Life cycle assessment of remanufacturing technologies for industrial robots

Yanshuang Jia[1], Mengyue Liu[1], Yue Yang[1], Xueliang Yuan[1,*], Qingsong Wang[1] and Qiao Ma[1]

*Corresponding author, e-mail address: yuanxl@sdu.edu.cn

[1]School of Energy and Power Engineering, Shandong University, Jinan 250061, China

Abstract: With the acceleration of industrialization, the mount of consumption and scrapping of industrial robots has been increasing rapidly. In this study, the life cycle assessment method was applied to quantify the environmental impact of remanufacturing technologies for industrial robots in the system boundary of “gate to gate”, with 1 iSNM remanufactured industrial robot as the functional unit. The results showed that fine particulate matter formation, human non-carcinogenic toxicity and global warming were the key impact categories, causing 95% of environmental impacts. The repair process and rated load operation process were key processes that caused the greatest environmental impact. By the critical substance identification, copper and aluminum were considered as the key inputs to the environmental impact of the robot remanufacturing, contributing 42.5% and 37.6% of the total environmental impacts, respectively. This research provided reference for a more sustainable industrial robot remanufacturing technology.

Keywords: Life cycle assessment; Environmental impact; Remanufacturing products; Industrial robots

1. Introduction

In recent years, the remanufacturing industry have developed in a more standardized way under the guidance of government. With public's increased understanding of low-carbon concept, the measurement of environmental impact and carbon emissions of various industries has attracted widely attention [8]. In the process of continuously exploring remanufacturing technologies, processes and equipment, the technical evaluation system of the remanufacturing industry has become a research hotspot. As an effective environmental assessment tool, life cycle assessment (LCA) has been gradually developed and applied [1]. Ziout et al. identified the environmental inventory of the remanufacturing process based on the LCA, which evaluated the environmental impact of the remanufacturing air conditioning process and provided decisions for manufacturers on the environmental performance in product manufacturing [10]. Pushkar et al. conducted a life cycle assessment of concrete beams using the ReCiPe2016 midpoint and endpoint and found that two-layer beams were more environmentally friendly than single-layer beams [6]. In addition, there were studies in energy system [7], electricity production [5] and buildings [2 have applied LCA to assess the environmental impacts. Remanufacturing is an effective and environment-friendly method to save resources, which can reduce pollutant emissions to a certain extent and meet relevant environmental standards [8]. Therefore, it is necessary to evaluate the remanufacturing process itself. However, most studies focus on the environmental impact assessment of traditional mechanical products currently, and few

EMIS 2023, February 24-26, Chengdu, People's Republic of China

DOI 10.4108/eai.24-2-2023.2330690

researches notice remanufacturing technology.

The waste industrial robot equipment has the characteristics of high recycling value. Therefore, it is imperative to establish a theoretical system to guide the technological upgrade of industrial robot remanufacturing. LCA is applied to evaluate the environmental impact of each production process of remanufactured industrial robots and identified the key processes and substances, and the results are conductive to improve the remanufacturing technology of industrial robots.

2. Methodology

2.1. System boundary and functional unit

Based on the ISO 14040 (ISO 2006)[3] and ISO 14044 (ISO 2006)[3], the ReCiPe 2016 model was used in this study to quantify the energy consumption, raw material consumption, pollutant discharge and other factors of the industrial robot remanufacturing process. The ReCiPe model includes 18 midpoint impact categories and 3 endpoint impact categories. The functional unit was determined to produce 1 iSNM remanufacturing industrial robot. In addition, the resource consumption, ecological environment and human health factors in the various production stages of industrial robot remanufacturing was also analyzed. The system boundary of this study was defined as "gate to gate", as shown in Figure 1.

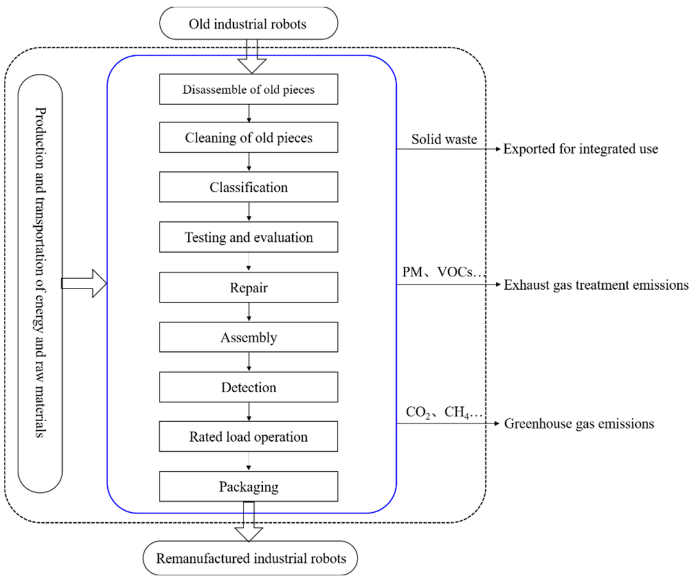

Figure 1. System boundary of industrial robot remanufacturing.

