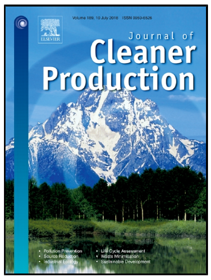

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The Effect of Remanufacturing and Direct Reuse on Resource Productivity of China's Automotive Production

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Abstract

Remanufacturing and direct reuse are considered important measures for promoting the circular economy and improving resource efficiency. Automotive production is a typical resource- and energy-intensive industrial sector, and is a prime market for remanufacturing and direct reuse. Assessing the effect of remanufacturing and direct reuse on the automotive production industry from the perspective of resource efficiency will provide an important reference for improving understandings of remanufacturing and guiding relevant policies in a broader context. A literature review reveals few studies focusing on the resource efficiency of remanufacturing and direct reuse, and the relative lack of a generally accepted indicator to assess the resource efficiency of industrial processes. This paper promotes a new indicator, *resource productivity of industrial process*, and constructs a material flow model to calculate the resource productivity of China's automotive industry. Results suggest that the indicator and its analytical model are effective tools to assess resource efficiency. Results also suggest that compared to a case where remanufacturing and direct reuse are not employed, adding these processes in China's automotive supply chain would increase *resource productivity of industrial process* by 7.1% in a high efficiency scenario. Based on these

findings, policy recommendations for applying the indicator at industry level and encouraging remanufacturing and direct reuse are provided.

Key Words: Material Flow Analysis, Remanufacturing, Direct Reuse, Resource Productivity, Automotive Manufacturing, China

1. Introduction

Worldwide economic growth is under increasing pressure from constraints on natural resource consumption and associated environmental impacts. Many countries are planning to implement circular economy strategies—decoupling of economic activity and resource use—to replace currently unsustainable resource- and energy-intensive development patterns (State Council of China, 2013; European Commission, 2015a). In this pursuit to promote circular economy development and improve resource efficiency, remanufacturing and direct reuse are considered important measures (Lieder and Rashid, 2016). Automotive production, a typical resource- and energy-intensive industrial sector, is a prime market for remanufacturing and direct reuse and thus a well-suited case study to assess the impacts of these strategies. China has been the world's largest automotive producer since 2012. And strong support from the Chinese government (National Development and Reform Commission of China, 2008, 2010) will usher in a new era of development in the remanufacturing and direct reuse industry (Zhang et al., 2011; Liu et al., 2017). Improvement in the resource efficiency of China's automotive production caused by the growth in the adoption of remanufacturing and direct reuse is therefore a common concern for governmental, industrial, and academic stakeholders alike.

Remanufacturing is an industrial process in which worn-out products are restored to like-new condition (Lund and Mundial, 1984; Nasr and Varel, 1997). Direct reuse is the repeated use of a product, object, or substance that is not waste for the same purpose with little if any additional processing at the end of the first life. Previous studies address the environmental performance of different types of equipment, such as computers, paper copiers, household appliances, and auto parts in the remanufacturing industry (Ayres et al., 1997; Zhang et al., 2004; Sundin and Bras, 2005; Chen et al., 2014). The resource- and energy-saving benefits of some auto parts remanufacturing has even been quantified in case studies on engines (Smith and Keoleian, 2004; Liu et al., 2014) and truck injectors (Amaya et al., 2010). Other studies have focused on the effect of remanufacturing and direct reuse on new product manufacturing processes and other industries from the perspective of energy savings and emissions reduction (McKenna et al., 2013; Feng et al., 2016). In terms of economic performance, remanufacturing can provide between 20% and 80% savings in production cost compared to manufacturing new products (Zhu et al., 2004). Remanufacturing thus conserves much of the value added compared to recycling, where products are reduced to their basic constituent materials (Giutini and Gaudette, 2003), and is believed more economically attractive than disposal, where all embodied value is simply relinquished (Kenne et al., 2012).

Remanufacturing and direct reuse changes the internal structure of automotive production by closing the material flow loop, thereby affecting the overall resource efficiency of automotive manufacturing industry. Assessing the effect will provide an important reference for understanding remanufacturing and formulating relevant policy guidance. In existing studies, researchers often use a set of indicators to measure industrial resource efficiency from different perspectives, such as material, energy, or water use efficiency (Michelsen et al., 2006; Kharel and Charmondusit, 2008; Nasr et al., 2011; Wang et al., 2011; Alves and de Medeiros, 2015; Ng et al, 2015; Yang et al., 2015). However, in practical application, a comprehensive indicator that fully reflects resource efficiency as its own metric may be more useful to governments and enterprises in guiding policy and business decisions that focus on resource efficiency specifically. Our literature review indicates that few studies have focused on the resource efficiency of remanufacturing and direct reuse as its own metric; furthermore, there appears to be no generally accepted indicator by which the resource efficiency of industrial processes may be assessed.

The *resource productivity* indicator is widely used to assess resource efficiency at the national level, which measures economic output per unit of resource utilization (European Commission, 2015b; Japan, 2003, 2008, 2013; China, 2011). And some studies try to apply this indicator at industry level. Wang et al. (2016) uses resource productivity to evaluate China's cement-based materials industry based on material flow analysis, but the indicator does not account for fossil fuel energy resources. Japan has calculated resource productivity of several industries based on input-output analysis (Japan, 2013). However, the input-output analysis focuses on the flows or connections between different sectors in the economy, but is not suitable for studying the effect of internal structure change in certain sector or production process.

In this paper, we define *resource productivity of industrial process* (RP^I) indicator to characterize the resource efficiency of industrial processes, and we use it to assess the effect of remanufacturing and direct reuse on automotive manufacturing industry. To calculate this indicator, we construct a material flow model that not only accounts for material flows, but also accounts for energy consumption and the value added of industrial processes. The effect of remanufacturing and direct reuse on the automotive supply chain and automotive manufacturing industry are studied simultaneously by applying two system boundaries. We calculate the RP^I of China's automotive industry from 2005 to 2014, and study the change in three principal components of RP^I: materials input, energy consumption, and value added. Then, we evaluate the potential for RP^I improvement by 2020 using scenario analysis considering the different growth in the adoption of remanufacturing and direct reuse. Finally, policy recommendations are presented based on these results.

