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# A quantitative analysis method of greenhouse gas emission for mechanical product remanufacturing based on Petri net

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**A B S T R A C T**

The increased greenhouse gas (GHG) emission is one of the consequences of environmental change. Waste mechanical products remanufacturing is a good production mode for environment protection. Nevertheless, GHG emissions are inevitably generated in the remanufacturing system. Some uncertainties would exist in the remanufacturing system due to the different damage statuses of old mechanical products, which result in dynamic GHG emissions. Recent studies on the characteristics of GHG emissions for mechanical product remanufacturing are not yet available. This study proposed a quantitative analysis method of GHG emissions for mechanical product remanufacturing based on Petri net. In this method, the boundary of the remanufacturing is initially defined, and the dynamic characteristics of GHG emissions are analysed. Then, a GHG emission analysis model based on Petri net is constructed. Finally, the GHG emission of a PCL803 centrifugal compressor rotor remanufacturing as a case is analysed by this proposed method. This method could provide a guidance to quantitatively analyse the characteristics of GHG emissions, and suggestions for mechanical product remanufacturing to realize cleaner production and sustainability.



**A R T I C L E I N F O**

*Keywords:*
Mechanical product remanufacturing;
Sustainability;
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## 1. Introduction

Climate change has become a serious environmental threat with potential impacts on global warming [1-2]. The energy and material consumptions vary in different production activities, which cause the diversified sources of greenhouse gas (GHG) emissions [3]. Therefore, it is necessary to explore an in-depth analysis of the GHG emissions for industrial activities. Comprehensive research studies have been conducted from different aspects and levels. For instance, Li *et al.* [4] constructed a carbon emission model for the manufacturing process of machine tools based on Petri net. Cao and Li [7] also proposed a simulation approach for displaying carbon emission dynamics based on hybrid Petri nets. Esteves *et al.* [6] presented a method to evaluate annually the environmental performance in terms of GHG emissions in relation to local tallow biodiesel. Teh *et al.* [7] proposed a quantified carbon footprint intensity analysis method for Australian cement and concrete production. Chen *et al.* [8] compared GHG emissions of compact fluorescent lamps with those of linear fluorescent lamps using life cycle assessment method under China's national conditions. From life cycle aspect, Murphy *et al.* [9] conducted a comprehensive, holistic evaluation of biomass-to-energy systems to reduce the production and transportation of GHG emissions by life cycle assessment (LCA) methodology. Hao *et al.* [10] compared GHG emissions and energy consumption for electric vehicle production by employing LCA framework. Magnusson and Mácsik [11] identified significant posts for energy and GHG emissions, which were associated with the construction, use, and removal of an artificial turf field. Many other GHG emission analysis methods have also been proposed, and fruitful research results have been achieved; research has involved waste disposal [12-13], agricultural industry [14-15], and energy consumptions [16].

Remanufacturing waste mechanical products is a good production mode of resource saving, environment protection, and GHG emissions reduction. Nonetheless, GHG emissions are inevitable in the remanufacturing system. In the remanufacturing process, some uncertainties exist in the material and energy consumptions due to the different damage conditions of old products, which would cause dynamic GHG emissions. Several research have recently involved the GHG emission of product remanufacturing, for example, Tornese *et al.* [17] characterized the carbon equivalent emissions associated with pallet remanufacturing operations for two repositioning scenarios. Peng *et al.* [18] compared two types of remanufacturing cleaning technologies from the perspective of environment emissions. Bazan *et al.* [19] developed a model of GHG emissions by considering manufacturing, remanufacturing, and transportation activities with penalty tax. When considering capital and/or carbon emission constraints, Yenipazarli [20] characterized the optimal GHG emission taxation policy to deliver the benefits of product remanufacturing and maximize the total profits. To determine optimal production quantities of a new or remanufactured product, Wang *et al.* [21] examined manufacturing/remanufacturing planning issues and presented three mathematical models.

More GHG emission analysis methods about product manufacturing activity have been proposed; however, limited in-depth studies have focused on product remanufacturing system. Consequently, the greenhouse effect of the remanufacturing system cannot be deeply understood, and effective measures for resource conservation and emission reduction cannot be performed. Therefore, exploring a quantitative GHG emission analysis method for mechanical product remanufacturing is an effective way to realize greener manufacturing and sustainability.

In this study, a GHG emission analysis method for mechanical product remanufacturing based on Petri net is proposed based on the research of Li *et al.* [4] about carbon emission modelling methods for the manufacturing processes of machine tools. Moreover, the dynamic characteristics of GHG emission are comprehensively analyzed.

## 2. GHG emission characteristic of the mechanical product remanufacturing

### 2.1 GHG emission boundary of the mechanical product remanufacturing

Generally, the remanufacturing process of mechanical product includes recycling, disassembly, cleaning, inspection, repairing, and assembly, during this process, raw materials (e.g., steel, alloy, etc.) and energy (e.g., electricity, kerosene, diesel oil, etc.) would be consumed, wastes (e.g., waste solid, waste water, waste gas, etc.) are discharged, and GHG emissions are inevitably generated. The system boundary is established in view of the remanufacturing process, as shown in Fig. 1 [22]. This system boundary comprises different resource inputs (i.e., resource flow), and GHG outputs (i.e., GHG flow).

### 2.2 GHG emission characteristic analysis of the mechanical product remanufacturing

GHG emissions would be analyzed from the two aspects of resource production and waste discharge and disposal based on the remanufacturing process.

When old mechanical products are transported to a workshop for remanufacturing, electricity and kerosene are consumed in the disassembly stage; electricity, water, and cleaning fluid are consumed in the cleaning stage; electricity is the main energy consumed in the inspection stage; a certain amount of electricity and metal materials, such as steel, iron and alloy, are consumed in the repairing stage; and electricity is mainly consumed in the assembly and testing stages. Considerable GHG emission is generated during the resource and energy production (i.e., mining and processing), and this part of GHG emissions coming from resource production should be considered.

