017). It is now widely used for product declarations, eco-labeling, and providing marketing information between alternative product systems and suppliers (Guinée et al., 2011; Weidema et al., 1999). Two basic methods are used in practice for compiling life cycle assessment: process-based analysis and input-output-based analysis (Suh et al., 2004). Process-based analysis assesses the resource uses and environmental emissions from the main production processes, as well as some important contributions from suppliers of inputs to the main processes within the system boundary. Economic Input-Output Life Cycle Assessment (EIO-LCA) is a linear economic input–output model, expanded by environmental data (Hendrickson et al., 2006; Virtanen et al., 2011). The input-output model is a top-down analysis using sectoral monetary transaction matrixes within a national economy. EIO-LCA usually involves a much higher degree of data work, which often results in a large time lag before data can be supplied for policy analysis and policy planning (Fischer-Kowalski et al., 2011). Available input-output tables are generally several years old; thus, assessing rapidly developing sectors and new technologies may introduce errors because of base-year differences between the product system under study and input − output data (Suh et al., 2004). EIO-LCA also relies on sector-level averages and may not be representative of a particular product; therefore, most remanufacturing LCA has used process-based analysis. Due to the insufficient disaggregation in the IO table (Kumar et al., 2016), this research will also use process-based LCA to assess the emerging remanufacturing technology in China. As the automotive machinery was the earliest industrial sector to undergo widespread remanufacturing, the environmental and economic benefits of automobile and related components remanufacturing are already well documented (Zhang and Chen, 2015; Zhang et al., 2011; McKenna et al., 2013). However, LCA research has not yet focused on the fast growing HDOR remanufacturing industry (Saidani et al., 2017). Only the environmental benefits of engine remanufacturing have been reported (Smith and Keoleian, 2004; Li et al., 2013; Shi et al., 2015), and the benefits of reverse logistics have been discussed for diesel engines (Liu et al., 2014). Compared to automotive components, LCA of remanufactured HDOR vehicles have not been well quantified, and empirical data indicating significant environmental gains from remanufacturing from a life cycle perspective may encourage greater use of this process.

Various perspectives, for example a product-based functional unit with relatively short time horizons (Kristian, 2016) and take-back strategies (Tornese et al., 2016) will lead to different LCA models and outcomes, and it is not easy to translate from functional-unit-based to real-world scenarios (Guinée et al., 2011). An important modeling choice in the LCA for remanufactured products is whether to take into account the environmental burdens of the original product. If the system boundary is expanded by assigning part of the environmental burdens of the remanufactured product to the original product, the environmental benefits of remanufacturing are much smaller (Biswas et al., 2013; Zanghelin et al., 2014). Most studies have focused on assessing the environmental impacts of remanufacturing products compared to manufacturing a new functional unit, providing a static snapshot. However, previous studies have not clearly addressed the current state and remanufacturing potential of loading machines in the long term. Because the future remanufacturing potential (including scrapped machine and the recycling rate) has not been taken into account, the long term environmental and economic effects have not been fully evaluated.

This research aims to compare the environmental and economic costs and benefits of manufacturing and remanufacturing with forward and reverse logistics, including the CO_2-eq reduction potential of the remanufacturing industry. The environmental and economic benefits under different scenarios for each functional unit are presented, and both the original use phase and a second lifespan are considered in order to estimate the environmental benefits of remanufacturing scenarios. A life distribution model was built to implement a long term dynamic simulation of loading machine scrapping. Based on estimated future recycling rates, we assessed the potential for remanufacturing benefits over a 25-year period, including urban climate change mitigation strategies. The results provide scientific evidence for the environmental impact reduction potentials to both remanufacturers, consumers and regulators, and improve understanding of the environmental and economic performances of remanufacturing loading machines in China's huge construction projects.

2. Case study

Xiamen XGMA Machinery Co. Ltd. (XGMA) was founded in 1951 and is one of the largest construction machinery manufacturing bases in China. It is located in a national-level circular economy (CE) industrial park in Xiamen, a coastal city in Fujian province (Fig. 1). XGMA has devoted considerable resources to promoting its remanufacturing businesses since 2012, and technical innovations have now enabled loading machines to be remanufactured. Key technology includes mechanical detection (ultrasonic flaw detection, eddy current inspection and dimension measurement) and surface repair techniques (brush electroplating and thermal spraying). The first whole-set loading machine was remanufactured in 2014, and XGMA has since been involved in the formulation of China's industrial standards on remanufacturing. The loading machine remanufacturing won several prizes at the national and city level in 2015, and XGMA Remanufacturing has been awarded a special subsidy by the Chinese National Development and Reform Commission as a pilot unit for CE. Every loading machine remanufactured by XGMA is stamped with a remanufacturing logo shown in the upper left of Fig. 1(A), and a comparison of an end-of-life loading machine and a remanufactured one is presented in Fig. 2(B) and (C). To promote the remanufacturing business and achieve wider market recognition, XGMA has launched a pilot project to upgrade their aftermarket service and provides training to dealers (who are also local mechanical engineering companies) in standardizing remanufacturing production requirements. After receiving training and obtaining remanufacturing certification from XGMA, eight pilot dealers have already completed their first remanufacturing (Fig. 2). As pilot remanufacturing sites are established by individual dealers, machines can mostly be remanufactured locally, allowing a more efficient closed-loop supply chain to be implemented. Our research takes whole-set loading machine remanufacturing as a technologically feasible example.

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