This paper is structured as follows. Section 2 defines the indicator and presents the methodology. Section 3 describes material flow in China's automotive production. Section 4 discusses the RP^I benefit of remanufacturing and direct reuse. Policy recommendations are provided in Section 5. Finally, Section 6 presents the conclusions.

2. Methodology

2.1. Resource Productivity of Industrial Process

Resource productivity at the national level is defined as the ratio between gross domestic product (GDP) and primary material used, including domestic and imported raw materials and imported semi-finished and finished goods (McKenna et al., 2013; Wang et al., 2016; Yu et al., 2017); it indicates the industrial structure and resource utilization structure of a nation or region. In this study, we define a new indicator, here termed *resource productivity of industrial process* (RP^I), to measure the resource efficiency of an industrial manufacturing process. It is the ratio between value added in the production process and materials input. The latter term includes net materials input for automotive production and fossil fuels consumption for energy production. The formulas are as follows.

$$RP_t^I = \frac{\Sigma VA_{i,j,t}}{\Sigma MB_{i,t} + FCE_t \times \Sigma EC_{i,j,t}} \quad (1)$$

$$FCE_t = \frac{FE_t}{EP_t} \quad (2)$$

where RP_t^I = resource productivity of industrial process at year *t*, USD/t, $VA_{i,j,t}$= value added generated in material *j* production in industry *i* at year *t*, USD. The value added is measured using 2010 as the base price year; $EC_{i,j,t}$= energy consumption for material *j* production in industry *i* for year *t*, PJ; $MB_{i,t}$= materials input or output across the system boundary in industry *i* for year *t*, t; FCE_t = fossil fuel consumption per unit of energy production for year *t*, t/PJ; FE_t= total amount of fossil fuels consumption for energy production for year *t*, t; EP_t= total energy production for year *t*, PJ.

Many materials are used in automotive production, and many industries are involved in the supply chain from raw material extraction and primary material processing to automotive manufacturing. We define the automotive supply chain as a system for RP^I calculation; the division of the industries is referenced from the National Bureau of Statistics of China (NBSC).

- Automotive supply chain: five stages, including fifteen industries, comprise this system. These are: raw materials extraction (six industries: coal mining and dressing, oil and gas mining, ferrous metal mining, copper mining and dressing, aluminum mining and dressing, and limestone mining), primary materials processing (seven industries: primary plastics and synthetic resin manufacturing, synthetic rubber manufacturing, glass manufacturing, ferrous metal smelting and casting, copper smelting and rolling, aluminum smelting and rolling, and tire manufacturing), automotive manufacturing (two industries: automotive manufacturing, parts and accessories manufacturing), use and maintenance, and end of use. Materials inputs are mainly raw materials, such as iron ore, copper ore, bauxite, limestone, crude oil and coal.

Auto parts remanufacturing and direct reuse is a subsector of automotive manufacturing. To characterize the impact of remanufacture and direct reuse on automotive manufacturing and guide business decisions, we define a relative smaller system inside the supply chain system:

- Automotive manufacturing industry: three stages, including two industries, comprise this system. They are: automotive manufacturing (two industries: automotive manufacturing, parts and accessories manufacturing), use and maintenance, and end of use. Material inputs are intermediate products, such as iron and steel, refined copper, extruded aluminum, plastics, rubber and glass.

Two system boundaries are shown in Figure 1. The automotive supply chain system can be used to assess the global effect of remanufacturing and direct reuse on the assembly of all industries relevant to automotive production. In contrast, the automotive manufacturing industry focuses on the local effect of remanufacturing and direct reuse on the automotive manufacturing industry. In this study, we apply the two systems to the RP^I calculation simultaneously.

2.2. Material Flow Analysis

Material Flow Analysis (MFA) is defined as the systematic assessment of material flows and stocks within a system defined in space and time, and has become a widely accepted tool for environmental, waste, and resource management (Habib et al., 2014). The basic principle of MFA is the conservation of matter, where input is equal to output plus any change in stock (Brunner and Rechberger, 2004). MFA usually comprises four important material life cycle stages: raw material extraction, manufacturing (into products), use and maintenance, and end of use. Some modifications are made to the classic material flow model. First, remanufacturing and direct reuse are loops that take material rejected from the supply chain and feed it back as a resource into an earlier stage. To accurately set their position in the material flow model, we further divide manufacturing into two stages: primary materials processing and automotive manufacturing. The simplified material supply and recovery system for automotive production is shown in Figure 1. Second, we estimate energy consumption and value added of primary materials processing in upstream industries based on homogeneity assumption due to the lack of statistical data. The homogeneity assumption is that for certain material such as steel, we use the average energy consumption and value added for per unit product in the whole steel industry without considering the specificity of steel in vehicle. Detailed descriptions about the material flow model are provided in section 3.

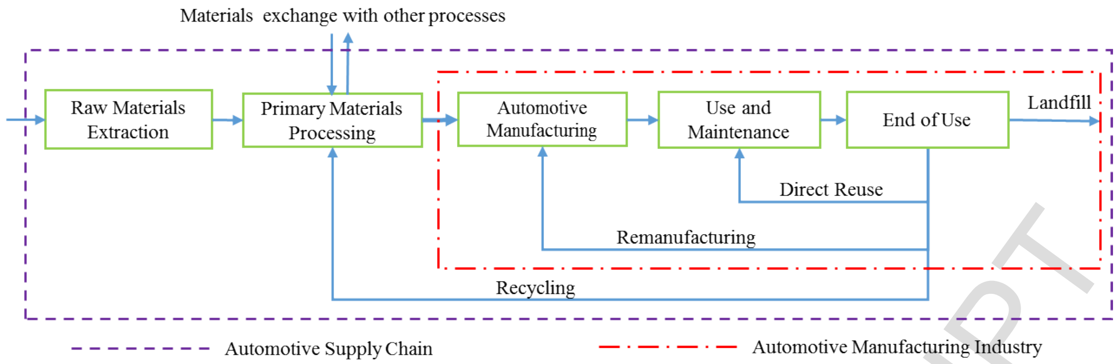

Figure1. Schematic representation of the material supply and recycling system for automotive production.