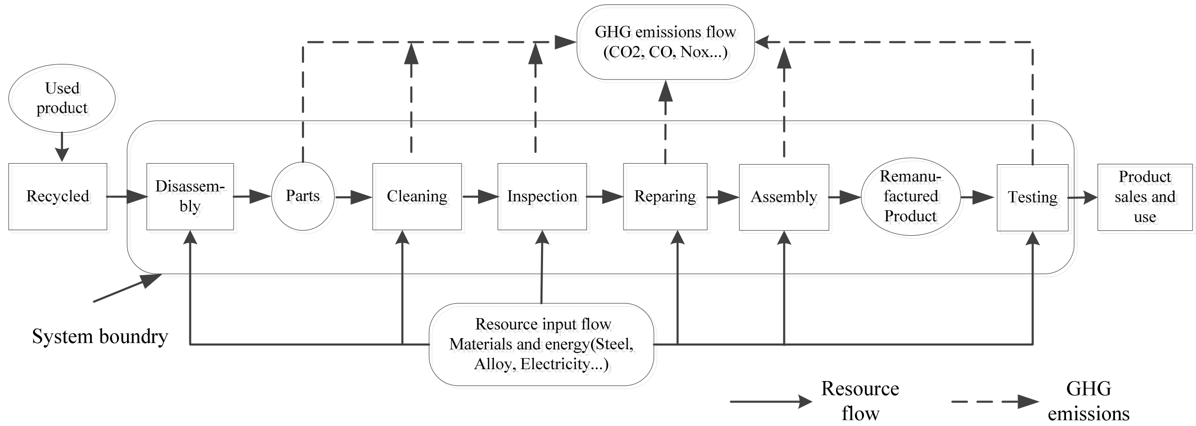


**Fig. 1** GHG emissions boundary of mechanical product remanufacturing

**Table 1** Main material composition of waste discharge

| Waste emission | Material construction |
|---|---|
| Waste water | Cleaning water and cleaning fluid in cleaning process, the main materials are: oil, scale, carbonate, sulfate, $Fe_xO_y$, sodium hydroxide, sodium carbonate, alkaline solution, acid, oxidant, kerosene, etc. |
| Waste gas | Dust, spray powder, working gas generated in the processes of disassembly and repairing, the main materials are: Cr, Ni, Co, CO, Si, TiC, $Al_2O_3$, $ZrO_2$, $SiO_2$. |
| Solid waste | The scrap metal parts generated in the process of disassembly and the metal chip, powder and corners generated in the process of repairing. |

A certain amount of waste which contains some GHG is discharged in the remanufacturing system, and in the waste disposal process, certain electricity and fossil energy are consumed, and an amount of GHG is generated during the energy production. Therefore, GHG emissions come from two sources in the waste discharge and disposal process. The main material composition of waste emissions is shown in Table 1.

## 3. GHG emission analysis model of the mechanical product remanufacturing

### 3.1 Definition of Petri net of GHG emission model

Petri net is a visual and qualitative analysis tool widely used for modelling and analysis in manufacturing system, which is composed of a continuous variable and a discrete event dynamic system. The advantages of organizational structure and dynamic behaviour allow the Petri net to clearly describe the dynamic GHG emissions by analysing the material flow, energy flow, and the dynamic situation of waste streams in the remanufacturing system. The GHG emission network model can be defined a six-element group, expressed as $\sum(P, T, F, K, W, M_0)$, where:

- $P = (P_1, P_2, P_3, \ldots, P_n)$ refers to limited place sets that represent the remanufacturing process or material, semi-finished product, and finished product warehouse, which is expressed by roundness;
- $T = (T_1, T_2, T_3, \ldots, T_m)$ denotes limited transition sets that represent the start or end of a remanufacturing activity, expressed by oval;
- $F$ is a directed flow that represents the flow relation between place and transition;
- $M_0: P \rightarrow N$ is the place of initial marking;
- $K: P \rightarrow N^+ \cup \{\infty\}$ is a place capacity function, supposing the place capacity is infinite;
- $W: F \rightarrow N^+$ is a flow function, where $F = ((P \times T) \cup (T \times P))$.

A GHG emission analysis model based on Petri network can be established according to the material and energy flow, as shown in Fig. 2. The elements and constraints are listed in Table 2.