2.2. Life cycle inventory

The process of remanufacturing industrial robots includes recycling of used parts, dismantling, cleaning, testing and evaluation, repair, assembly, testing and packaging. In this study, the relevant data list was established according to the energy consumption, material consumption, transportation, and pollutant emission of every process. The repair process including replacing the robot's wire harness, controller, and displayer. The main materials and consumption of the above three types of components were collected through literature review. The environmental impact of the repair process was quantified by the consumption of raw materials. The monitoring data for the LCA was obtained from field research. The background data used for this evaluation was mainly from the CPLCID database. For the data not involved in the CPLCID database, we used the underlying data from the Ecoinvent database. Table 1 showed the life cycle inventory of industrial robot remanufacturing.

Table 1. Data list for iSNM industrial robot remanufacturing.

Process	Input/Output	Item	Unit	Value
Testing and evaluation	Input	Electricity	kWh	4
Repair	Input	Copper	g	759.566
	Input	PVC	g	5
	Input	Lead	g	84
	Input	Quartz sand	g	5.819
	Input	Fiberglass	g	17.456
	Input	Epoxy resin	g	14.051
	Input	Polyethylene terephthalate	g	156.4
	Input	Alumina	g	2.328
	Input	Soda ash	g	6.983
	Input	Kraft paper	m^2	0.024
	Input	Aluminum	kg	3.143
	Input	Sodium hydroxide	g	1.164
	Input	Polyurethane tri-proof oil	g	1.995
	Input	Lead-free solder paste	g	1.995
	Input	Lead-free solder wire	g	1.824
	Input	Anhydrous ethanol	g	1.001
	Input	Silicone resin	g	10.005
	Input	Polycarbonate	g	300
	Input	Silicon	g	97.391
	Input	PBT engineering plastics	g	547.635
	Input	Deionized water	g	232.742
	Input	Tap water	g	25601.598
	Input	Electricity	kWh	0.465
Assembly	Input	Stainless steel	kg	1.2
Detection	Input	Electricity	kWh	2
Rated load operation	Input	Electricity	kWh	40
Packaging	Input	Wood	kg	3
	Input	Plastic bag	kg	0.2

3. Results and Discussions

3.1. Characterization Results

Based on the life cycle inventory, the characteristic results of industrial robot remanufacturing were obtained. The results were presented for the total emissions of the pollutants for each environmental impact category within the system boundary, see Table 2.

Table 2. Characteristic results of industrial robot remanufacturing.

Environmental categories	Abbreviations	Unit	Value
Global warming	GW	kg CO_2 eq	1.24E+02
Stratospheric ozone depletion	SOD	kg CFC11 eq	5.43E-05
Ionizing radiation	IR	kBq Co-60 eq	8.32E+00
Ozone formation human health	OFHH	kg NOx eq	3.64E-01
Fine particulate matter formation	FPMF	kg $PM_{2.5}$ eq	3.51E-01
Ozone formation terrestrial ecosystems	OFTE	kg NOx eq	3.72E-01
Terrestrial acidification	TA	kg SO_2 eq	7.92E-01
Freshwater eutrophication	FEC	kg P eq	1.08E-01
Marine eutrophication	MEU	kg N eq	3.96E-03
Terrestrial ecotoxicity	TEC	kg 1,4-DCB	3.09E+03
Freshwater ecotoxicity	FEC	kg 1,4-DCB	5.47E+01
Marine ecotoxicity	MEC	kg 1,4-DCB	6.92E+01
Human carcinogenic toxicity	HCT	kg 1,4-DCB	1.66E+01
Human noncarcinogenic toxicity	HNCT	kg 1,4-DCB	7.30E+02
Land use	LU	m^2a crop eq	8.06E+00
Mineral resource scarcity	MRS	kg Cu eq	1.10E+00
Fossil resource scarcity	FRS	kg oil eq	2.91E+01
Water consumption	WC	m^3	1.49E+00

3.2. Identification of key processes

ReCiPe endpoint model was applied to quantify the environmental impact of industrial robot remanufacturing process, and the results were shown in Figure 2. FPMF was the highest environmental impact among all categories, accounting for 37.5% of the total environmental impact. This followed by HNCT and GW, which accounts for 28.3% and 21.5%, respectively. HCT contributes 9.4% of the environmental impact load. The above environmental impact categories produce a total of more than 95% of environmental impacts.