2.3. Scenario Analysis

Scenario analysis is used to assess the potential effect of remanufacturing and direct reuse in the future. Vehicle and ELV stocks are rapidly growing in China; therefore, remanufacturing and direct reuse are expected to expand in the near term. This study focuses on the effect of remanufacturing and direct reuse on RP^I in two systems in 2020. We set 2014 as the base year for scenario analysis, when the latest statistical data is available. The volume of vehicle production in 2020 is projected using polynomial extrapolation based on historical data. The volume of in-use vehicles and ELVs in 2020 is estimated using vehicle production and stock historical data. The projections for value added and energy consumption from automotive production in 2020 are based on production efficiency in 2014, and are adjusted based on the Chinese macro-plan for the manufacturing sector (State Council of China, 2015). And future trends such as light-weighting and electrification of vehicles are considered in the scenario analysis by quantifying their impact on the materials flow in automotive production, which is presented in section 4.2. Based on projections, three scenarios with different development expansion in remanufacturing and direct reuse are established to assess the possible range of their effects.

3. Material Flows Analysis in China's Automotive Production

3.1. Materials Flow in Automotive production

Based on industry averages and technically implicit industry homogeneity, all vehicles are assumed to have the same weight, material composition, and parts in the material flow model. Vehicle is defined to consist of 35 main components. The weight, primary material, and replacement rates of each part are estimated based on previous studies (Schultmann et al., 2006; Che et al., 2011; Keoleian and Sullivan, 2012; Gradin et al., 2013) and the China Automotive Industry Yearbooks (2005-2014). Seven types of materials, which account for 86% of vehicle average weight in 2010, are considered: steel and iron at 62 wt%, plastics at 7 wt%, rubber at 7 wt%, aluminum at 6 wt%, copper at 2 wt%, and glass at 2 wt%. A linear model is constructed to simulate the material composition change from 2005 to 2014. During this period, the proportion of ferrous materials decreased significantly as a result of light-weighting. However, average vehicle weight increased slightly because of the growth in the sport utility vehicle (SUV) market share and the necessity of larger engines required for associated increases in horsepower and acceleration. The material consumption estimation in two system boundaries $MCAM_{j,t}$ and $MCSC_{j,t}$ are as follows.

$$MCAM_{j,t} = VP_t \cdot \sum_s MCAP_{s,j,t} + VU_t \cdot \sum_s \left(MCAP_{s,j,t} \cdot RRAP_s\right) - MCRe_{j,t} - MCRm_{j,t} \tag{3}$$

$$MCSC_{j,t} = F_{P_{j,t}} \cdot (MCAM_{j,t} - (1 - LR_{j,t}) \cdot (VU_t \cdot \sum_s \left(MCAP_{s,j,t} \cdot RRAP_s\right) + ELV_t \cdot \sum_s MCAP_{s,j,t} - MCRe_{j,t} - MCRm_{j,t})) \tag{4}$$

$$MCRe_{j,t} = ReR_t \cdot ELV_t \cdot \sum_s \left(MCAP_{s,j,t} \cdot f_{Re_s}\right) \tag{5}$$

$$MCRm_{j,t} = RmR_t \cdot ELV_t \cdot \left(1 - F_{Rm}\right) \sum_s MCAP_{s,j,t} \cdot \left(f_{Rm_s} - f_{Re_s} \cdot ReR_t\right) - RmR_t \cdot VU_t \cdot \left(1 - F_{Rm}\right) \sum_s \left(MCAP_{s,j,t} \cdot RRAP_s \cdot f_{Rm_s}\right) \tag{6}$$

Where $MCAM_{j,t} =$ material *j* consumption in automotive manufacturing system boundary at year *t*, $MCSC_{j,t} =$ material *j* consumption in automotive supply chain system boundary at year *t*, $MCRe_{j,t} =$ material *j* conservation through direct reuse at year *t*, $MCRm_{j,t} =$ material *j* conservation through remanufacture at year *t*, $VP_t =$ volume of vehicle production at year *t*, $VU_t =$ volume of in-use vehicle at year *t*, $ELV_t =$ volume of end-of-life vehicle at year *t*, $MCAP_{s,j,t} =$ material *j* content in auto part *s* at year *t*, $RRAP_s =$ replacement rate of auto part *s* in vehicle, $f_{Re_s} =$ direct reuse factor of auto part *s*, ($f_{Re_s} = 1$ if auto part *s* could be direct reused, otherwise $f_{Re_s} = 0$), $f_{Rm_s} =$ remanufacture factor of auto part *s*, ($f_{Rm_s} = 1$ if auto part *s* could be remanufactured, otherwise

$f_{Rm_s} = 0$), $F_{Rm} =$ material conservation correction factor of remanufacture, $F_{P_{j,t}} =$ material extraction and processing coefficient factor of material *j* at year *t*, $ReR_t =$ direct reuse rate at year *t*, $RmR_t =$ remanufacture rate at year *t*, $LR_{j,t} =$ landfill rate of material *j* at year *t*.

The material flow model in this study consists of linear material flow and feedback loops, which are shown in figure 1. The quantification of linear material flow is primarily based on the new vehicle production and in-use vehicles repair. Material consumption for in-use vehicles repair is estimated based on the volume of in-use vehicles and components replacement rates. Replacement rate, also referred to as repair rate or failure rate, is the likelihood that a vehicle component will need to be replaced due to failure or normal wear and tear. Replacement rates of auto parts are estimated based on statistical data in China Automotive Industry Yearbook. The material conservations caused by feedback loops are quantified based on the volume of ELVs, repair of in-use vehicles, direct reuse rate and remanufacture rate. In the model, direct reuse rate is defined as the ratio of the quantity of parts directly reused to the overall potential quantity of parts that *could be* directly reused in ELVs. Remanufacturing rate is defined as the ratio of the quantity of parts remanufactured to the overall potential quantity of worn or damaged parts in in-use vehicles and parts in ELVs that *could be* remanufactured. Landfill rate is the ratio of the quantity of materials sent to landfills to the overall potential quantity of materials in worn or damaged parts in in-use vehicles and all parts in ELVs. The materials, which are not directly reused, remanufactured or landfilled, are assumed to be recycled as secondary materials.

It should be noted that directly reused and remanufactured parts can only be used for vehicle repair, not for new vehicle manufacturing (Subramoniam et al., 2009). In the model, if the supply of reused and remanufactured parts is larger than the demand for vehicle repair, the excess parts are recycled as secondary materials. In the model, most auto parts can be directly reused, except wear parts, such as brakes and tires. Engines, transmissions, and most types of electrical parts can be remanufactured. The lifetime of the body and chassis are assumed to be identical to the entire vehicle, so they should not be remanufactured or directly reused. We use f_{Re_s} and f_{Rm_s} to distinguish whether a part could be direct reused or remanufactured. As remanufacturing requires additional materials input, we use

F_{Rm} to correct material conservation in remanufacture.