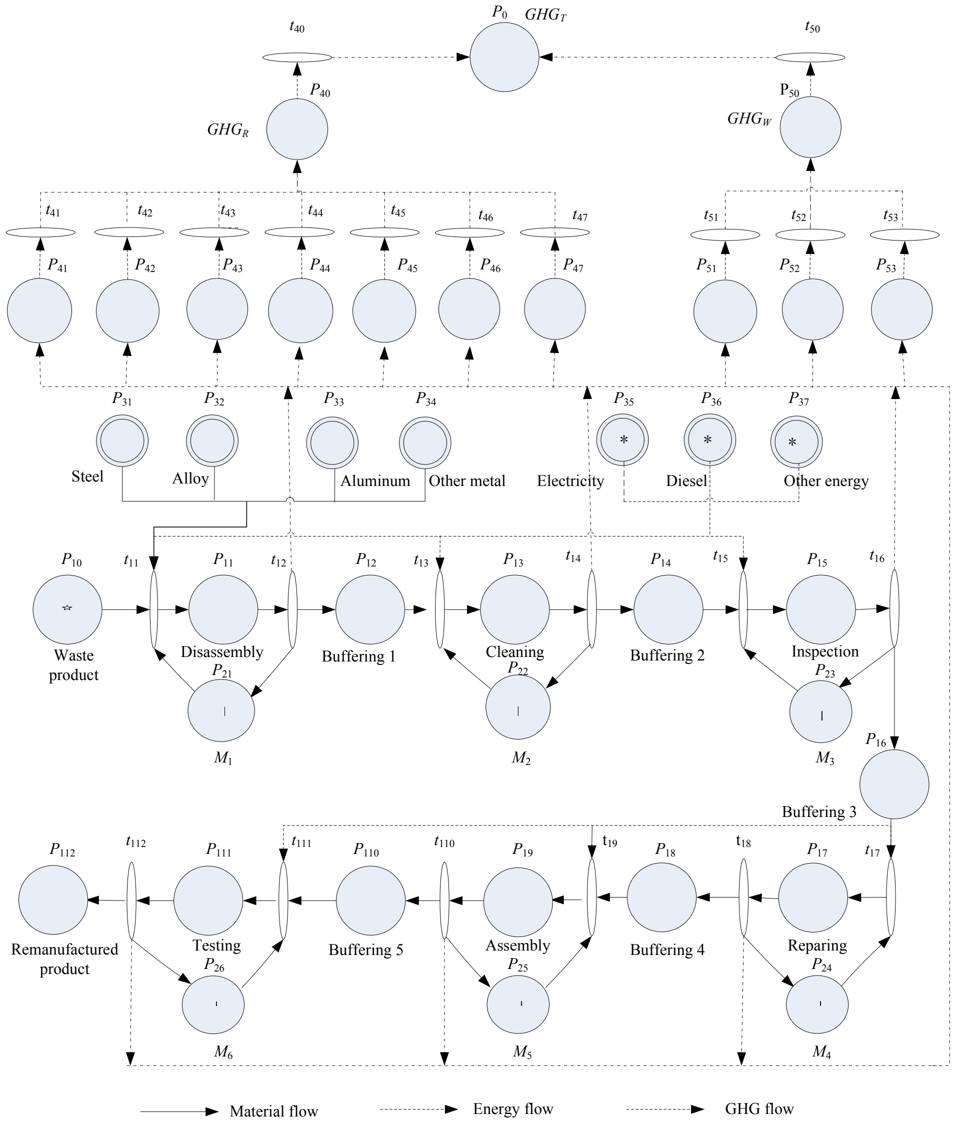


**Fig. 2** GHG emissions model of mechanical product remanufacturing based on Petri network

### 3.2 Construction of GHG emission model

From Fig. 2, remanufacturing is associated with the consumption and transition of materials, energy, and waste. GHG emissions are generated from the following two sources: GHG emissions generated by resource production and by waste discharge and disposal. The parameter descriptions and function expressions of material, energy, and waste flows are as follows:

- $i$ represents the $i$-th resource entered into the remanufacturing system, $n$ represents the total categories of resources, the former $q$ is material, and the latter $(n\text{-}q)$ is energy.
- $j$ represents the $j$-th remanufacturing stage, $m$ is the total number of remanufacturing stages, $k$ indicates the waste category, and $l$ waste categories exist in total.

The function of the $i$-th resource consumption in the $j$-th remanufacturing stage during remanufacturing time $T$ is expressed as follows:

$$M(i,j) = \int_0^T f_j^i\,(t)dt \tag{1}$$

The function of the $k$-th waste discharge or disposal in the $j$-th remanufacturing stage during remanufacturing time $T$ is expressed as:

$$W(k,j) = \int_0^T w_j^k\,(t)dt \tag{2}$$

**Table 2** Elements and constraints of GHG emission model

| Element | Constraints explanation |
|---|---|
| $P_{10}$ | Waste products recycled ready for remanufacturing, $M_0(P)$ = 1 |
| $P_{11}$,$P_{13}$,$P_{15}$,$P_{17}$,$P_{19}$,$P_{111}$ | Process of disassembly, cleaning, inspection, repairing, assembly and testing, $M_0(P)$ = 0 |
| $P_{12}$,$P_{14}$,$P_{16}$,$P_{18}$,$P_{110}$ | Transfer process of remanufacturing , $M_0(P)$ = 0 |
| $P_{21}$,$P_{22}$,$P_{23}$,$P_{24}$,$P_{25}$,$P_{26}$ | Idle state of the remanufacturing process, $M_0(P)$ = 1 |
| $P_{31}$, $P_{32}$, $P_{33}$, $P_{34}$ | Four major metals consumption, $M_0(P)$ = 0 |
| $P_{35}$, $P_{36}$, $P_{37}$ | Three main energy consumption, $M_0(P)$ = 0 |
| $P_{41}$,$P_{42}$,$P_{43}$,$P_{44}$,$P_{45}$,$P_{46}$,$P_{47}$ | GHG emissions generated by seven main resources (steel, electricity, …) production, $M_0(P)$ = 0 |
| $P_{51}$,$P_{52}$,$P_{53}$ | GHG emissions generated by waste discharge or disposal (waste gas, water, solid), $M_0(P)$ = 0 |
| $P_{40}$ | Total GHG emissions generated by resource production, $M_0(P)$ = 0 |
| $P_{50}$ | Total GHG emissions generated by waste disposal, $M_0(P)$ = 0 |
| $t_{ij}$ ($i$ = 1,2,...,5, $j$ = 1,2,...,12) | Start and end position of each stage |
| $K$ | Capacity functions of each place of $P_{ij}$, $K(P_{ij}) = \infty$ |
| $W$ | Arc power function between the place $P_{ij}$ and the transition $t_{ij}$: $W(P_{ij}, t_{ij})$<br>Arc weight between resource place ($P_{31}$,$P_{32}$,$P_{33}$,$P_{34}$,$P_{35}$,$P_{36}$,$P_{37}$) and transition ($t_{11}$,$t_{13}$,$t_{15}$,$t_{17}$,$t_{19}$,$t_{111}$) represent the amount of resources consumption |
| | The arc weight function of the transition $t_{ij}$ and the place $P_{ij}$ is expressed as: $W(t_{ij}, P_{ij})$<br>The arc weights between transition $t_{12}$,$t_{14}$,$t_{16}$,$t_{18}$,$t_{110}$,$t_{112}$ and place $P_{41}$-$P_{47}$ represent the GHG emissions generated by resources production<br>The arc weights between transition $t_{12}$, $t_{14}$, $t_{16}$, $t_{18}$, $t_{110}$, $t_{112}$ and place $P_{51}$ ,$P_{52}$, $P_{53}$ represent the GHG emissions generated by waste discharge or disposal |
| | All the other arc weights are 1 |