3.2 Calculation of Energy Consumption and Value Added

The value added and energy consumption at each stage in automotive production is calculated based on the material flow data and China yearbooks for different industries. Due to data limitations, it is difficult to obtain accurate data for energy consumption and value added in upstream industries. The estimation is based on an assumption of homogeneity. The formulae are as follows:

$$VA_{i,j,t} = M_{i,j,t} \times \frac{VA_{i,j,t}^{T}}{M_{i,j,t}^{T}} \quad (7)$$

$$EC_{i,j,t} = M_{i,j,t} \times \frac{EC_{i,j,t}^{T}}{M_{i,j,t}^{T}} \quad (8)$$

where $VA_{i,j,t}$= value added associated with automotive production of material *j* processed in industry *i* for year *t*, USD; $M_{i,j,t}$= volume of material *j* processed in industry *i* used for automotive production for year *t*, t; $M_{i,j,t}^{T}$= total volume of material *j* processed in industry *i* for year *t*, t; $VA_{i,j,t}^{T}$ = total value added generated in material *j* processing in industry *i* for year *t*, USD; $EC_{i,j,t}$= energy consumption for material *j* processing in industry *i* for year *t*, PJ; and $EC_{i,j,t}^{T}$= total energy consumption in material *j* processing in industry *i* for year *t*, PJ.

3.3 Remanufacturing and Direct Reuse

In the model, parameters specification for remanufacturing and reuse are based on previous research (Smith and Keoleian, 2004; Liu et al., 2014; Chen et al., 2014) and expert consulting (Yuke Li, deputy director of Policy Research Institute, China Automotive Technology & Research Center, in personal communication, December 21st, 2016). Compared to manufacturing new products, materials input in remanufacturing is generally 46% to 90% less, and energy consumption is generally 68% to 82% less. Energy consumption in direct reuse is estimated at 84% to 91% less. However, little research has focused on the value added in remanufacturing and direct reuse. In the model, the value added is estimated using the following formula:

$$VA = GO - IC \quad (9)$$

Where VA = Value Added, USD, GO = Gross Output, USD, and IC = intermediate consumption (material, labor, energy and management), USD.

For Formula 9, the total output has a close relationship with the selling price. The results of market research and expert consultation shows that remanufactured parts prices are generally 30% to 70% cheaper than the new parts, and reused parts prices are 65% to 85% cheaper than the new parts (Smith and Keoleian, 2004). We choose material, labor, and energy as the major factors influencing industrial intermediate input. The labor input is assumed to be twice that of manufacturing new products because remanufacturing is more labor-intensive (Giutini and Gaudette, 2003).

Based on these results of literature review and estimation, the materials input, energy consumption and value added parameters of remanufacturing and direct reuse are shown in Table 1. There are some uncertainties in the parameters, and we make uncertainty analysis in Section 4.4.

Table 1. The materials input, energy consumption and value added of remanufacturing and direct reuse compared to manufacturing new products.

	Materials input	Energy consumption	Value added
Remanufacturing	32 ± 22%	25 ± 7%	80 ± 22%
Direct Reuse	—	13 ± 4%	54 ± 18%

3.4 Material Flow, Energy Consumption and Value Added of Automotive Production in China

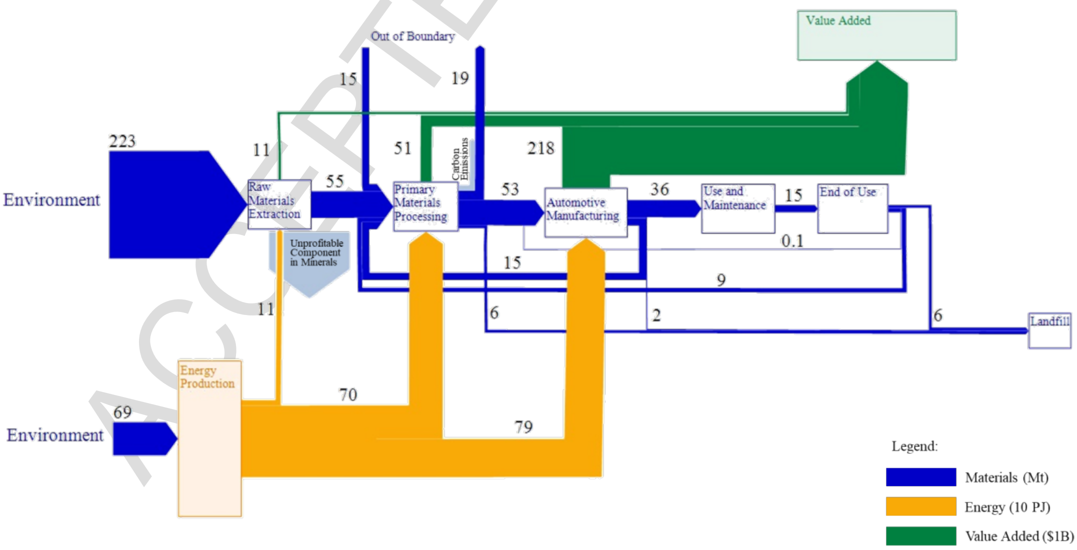

Figure 2. Material flow, energy consumption and added value in China's automotive production in 2014.

The 2014 material flow, energy consumption and value added in China's automotive production is presented in Figure 2. A total of 292.5 Mt raw materials was extracted for automotive production in China; 223.1 Mt minerals was used for materials production, and 1602.9 PJ energy was consumed in automotive production which is generated by burning 69.4 Mt fossil fuels. The material volume in the linear material flow decreased rapidly in the raw material extraction and primary material processing stages. At the raw materials extraction stage, there was a large waste flow composed of unprofitable mineral components. Furthermore, at the primary materials processing stage, in the ferrous metal smelting and casting industry, coal serves as a deoxidant and energy carrier; large quantities of coal are therefore converted into carbon emissions leaving the system at this stage. Due to the lack of official statistical data on remanufacture and direct reuse, we estimated remanufacturing rate based on output values of remanufacturing and output values of vehicle repair. The remanufacturing rate is thus estimated as nearly 2% in 2014. Remanufacturing made a 93.2 Kt materials feedback loop from end of use to automotive manufacturing.

The energy consumption and value added increased rapidly from raw material extraction to automotive manufacturing in the supply chain. In total, 1602.9 PJ energy was consumed in automotive production: 109.2 PJ in raw materials extraction, 698.2 PJ in primary materials processing, and 795.5 PJ in automotive manufacturing. Furthermore, $279.9B USD was generated in automotive production: $11.0B USD in raw materials extraction, $51.3B USD in primary materials processing, and $217.6B USD in automotive manufacturing. The automotive manufacturing stage accounted for 77.7% of the total value added alone.

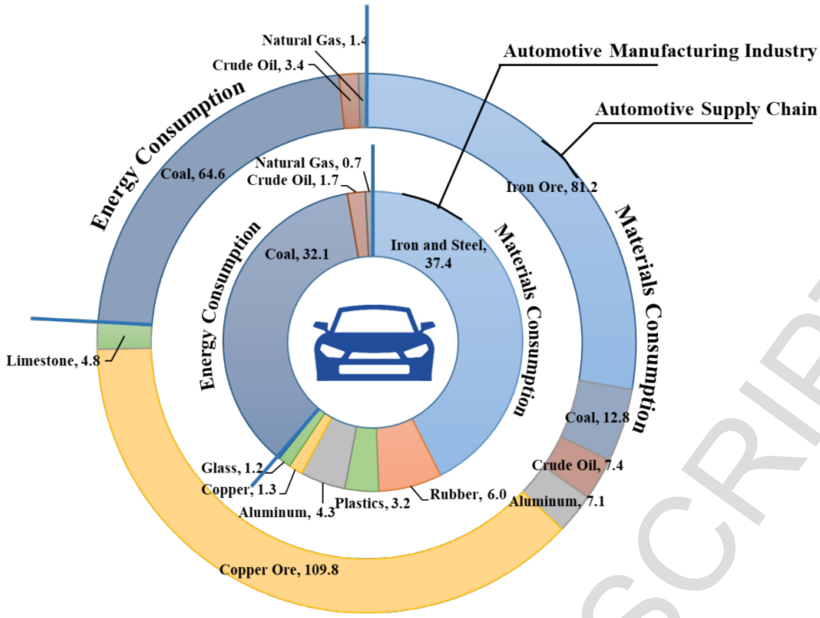

Figure 3. Resource consumption (in Mt) in China's automotive production in 2014.

In the automotive supply chain system, 292.5 Mt of raw materials were extracted for automotive production, 76.3% were used for material processing and 23.7% were fossil fuels used for energy production. Copper ore, iron ore, and coal were the three largest resources consumed in production. Iron and steel were the main vehicle materials, and 81.2 Mt of iron ore was extracted for steel production. The amount of copper used in a vehicle is relatively small, but copper ore grade is extremely poor in China; 1.3 Mt of copper requires 109.8 Mt of copper ore. Due to the leading role of coal in the energy structure in China, 64.6 Mt of coal was used as energy source. Another 12.8 Mt of coal was used for steel smelting.

In the automotive manufacturing industry system, 87.8 Mt of materials were used in automotive manufacturing, 60.8% for materials in vehicles and 39.2% for fossil fuels used for energy production. In total, 37.4 Mt of iron and steel were used in automotive production, and 6.0 Mt of rubber was consumed, which was primarily used for tire production. To meet automotive light-weighting requirements, aluminum occupies a large proportion of vehicle materials and 4.3 Mt of aluminum was used in automotive production. In the two systems comparison, the automotive supply chain system indicates the impact of automotive production on the environment more accurately, while the automotive manufacturing industry system indicates the utilization efficiency of critical metals and fossil fuels.

4 Resource Productivity Effect from Remanufacturing and Direct Reuse

4.1. Resource Productivity in China's Automotive Production from 2005 to 2014

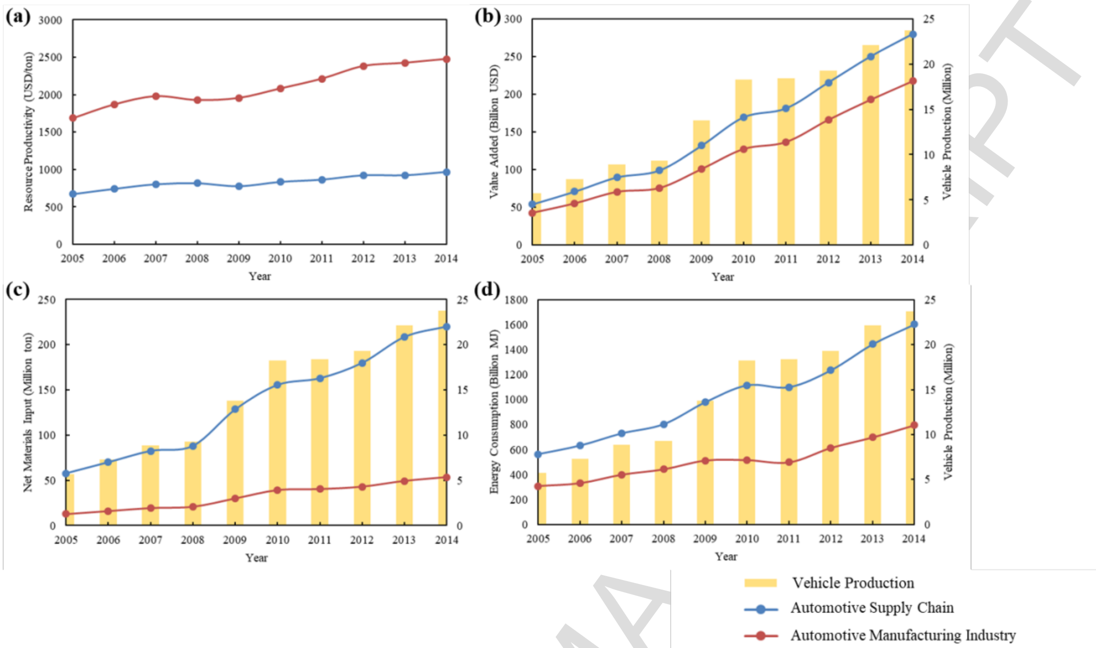

Figure 4. Changes in the automotive supply chain and manufacturing industry from 2005 to 2014: (a) resource productivity, (b) value added, (c) materials input and (d) energy consumption.