The parameters of GHG emissions are described as: $GHG_R^{(i,j)}$: GHG emissions generated by the $i$-th resource production in the $j$-th stage; $GHG_R^i$: GHG emissions generated by the $i$-th resource production; $GHG_R$: total GHG emissions generated by resource production; $GHG_W^{(k,j)}$: GHG emissions generated by the $k$-th waste discharge and disposal in the $j$-th remanufacturing stage; $GHG_W^k$: GHG emissions generated by the $k$-th waste; $GHG_W$: total GHG emissions generated by waste; $GHG_T$: total GHG emissions. The function relationship are expressed as:

$$GHG_R = \sum_{i=1}^{n} GHG_R^i = \sum_{i=1}^{n}\sum_{j=1}^{m} GHG_R^{(i,j)} \tag{3}$$

$$GHG_W = \sum_{k=1}^{l} GHG_W^k = \sum_{k=1}^{l}\sum_{j=1}^{m} GHG_W^{(k,j)} \tag{4}$$

$$GHG_T = GHG_R + GHG_W \tag{5}$$

### 3.3 GHG composition and characteristic parameters

GHG refers to the atmospheric gases that can absorb the solar radiation reflected by the ground that can in turn release some additional gases. The main components of GHG include $CO_2$, CO, NOx, and $CH_4$, and these gases can make the Earth's surface become warmer. Because the contribution of each gas to the potential greenhouse effect varies, the equivalent factor is used in this study to calculate the potential value of the greenhouse effect, $CO_2$ is considered as the benchmark gas in greenhouse effect, and its potential influence is assigned to a value of unity. The potential influences of other GHGs could be transformed to the equivalent factor of $CO_2$. The equivalent factors [23] of GHGs are shown in Table 3.

**Table 3** Composition of greenhouse gases and equivalent factors

| Environmental impact | Inventory | Equivalent Factor | Benchmark gas |
|---|---|---|---|
| GHG | $CO_2$ | 1 | kg $CO_2$ eq |
| | $CH_4$ | 25 | |
| | NOx | 320 | |
| | CO | 2 | |

*GHG emissions of resource production*

Suppose that $GHG_R^i$ represents the GHG emissions generated by the $i$-th resource production, which is expressed as

$$GHG_R^i = \sum_{c=1}^{r} M_i \times EP_c^i \tag{6}$$

where $M_i$ represents the consumption amount of the $i$-th resource (kg), and $EP_c^i$ is the equivalent factor ($CO_2$/kg ce) of the $c$-th GHG.

During remanufacturing time $T$, the GHG emissions generated by the $i$-th resource production in the $j$-th remanufacturing stage can be calculated as:

$$GHG_R^{(i,j)} = \int_0^T f_j^i\,(t)dt \times GHG_R^i = \sum_{c=1}^{r} \int_0^T f_j^i\,(t)dt \times M_i \times EP_c^i \tag{7}$$

The GHG emissions generated by the $i$-th resource production during time $T$ is expressed as follows:

$$GHG_R^i = \sum_{j=1}^{m} GHG_R^{(i,j)} = \int_0^T f_j^i\,(t)dt \times GHG_R^i = \sum_{c=1}^{r}\sum_{j=1}^{m} \int_0^T f_j^i\,(t)dt \times M_i \times EP_c^i \tag{8}$$

The total GHG emissions generated by resource production during time $T$ are expressed as

$$GHG_R = \sum_{i=1}^{n} GHG_R^i = \sum_{i=1}^{n}\sum_{j=1}^{m} \int_0^T f_j^i\,(t)dt \times GHG_R^i = \sum_{i=1}^{n}\sum_{j=1}^{k}\sum_{c=1}^{r} \int_0^T f_j^i\,(t)dt \times M_i \times EP_c^i \tag{9}$$

*GHG emissions of waste discharge and disposal*

In the waste discharge and disposal, suppose that $GHG_W^k$ is the GHG emissions generated by the $k$-th waste discharge or disposal. Then,

$$GHG_W^k = \sum_{e=1}^{h} M_k \times EP_e^k \tag{10}$$

where $M_k$ represents the $k$-th waste discharge or disposal, and $EP_e^k$ is the GHG equivalent factor of the $e$-th GHG ($CO_2$/kg ce).