The RP^{I} and its constituents are shown in Figure 4. China's automotive industry experienced rapid development from 2005 to 2014. The figure shows that the RP^{I} improved remarkably as well. In the automotive supply chain, value added grew by 415.5% from \$54.3B to \$279.9B USD. Material inputs rose by 286.0% from 57.8 to 223.1 Mt. Energy consumption increased by 185.0% from 562.5 to 1602.9 PJ. In total, automotive supply chain RP^{I} improved by 43.5% from 673.7 to 967.0 USD/t. In the automotive manufacturing industry, total value added increased by 410.8% from \$42.6B to \$217.6B USD. Material inputs rose by 317.6% from 12.8 to 53.3 Mt. Energy consumption rose by 158.4% from 307.9 to 795.5 PJ. The automotive manufacturing industry RP^{I} improved by 46.8%, from 1686.9 to 2477.3 USD/t.

The automotive supply chain RP^{I} indicates the resource efficiency of all industries relevant to automotive production, while the automotive manufacturing industry RP^{I} focuses on the resource efficiency of manufacturing industry. A short-term decline in automotive manufacturing industry RP^I of 2.6% occurred during the 2008 financial crisis, and then automotive supply chain RP^I dropped up by 4.7% in 2009. The Chinese government began to make large-scale investments in infrastructure to stimulate economic growth after the financial crisis in 2008; this resulted in extensive growth in the materials extraction and processing industries without concern for resource utilization efficiency. Therefore, the resource efficiency of industry decreased, and RP^I responded in kind.

4.2 Resource Productivity Improvement Potential from Remanufacturing and Direct Reuse

In 2014, 23.73 million vehicles were produced, there were 154.47 million in-use vehicles (NBSC, 2015), and there were nearly 6.18 million ELVs. The volume of in-use vehicles and ELVs is rapidly growing in China. The vehicle projection module in the model shows that by 2020, the volume of vehicle production could be 28.77 million per year, in-use vehicle volume could be 257.53 million, and there could be 12.5 million ELVs in China. And in order to simulate the 2020 scenario more accurately, two important future trends in automotive industry are taken into account: light-weighting and electrification of vehicles. The light-weighting impact is estimated based on the linear model simulating automotive material composition change which is introduced in section 3.1. Further, the production of electric vehicles would be 2 million according to development plans in Chinese automotive industry (State Council of China, 2012; Ministry of Industry and Information Technology of China, 2017), a volume for which we assume that plug-in hybrid electric vehicles and battery electric vehicles both represent 50%. In this light, we distinguished, the material compositions in plug-in hybrid electric vehicles, battery electric vehicles and fuel vehicles in the model. We built three scenarios to assess potential RP^I improvement by developing remanufacturing and direct reuse by 2020. Scenario 1 is the low efficiency scenario, with zero remanufacturing rate and direct reuse rate, and an extremely high landfill rate. Scenario 2 is a medium efficiency scenario, and Scenario 3 is a high efficiency scenario. The details of the scenarios are provided in Table 2.

Table 2. Scenarios to address the potential effect of remanufacturing and reuse

Parameters	Scenario-1	Scenario-2	Scenario-3
Direct reuse rate	0%	10%	20%
Remanufacturing rate	0%	10%	30%

Comparing Scenario 2 (medium efficiency scenario) with the 2014 values shows that resource efficiency in automotive production would be improved by direct reuse and remanufacturing. In 2020, the automotive supply chain RP^I is projected at 1153.2 USD/t, 19.3% higher than in 2014, and the automotive manufacturing industry RP^I is 2789.7 USD/t, 12.6% higher than in 2014. The differences are caused by three factors: a) an increase in the rate of ELV generation relative to new vehicle production, which means more materials from ELVs serving as secondary materials for new vehicle production; b) an increase in value added per unit of output value in the supply chain; c) growth in the adoption of remanufacturing and direct reuse.

The scenarios analysis show that remanufacturing and direct reuse have positive impact on RP^I. Comparing Scenario 1 with Scenario 2, without remanufacturing and direct reuse, the automotive supply chain RP^I would be 3.0% lower, and the automotive manufacturing industry RP^I would be 1.5% lower. Comparing Scenario 3 and Scenario 2, higher rates of remanufacturing and direct reuse make automotive supply chain RP^I increase by 3.9%, and automotive manufacturing industry RP^I increase by 2.8%. The automotive supply chain RP^I in Scenario 3 is 7.1% higher than in Scenario 1, which indicates big resource efficiency improvement potential of remanufacturing and direct reuse.

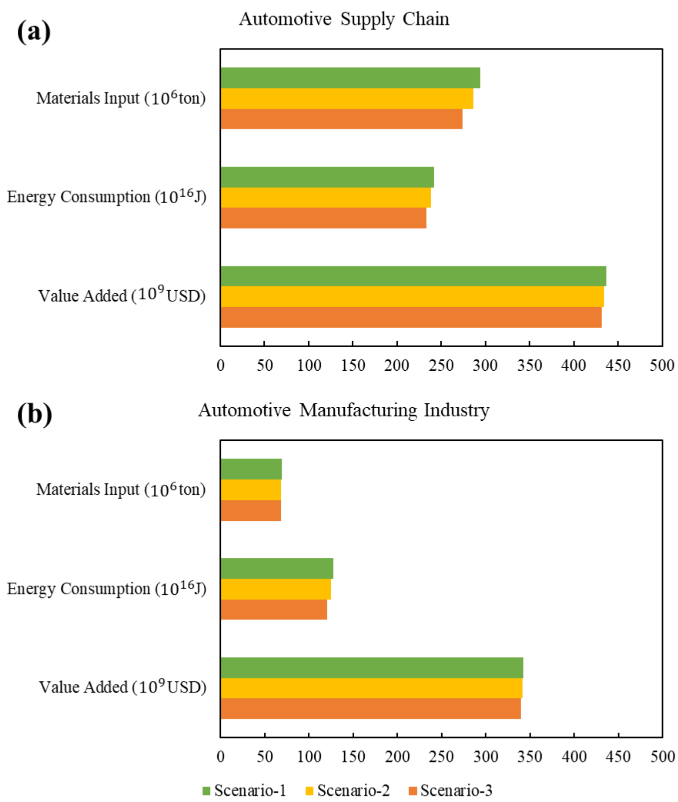

Figure 5. The material input, energy consumption and value added for different scenarios. (a) automotive supply chain, (b) automotive manufacturing industry.

The details of three scenarios are shown in Figure 5. Materials input, energy consumption, and value added in Scenarios 3 and 2 are smaller than in Scenario 1 in both systems. In the automotive supply chain, compared to Scenario 1, material input is lower by 6.6% and energy consumption is lower by 3.5% in Scenario 3. This means that 39.12 Mt of copper ore, 7.63 Mt of iron ore, 2.60 Mt of aluminum ore, 1.19 Mt of coal, and 85.7 PJ energy could be saved by raising remanufacturing and direct reuse rates. However, the value added is 1.2% lower, because in the vehicle repair market, remanufactured or reused parts are substitute for new parts. The value added from remanufacture and direct reuse is lower than manufacturing new ones. Researches have shown that remanufacturing is deliberately ignored by original equipment manufacturer (OEM) because of the potential for cannibalizing higher-margin new product sales (Atasu et al., 2010; Ferguson and Toktay, 2006; Xia et al., 2015). Seitz (2007) showed that among the reasons of inducing engine remanufacturing to OEM, the influence of direct profitability or profit maximization is low.

Comparing the RP^I in two system boundaries, automotive supply chain RP^I is more sensitive to the change of remanufacturing and direct reuse rate, and remanufacturing and direct reuse can reduce the raw materials extraction significantly. In automotive manufacturing industry, remanufacturing and direct reuse have a better performance in energy saving.

4.3 Effect of Remanufacturing and Direct Reuse

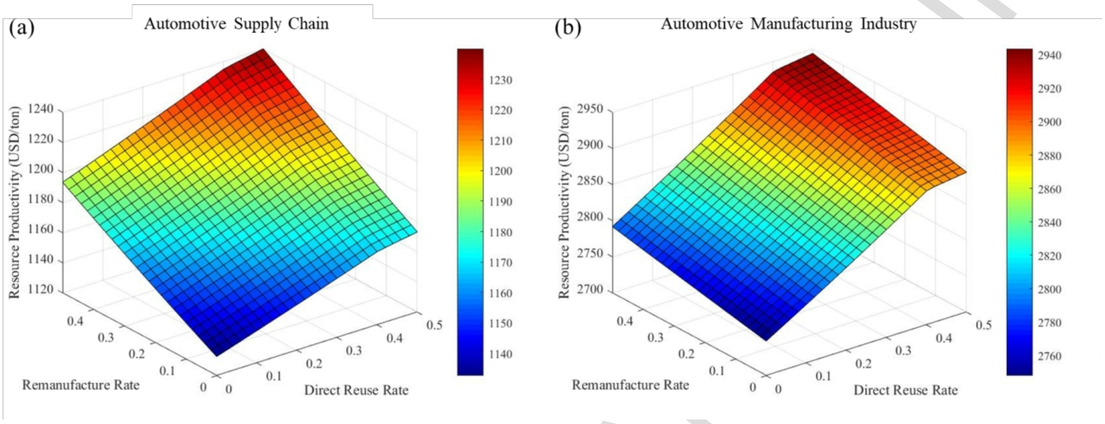

Figure 6. Effect of remanufacturing and direct reuse rates on resource productivity: (a) automotive supply chain, (b) automotive manufacturing industry.

The effects of remanufacturing and direct reuse rates on RP^I are separately studied further. The results indicate that marginal effect of resource productivity improvement would be diminishing with the growth of remanufacturing and direct reuse rates, and the magnitude of the effect from remanufacturing and direct reuse on RP^I vary between the different systems. As shown in Figure 6(a), there is a larger improvement from direct reuse than remanufacturing in the automotive supply chain. As shown in Figure 6(b), there is a larger improvement from remanufacturing than direct reuse at the initial stage of the automotive manufacturing industry. Due to reused and remanufactured parts being used for vehicle repair, once the reused and remanufactured parts supply meets the demand from vehicle repair, the excess parts should be recycled as secondary materials. Therefore, with an increase in remanufacturing or direct reuse rate, the resource productivity growth rate would slow. The industrial scale of remanufacturing and direct reuse is limited by the demand from vehicle repair.

4.4 Uncertainty Analysis

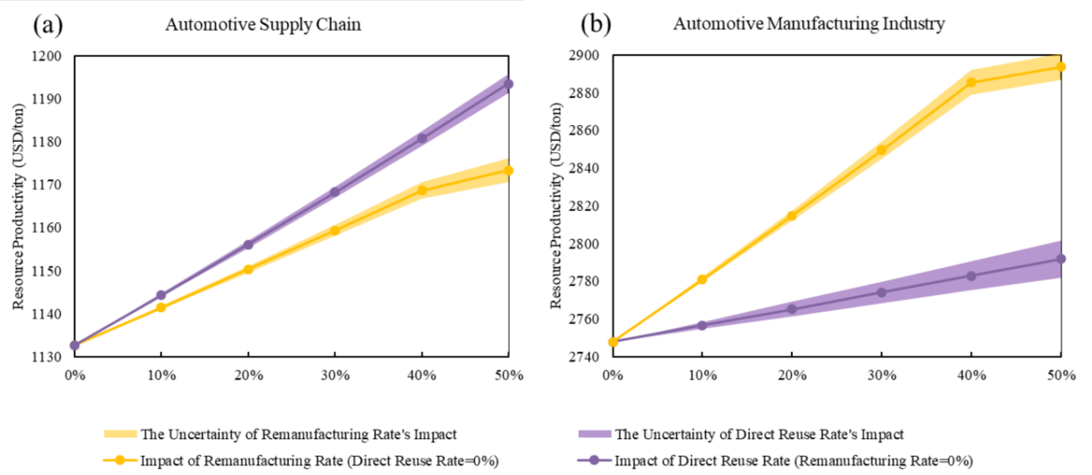

Figure 7. The uncertainty in the effect of remanufacturing rate and direct reuse rate on resource productivity: (a) automotive supply chain, (b) automotive manufacturing industry.