The GHG emissions generated by the $k$-th waste discharge or disposal in the $j$-th remanufacturing stage during time $T$ are calculated as follows:

$$GHG_W^{(k,j)} = \int_0^T w_j^k\,(t)dt \times GHG_W^k = \sum_{e=1}^{h} \int_0^T w_j^k\,(t)dt \times M_k \times EP_e^k \tag{11}$$

The GHG emissions generated by the $k$-th waste discharge or disposal during time $T$ are expressed as:

$$GHG_W^k = \sum_{j=1}^{m} GHG_W^{(k,j)} = \int_0^T w_j^i\,(t)dt \times GHG_W^k = \sum_{j=1}^{m}\sum_{e=1}^{h} \int_0^T w_j^k\,(t)dt \times M_k \times EP_e^k \tag{12}$$

The total GHG emissions generated by waste discharge and disposal during time $T$ can be expressed as:

$$GHG_W = \sum_{i=1}^{l} GHG_W^k = \sum_{k=1}^{l}\sum_{j=1}^{m} \int_0^T w_j^k\,(t)dt \times GHG_W^k = \sum_{k=1}^{l}\sum_{j=1}^{m}\sum_{e=1}^{h} \int_0^T w_j^k\,(t)dt \times M_k \times EP_e^k \tag{13}$$

## 4. Case study

PCL803 centrifugal compressor is commonly used in long distance pipeline unit, which serves the key project of "west-east gas transmission" in China. The compressor rotor, as the core part of the equipment is with a complex manufacturing process and highly manufacturing cost. Therefore, it is of high economic value to remanufacture the compressor rotor. The object in this study is a recycled old PCL803Centrifugal compressor rotor remanufactured by a well-known large compressor manufacturer in China. The GHG emissions are analyzed in the following section.

### 4.1 Resource consumption and waste discharge and disposal analyses

Alloy steel, stainless steel, carbon steel and babbitt alloy are the main metal materials consumed in compressor rotor remanufacturing. The *i*-th material consumption function is expressed as follows:

$$M_i = K_i \times T \quad (14)$$

where $K_i$ represents the average consumption of the *i*-th metal each day (kg/d), and $T$ is the remanufacturing time (d).

In compressor rotor remanufacturing, the consumed energy mainly includes electricity, diesel, and kerosene. The relationship between energy consumption $M_e$ and remanufacturing time $T$ presents a linear correlation, the electricity consumption function is expressed as

$$M_e = 24 \times P \times T \quad (15)$$

where $P$ is the average power of electricity (kW).

The consumption function of kerosene and diesel is calculated as follows:

$$M_f = V_f \times T \quad (16)$$

where $V_f$ is the consumption rate of kerosene or diesel (kg/d).

According to an on-the-spot investigation and Eq. 14-16, the resource consumption functions in each compressor rotor remanufacturing stage are established, as shown in Table 4.

Wastes are mainly waste water, waste gases, and waste metals, and the function relation of waste water and remanufacturing time $T$ is

$$W_w = V_w \times T \quad (17)$$

where $V_w$ is the quantity of waste water discharge (kg/d).

The function relation of waste gases and remanufacturing time $T$ is

$$W_g = V_g \times T \quad (18)$$

where $V_g$ is the quantity of waste gas discharge ($m^3$/d).

The function relation of waste metals and remanufacturing time $T$ is

$$W_s = V_s \times T \quad (19)$$

where $V_s$ is the quantity of waste metal (kg/d).

**Table 4** Resource consumption function in each compressor rotor remanufacturing process $M(i,j)$

| Resource consumption | Compressor rotor remanufacturing stage | | | | | |
|---|---|---|---|---|---|---|
| | Disassembly | Cleaning | Inspection | Repairing | Assembly | Testing |
| Alloy steel $M_a = K_a \times T$ | - | - | - | 336 $T$ | - | - |
| Stainless steel $M_s = K_s \times T$ | - | - | - | 63.15 $T$ | - | - |
| Carbon steel $M_c = K_c \times T$ | - | - | - | 76.95 $T$ | - | - |
| Bobbitt alloy $M_b = K_b \times T$ | - | - | - | 36 $T$ | - | - |
| Kerosene $M_k = V_k \times T$ | 7.2 $T$ | 36 $T$ | - | - | - | - |
| Diesel $M_d = V_d \times T$ | 30 $T$ | 99 $T$ | - | - | - | - |
| Electricity $M_e = 24 \times P \times T$ | 45 $T$ | 222 $T$ | 93 $T$ | 30 $T$ | 18 $T$ | 15 $T$ |

**Table 5** Waste discharge functions in each compressor rotor remanufacturing process $W(k,j)$

| Waste emission | Compressor rotor remanufacturing stage | | | | | |
|---|---|---|---|---|---|---|
| | Disassembly | Cleaning | Inspection | Repairing | Assembly | Testing |
| Waste water $W_w = V_w \times T$ | - | 7.23 $T$ | - | - | - | - |
| Waste gas $W_g = V_g \times T$ | 210 $T$ | 19.5 $T$ | - | 16.2 $T$ | 75 $T$ | - |
| Waste solid $W_s = V_s \times T$ | 1536 $T$ | 10.2 $T$ | 1.5 $T$ | 2.4 $T$ | - | - |

The waste discharge functions of compressor rotor remanufacturing can be established according to Eq. 17-19, as shown in Table 5.

### 4.2 GHG emission calculation based on Petri net

The compressor rotor remanufacturing time in each stage comprises: 78 h of disassembly, 85 h of cleaning, 50 h of inspection, 240 h of repairing, 46 h of assembly, and 80 h of testing. The simulation benchmark is 1 d in the Petri net model, and the resource consumption and GHG emission simulation cycle is 365 d. The parameters of the Petri net model are set as follows:

*Time delay parameter setting*

The time delay of the remanufacturing process place is expressed as

$$D_i = (process\ time \times 2)/24 \tag{20}$$

From Eq. 20, the time delays of each remanufacturing place for $P_{11}$, $P_{13}$, $P_{15}$, $P_{17}$, $P_{19}$, and $P_{111}$ are $D_{11}$ = 6.5 d, $D_{13}$ = 7.08 d, $D_{15}$ = 4.17 d, $D_{17}$ = 20 d, $D_{19}$ = 3.83 d, $D_{111}$ = 6.67 d.

The other time delay of the remanufacturing process place is 0.