There are some uncertainties in the material input, energy consumption, and value added parameters of remanufacturing and direct reuse. The parameters and extents of variations are shown in Table 1. We studied the uncertainties of RP^I change caused by them. The results are shown in Figure 7. The uncertainties of remanufacturing and direct reuse are simulated separately. When we analyze the uncertainty caused by one rate, the other rate is set zero to eliminate its influence. The automotive supply chain RP^I would rise by 3.59±0.23% with 50% remanufacturing rate, and by 5.37±0.18% with 50% direct reuse rate. The automotive manufacturing industry RP^I would rise by 5.30±0.25% with 50% remanufacturing rate, and by 1.59±0.35% with 50% direct reuse rate. It shows that even though the maximum uncertainty of RP^I change may reach 22%, the effect of remanufacturing and direct reuse would still be positive.

5 Policy Recommendations

This case study of China's automotive production indicates that the automotive production RP^I improved significantly from 2005 to 2014. Based on this analysis, we suggest that the *resource productivity of industrial process* indicator should be adopted in policy-making to assess resource efficiency for the important industries. Many governments have established targets for resource productivity while formulating future national development plans (European Commission, 2015b;

Japan, 2003; China, 2011). However, realization of targets is full of uncertainties, because it is difficult to assess contributions for resource productivity improvement of specific policy. Industry is a substantial contributor to economic development. At the industrial level, the RP^{I} indicator can be used to monitor the resource efficiency of important industries, and set specific improvement targets for some resource efficiency lagging industries.

The results indicate that remanufacturing and direct reuse are effective ways to enhance resource efficiency and reduce environmental impacts associated with primary material production and traditional linear manufacturing. However, promoting the growth of remanufacturing and direct reuse is a complicated systemic task, which should overcome different barriers in legislation and regulatory, collection and diversion system, and remanufacturing technology. Both governments and industry should play an important role in the promotion. In the past the remanufacturing and direct reuse did not get enough support from the governments, and there are lack of effective policy strategies for promoting them currently. Based on our research results and communications with stakeholders, some policy recommendations are given as follows:

- Improve the legislation and regulation system to support remanufacturing and direct reuse. Especially for emerging economies where the number of EVLs is growing rapidly, it is important to cancel the policy limitations of remanufacturing and reuse, and make industrial standards. There could be some existing regulations which would make barriers to the development of remanufacturing. Recently, the Chinese government is revising the *Statute 307: recovery and management of End of Life Vehicles* (State Council of China, 2001), to reduce restrictions and give more support to remanufacturing and direct reuse. And governments should make industrial standards to prevent unauthorized collection and illegal reuse of scrap parts, which would hurt the reputation of remanufacturing and cause traffic safety hazards (Xia et al, 2015).

- Support to build ELVs collection and diversion system. The adequate and secure supply of parts and end-of-life vehicles serves as the basis for developing the remanufacturing and direct reuse industry. The European Commission and Japanese government both set targets for end-of-life vehicle recycling in their directives or laws (EU-Directive, 2000; Zhao and Chen, 2011). There are some effective policy options such as constructing collection and diversion infrastructure, and implementing extended producer responsibility.

- Strengthen fiscal policy to support the expansion of the remanufacturing and direct reuse industry. The results show that economic output in remanufacturing and direct reuse is relatively small compared to manufacturing new products. The government could support remanufacturing enterprise, and expand the scale of the remanufacturing industry, through preferential taxation, subsidy policies, or by providing credit guarantees. Furthermore, the government could support remanufacturing technology research and development to improve the economic output from remanufacturing. The Chinese government has begun to explore the way to support remanufacturing and direct reuse by carrying out auto parts remanufacturing pilot program since 2008.

In addition, it is also important to increase customer openness to and acceptance of remanufacturing and direct reuse products, and make original equipment manufacturer take remanufacturability and recyclability into consideration in the product design stage (Hu et al., 2011). Besides, the research results show that the growth in the adoption of remanufacturing and direct reuse might disadvantage the interest of some original equipment manufacturers, especially for non-integrated manufacturers (Xiong et al., 2013). While formulating policies to support direct reuse and remanufacturing enterprises, governments should take the loss of non-integrated original equipment manufacturers into consideration.

6 Conclusion

In the paper, we define a new indicator *resource productivity of industrial process*, and construct a material flow model to quantify the indicator. The results show that the China's automotive production RP^I experienced rapid growth from 2005 to 2014. Based on this indicator, we study the effect of remanufacturing and direct reuse on the China's automotive production RP^I in two different scale systems. The results shows that remanufacturing and direct reuse can positively affect the RP^I of automotive production. In order to enable further benefits in resource efficiency in pursuit of a more circular economy, greater efforts are needed to expand the adoption of remanufacturing and direct reuse, including a focus on legislation, collection, and technical barriers that currently impede growth. Based on the results, four policy recommendations are provided: (i) adopt the *resource productivity of industrial process* indicator in policy to assess resource efficiency of the important industries to the economy; (ii) improve the legislation and regulation system to support remanufacturing and direct reuse; (iii) support to build ELVs collection and diversion system; and (iv) strengthen fiscal policy to support the development of remanufacturing and direct reuse enterprises.

Besides, there are still some limitations of the study. Automotive production is complicated process which involving many sectors of the economy. Some assumptions and simplifications are made in the material flow model to simulate the process. One key simplification is that all vehicles are assumed to have the same weight, material composition, and parts. But different types and different brands of auto parts are different, which would make actual remanufacturing and direct reuse rate lower than ideal level. The other is that in the model, materials input, energy consumption and value added projection about automotive production in 2020 is based on the technology and efficiency in 2014. However, the automotive industry is undergoing profound changes, which would bring uncertainties to the results. In addition, the research didn't take rebound effect into consideration, which has drawn the attentions of many researchers in recent years (Galbreth et al, 2013). There is one weakness of the paper that detailed cost-benefit analysis of policy options are not given. We believe the feasibility of the policy options are complicated issues which worth in-depth study in the future.

Remanufacturing and direct reuse are regarded by many countries as major measures for circular economy, with the goal of improving national resource productivity (State Council of China, 2013; European Commission, 2014).Although the development of remanufacturing and direct reuse still faces many challenges in technology, business models, and consumer acceptance currently. We believe that remanufacturing and direct reuse will play a more important role in automotive production as more researches and policies practices are carried out.

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Highlights:

- Resource productivity of industrial process indicator is developed and demonstrated
- A material flow model for China's automotive production is constructed
- Effect of remanufacturing and direct reuse on resource productivity is evaluated