*Initial place mark setting*

The place mark of compressor rotor remanufacturing is the resource consumption of 1 year (365 d). Resource consumption function $G(i, j)$ in Table 4 indicates that the initial marks of resources supply places of $P_{31}$-$P_{37}$ are:

$M_0(P_{31})$ = 122640 kg, $M_0(P_{32})$ = 56994.75 kg, $M_0(P_{33})$ = 28086.75 kg
$M_0(P_{34})$ = 13140 kg, $M_0(P_{35})$ = 15768 kg, $M_0(P_{36})$ = 47085 kg, $M_0(P_{37})$ = 154396 kW

The initial mark of the other place is 0.

*Place capacity*

The capacity of each place $P$ is assumed to be infinite.

*Arc weight function setting*

The arch weights between places $P_{31}$–$P_{37}$ and transitions $t_{11}$, $t_{13}$, $t_{15}$, $t_{17}$, $t_{19}$, and $t_{110}$ represent the resource consumption in each stage. The production of remanufactured compressor rotor is 1000 per year and average 3 per day. According to Table 4, the arc weight $W(P_i, t_j)$ is determined, the results are as shown in Table 6. The arc weights between transitions $t_{12}$, $t_{14}$, $t_{16}$, $t_{18}$, $t_{110}$, $t_{112}$ and places $P_{41}$-$P_{47}$ represent the GHG emissions generated by the production of alloy steel, stainless steel, carbon steel, babbitt alloy, kerosene, diesel, and electricity respectively. The GHG emissions generated by resource production are referred to Chinese Life Cycle Database (CLCD) [24], shown in Table 7. The GHG emission weight by resource production could be determined according to Eq. 6-9, as shown in Table 8.

The arc weight between transitions $t_{12}$, $t_{14}$, $t_{16}$, $t_{18}$, $t_{110}$, $t_{112}$ and places $P_{51}$-$P_{53}$ represent the GHG emissions generated by waste discharge or disposal. The average electricity consumption of waste metal disposal is 0.45 kWh/kg. For waste water disposal, the consumed energy is mainly electricity, and the average consumption is 0.3 kWh/m$^3$. In the remanufacturing process, the GHG emission is mainly CO, and the density is 1.25 kg/m$^3$, assuming that 1 % of waste gases discharge is CO. According to Eq. 6, GHG emissions generated by waste discharge and disposal are obtained, shown in Table 9. Based on Eq. 10-13, Tables 5 and 9, GHG emission arc weights generated by waste discharge and disposal are determined, as shown in Table 10.

**Table 6** Weight of resource consumption $W$ ($P_i$, $t_j$)

| | $t_{11}$ | $t_{13}$ | $t_{15}$ | $t_{17}$ | $t_{19}$ | $t_{111}$ |
|---|---|---|---|---|---|---|
| $P_{31}$ | - | - | - | $W(P_{31},t_{17})$ = 112 | - | - |
| $P_{32}$ | - | - | - | $W(P_{32},t_{17})$ = 21.5 | - | - |
| $P_{33}$ | - | - | - | $W(P_{33},t_{17})$ = 25.65 | - | - |
| $P_{34}$ | - | - | - | $W(P_{34},t_{17})$ = 12 | - | - |
| $P_{35}$ | $W(P_{35},t_{11})$ = 2.4 | $W(P_{35},t_{13})$ = 1.2 | - | - | - | - |
| $P_{36}$ | $W(P_{36},t_{11})$ = 10 | $W(P_{36},t_{13})$ = 33 | - | - | - | - |
| $P_{37}$ | $W(P_{37},t_{11})$ = 15 | $W(P_{37},t_{13})$ = 74 | $W(P_{37},t_{15})$ = 31 | $W(P_{34},t_{17})$ = 10 | $W(P_{34},t_{17})$ = 6 | $W(P_{34},t_{17})$ = 5 |

**Table 7** GHG emission per unit resource production (kg)

| GHG | Equivalent Factor | Alloy steel | Stainless steel | Carbon steel | Babbitt alloy | Kerosene | Diesel | Electricity |
|---|---|---|---|---|---|---|---|---|
| $CO_2$ | 1 | 2.75E+00 | 4.99E+00 | 2.03E+00 | 1.9E+00 | 1.9E-02 | 4.0E-04 | 9.1E-01 |
| CO | 2 | 2.05E-02 | 2.04E-02 | 2.99E-02 | 3.3E-02 | 2.5E+01 | 3.8E-01 | 2.0E-04 |
| NOx | 320 | 5.28E-03 | 1.24E-02 | 2.52E-03 | 5.8E-03 | 1.0E-01 | 6.0E-04 | 2.6E-03 |
| $CH_4$ | 25 | 4.67E-03 | 1.28E-02 | 4.25E-03 | 5.8E-03 | 7.2E-02 | 2.1E-02 | 2.7E-03 |
| GHGs of the *i*-th resources | | 4.60E+00 | 9.32E+00 | 3.00E+00 | 4.0E+00 | 1.5E+00 | 8.4E+01 | 1.8E+00 |

**Table 8** GHG emission weight generated by resource production $W$($t_j$, $P_i$)

| | $P_{41}$ | $P_{42}$ | $P_{43}$ | $P_{44}$ | $P_{45}$ | $P_{46}$ | $P_{47}$ |
|---|---|---|---|---|---|---|---|
| $t_{12}$ | - | - | - | - | $W(t_{12},P_{45})$ = 3.6 | $W(t_{12},P_{46})$ = 18 | $W(t_{12},P_{47})$ = 81 |
| $t_{14}$ | - | - | - | - | $W(t_{14},P_{45})$ = 1.8 | $W(t_{14},P_{46})$ = 59.4 | $W(t_{14},P_{47})$ = 399.6 |
| $t_{16}$ | - | - | - | - | - | - | $W(t_{16},P_{47})$ = 167.4 |
| $t_{18}$ | $W(t_{18},P_{41})$ = 514 | $W(t_{18},P_{42})$ = 196.1 | $W(t_{18},P_{43})$ = 77 | $W(t_{18},P_{44})$ = 48 | - | - | $W(t_{18},P_{47})$ = 54 |
| $t_{110}$ | - | - | - | - | - | - | $W(t_{110},P_{47})$ = 32.4 |
| $t_{112}$ | - | - | - | - | - | - | $W(t_{112},P_{47})$ = 27 |

**Table 9** Waste quantity and GHG emission generated by waste disposal

| Waste | Energy consumption of waste disposal | | | GHG kg $CO_2$ ce |
|---|---|---|---|---|
| | Waste quantity | Electricity consumption | $CO_2$ Equivalent factor | |
| Waste water | 2.41 m$^3$ | Electricity 0.72 kWh | 1.8kg $CO_2$ ce/kWh | 1.3 |
| Waste gas | 106.9m$^3$ | CO 1.3 kg | 2 kg $CO_2$ ce | 2.6 |
| Waste solid | 516.7 kg | Electricity 232.5 kWh | 1.8kg $CO_2$ ce/kWh | 418.5 |

**Table 10** GHG emission weight generated by waste discharge and disposal $W$($t_j$, $P_k$)

| | $P_{51}$ | $P_{52}$ | $P_{53}$ |
|---|---|---|---|
| $t_{12}$ | - | $W(t_{12}, P_{52})$ = 1.70 | $W(t_{12}, P_{53})$ = 412 |
| $t_{14}$ | $W(t_{14}, P_{51})$ = 1.3 | $W(t_{14}, P_{52})$ = 0.16 | $W(t_{14}, P_{53})$ = 2.75 |
| $t_{16}$ | - | - | $W(t_{16}, P_{53})$ = 5.56 |
| $t_{18}$ | - | $W(t_{18}, P_{52})$ = 0.13 | $W(t_{18}, P_{53})$ = 0.65 |
| $t_{110}$ | - | $W(t_{110}, P_{52})$ = 0.61 | - |
| $t_{112}$ | - | - | - |

### 4.3 GHG emission results

By Table 8 and Table 10, GHG emissions generated by above two sources are calculated according to Eqs. 1-5, as follows:

GHG emission place generated by resource production (unit: kg $CO_2$):

$$M(P_{41}) = 514,\ M(P_{42}) = 196.1,\ M(P_{43}) = 77,\ M(P_{44}) = 48$$
$$M(P_{45}) = 5.4,\ M(P_{46}) = 77.4,\ M(P_{47}) = 761.4,\ M(P_{40}) = 1679.3$$

GHG emission place generated by waste discharge and disposal (unit: kg $CO_2$):

$$M(P_{51}) = 1.3,\ M(P_{52}) = 2.6,\ M(P_{53}) = 420.96,\ M(P_{50}) = 424.9$$

Total GHG emission place (unit: kg $CO_2$):

$$M(P_0) = M(P_{40}) + M(P_{50}) = 2104.2$$

### 4.4 Result analysis

The GHG emissions in different remanufacturing stage are shown in Table 11 and Fig. 3, and the comparison of GHG emissions generated by two sources is shown in Fig. 4 (expressed in logarithmic form).

**Table 11** Total GHG emissions in each compressor rotor remanufacturing stage (kg)

| GHG emissions category | GHG emissions ($CO_2$ eq kg) | | | | | | Total |
|---|---|---|---|---|---|---|---|
| | Disassembly | Cleaning | Inspection | Repairing | Assembly | Testing | |
| Alloy steel | - | - | - | 514 | - | - | 514 |
| Stainless steel | - | - | - | 196.1 | - | - | 196.1 |
| Carbon steel | - | - | - | 77 | - | - | 77 |
| Babbitt alloy | - | - | - | 48 | - | - | 48 |
| Kerosene | 3.6 | 1.8 | - | - | - | - | 5.4 |
| Diesel | 18 | 59.4 | - | - | - | - | 77.4 |
| Electricity | 81 | 399.6 | 167.4 | 54 | 32.4 | 27 | 761.4 |
| $GHG_R$ total | 102.6 | 460.8 | 167.4 | 889.1 | 32.4 | 27 | 1679.3 |
| Waste water | - | 1.3 | - | - | - | - | 1.3 |
| Waste gas | 1.7 | 0.16 | - | 0.13 | 0.61 | - | 2.6 |
| Waste solid | 412 | 2.75 | 5.56 | 0.65 | - | - | 420.96 |
| $GHG_W$ total | 413.7 | 4.21 | 5.6 | 0.78 | 0.61 | 0 | 424.9 |
| $GHG_T$ total | 516.3 | 465 | 173 | 889.88 | 33.41 | 27 | 2104.2 |

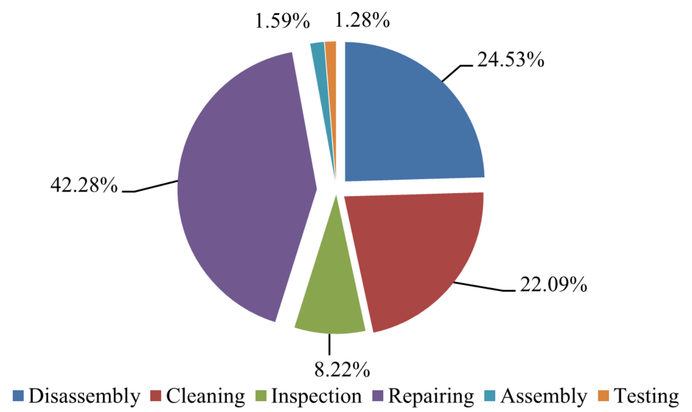


**Fig. 3.** GHG emission proportion in each rotor remanufacturing stage

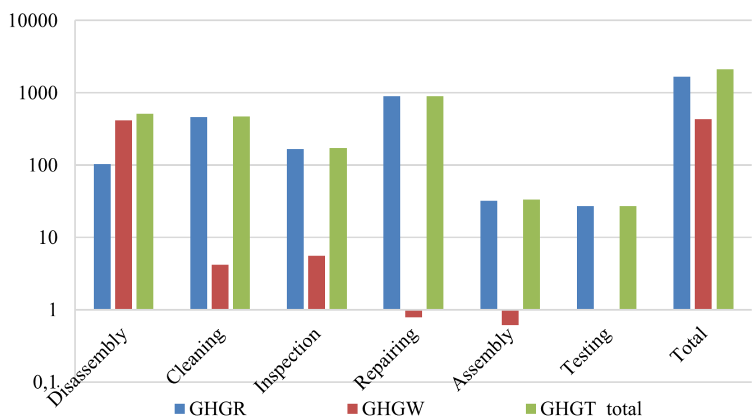


**Fig. 4** GHG emission comparison of resource consumption and wastes discharge for rotor remanufacturing

*GHG emission analysis in each remanufacturing stage*

Table 11, Fig. 3 and Fig. 4 reveal that the most GHG emissions are generated in the repairing stage (42.28 % of the total GHG emissions), followed by those in the disassembly stage (24.53 % of the total), and the least GHG emissions are generated in the testing stage (1.28 % of the total).

Table 11 and Fig. 4 show that in resource production, most GHG emissions are produced, about 79.80 % of the entire GHG emissions (1679.3/2104.2 × 100 % = 79.80 %), especially in repairing, cleaning and inspection stages, accounting for 90.25 % of the total GHG emissions generated by resource production ((889.1 + 460.8 + 167.4)/1679.3 × 100 % = 90.25 %). For waste discharge and disposal, the GHG emissions in the disassembly stage are more than those in other stages, accounting for 97.36 % of the total GHG emissions generated by waste discharge and disposal (413.7/424.9 × 100 % = 97.36 %).

Above results are caused by the significant consumption of alloy steel, stainless steel, as well as electricity in repairing and cleaning stages. On the other hand, because most waste metals are discharged in the assembly stage and significant amounts of electricity are consumed to dispose these wastes. Therefore, large amounts of GHG emission are generated during these resource production. By contrast, almost no waste discharge and minimal electricity consumption in the testing and assembly stages, which resulted fewer GHG emissions.

*GHG emission analysis of resource production*

Table 11 implies that most GHG emissions are generated from electricity production in resource production, which account for 50.74 % (761.4/1679.3 × 100 % = 50.74 %) of the total GHG emissions generated by resource production; followed by alloy steel and stainless steel production, which are 30.61 % (514/1679.3 × 100 % = 30.61 %) and 11.67 % (196.1/1679.3 × 100 % = 11.67 %) respectively; and the GHG emissions of kerosene production are the least, which account only for 0.32 % (5.4/1679.3 × 100 % = 0.32 %) of the total GHG emissions.

*GHG emission analysis of waste discharge and disposal*

Table 11 presents that solid waste disposal produce large GHG emissions, which account for 99.05 % (420.96/424.9 × 100% = 99.05 %) of the total GHG emission generated by waste discharge and disposal, because considerable electricity is consumed. The proportion of GHG emissions generated by waste water and gas discharge (0.95 %) is only small, but they cannot be ignored.

### 4.5 Discussions on countermeasures

Compressor rotor remanufacturing greatly reduced GHG emissions, however, further efforts are required to improve the remanufacturing process. First, reducing the consumption of metal materials (e.g., alloy steel and stainless steel) that generate high GHG emissions in the production process is the most important approach, alternative materials that generate minimal GHG emissions are encouraged to be utilized in the compressor rotor repairing stage, therefore, optimization of process route, methods, equipment, parameters, and scheme is necessary in remanufacturing process design. Second, reduction energy consumption (mainly electricity) in the compressor rotor cleaning and inspection stage is also an effective way to decrease GHG emissions. Finally, waste metal production should be minimized in the disassembly stage, disassembly efficiency should be improved, and old compressor rotor parts should be fully recycled and remanufactured.

## 5. Conclusion

This study presented a quantitative GHG emission analysis model based on Petri net for mechanical product remanufacturing. In this model, the remanufacturing system boundary of mechanical products is initially determined, and GHG emission characteristics are then analyzed. Subsequently, the GHG emission model based on Petri net is constructed, and dynamic GHG emissions are analyzed according to the dynamic resource consumption and waste discharge in different remanufacturing stages. Finally, GHG emission analysis for an old PCL803 centrifugal compressor rotor remanufacturing is conducted. This model provides an effective way to analyze the GHG emissions for mechanical product remanufacturing, and the countermeasures for GHG emission reduction are accordingly introduced. The results of this typical application provide a reference and guidance for cleaner production in product remanufacturing industry and resource selection for greener consumption and sustainability.

In fact, this method could also be applied to other mechanical product remanufacturing and newly manufacturing. For product newly manufacturing when employ this GHG analysis method, the boundary would be modified in accordance with the manufacturing process. Simplifications and hypotheses may also increase the uncertainties for other future cases in results, therefore the sensitivity analysis should be performed when utilizing this proposed model. Computer-aided software could be further developed to achieve the generality and wide applications of this method.

In addition, this study only conducted the GHG emission analysis for mechanical product remanufacturing, other types of environmental impacts, such as acidification, eutrophication, and human toxicity, are not involved. Harmful substances of $SO_2$, CFCs, COD, and smoke dust are inevitably produced whether in the resource production or remanufacturing process, the analysis methods of the environmental impacts generated by these harmful emissions need to be further researched. Furthermore, average data of GHG emissions are used in this study, and supplementary research for more detailed dynamics of resource consumption should be conducted in the future.

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