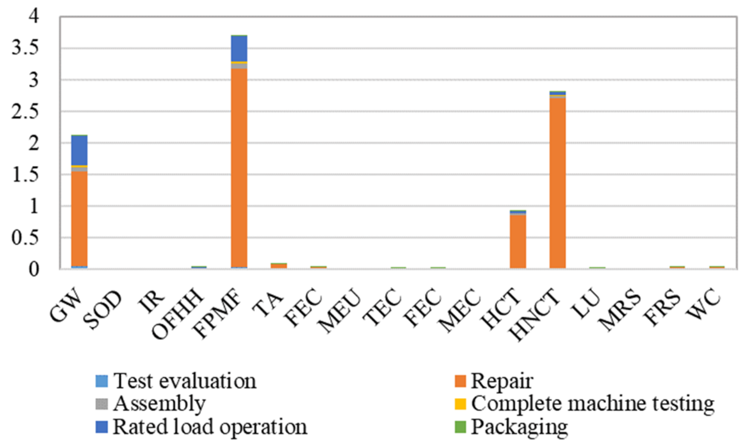

Figure 2. Key processes at the middle point of industrial robot remanufacturing.

We also analyzed the endpoint impact categories, see Table 3. The results showed that the repair and rated load operation stage was the key process which has the most impact on the environment. The repair process accounts for 85.8%, 76.1% and 75.9% of human health, ecological damage and resource depletion, respectively.

Table 3. Endpoint characterization impact evaluation results of industrial robot remanufacturing.

Impact category	Unit	Value	Process
Human health	DALY	5.59E-04	Repair 85.8%+Rated load operation 9.9+Others 4.3%
Ecological damage	Species.year	7.99E-07	Repair 76.1%+Rated load operation 14.5+ Packaging 4.8%+Others 4.6%
Resource depletion	$	5.87E+00	Repair 75.9%+Rated load operation 15.4+Others 8.6%

3.3. Identification of key factors

According to the identified key environmental impact categories and processes, the key substances contributing to the environmental impact were further traced. As shown in Figure 3.

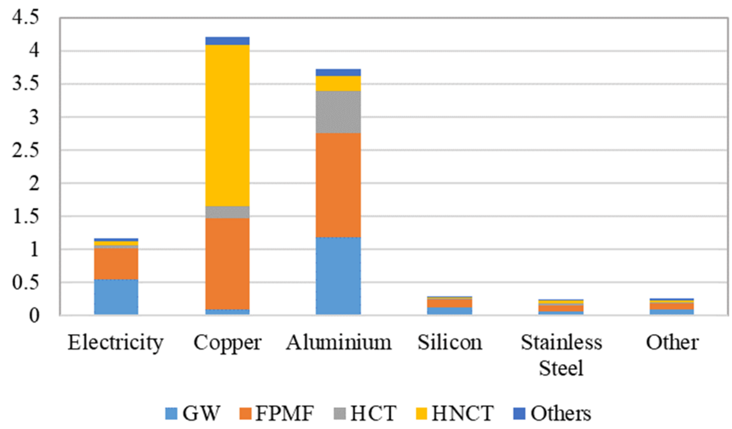

Figure 3. Identification of key substances for industrial robot remanufacturing.

It can be seen that copper and aluminum were the main substances, contributing 42.5% and 37.6% to the total environmental impact in the robot remanufacturing process, respectively. In the repairing process, the raw material of wire harness, PCB board in the controller and displayer, contains copper. The environmental effects of upstream production process of these material mainly focus on HNCT and FPMF, contributing 57.5% and 32.5% to the total environmental impact respectively. The environmental impact of aluminum production process was concentrated on FPMF (42.1%) and GW (31.7%). In addition, power generation was a major driver of global warming and FPMF, as well as an important environmental impact in the remanufacturing process of industrial robots, contributing 11.8% of the total environmental impact load.

4. Conclusion

LCA method was used to evaluate the environmental impact of 1 iSNM remanufactured industrial robot in the system boundary of "gate to gate". FPMF, HNCT and GW were the key impact categories of environmental impacts, accounting for 37.5%, 28.3% and 21.5% of total environmental impacts, respectively. The key processes and substances of the environmental impact of industrial robot remanufacturing process were also analyzed. The repair and rated load operation stages were the key processes that caused environmental impact, among which, the repair process has the largest environmental impact, accounting for 85.8%, 76.1% and 75.9% of the three end-point categories of human health, ecological damage and resource depletion, respectively. Copper and aluminum were the main substances that contributed to the environmental impact of the robot remanufacturing process. The results of the study can provide reference for a more sustainable industrial robot remanufacturing.

Acknowledgement: This research is supported by National Key R&D Plan of China (2020YFC1910000), Natural Science Foundation of China (71974116), Shandong Social Science Planning Research Project (21BKRJ02).

References

[1] Alengebawy, A., Mohamed, B. A., Ran, Y., Yang, Y., Pezzuolo, A., Samer, M., Ai, P. (2022). A comparative environmental life cycle assessment of rice straw-based bioenergy projects in China. *Environ. Res.*, 212, 113404. https://doi.org/10.1016/j.envres.2022.113404.

[2] Ben-Alon, L., Loftness, V., Harries, K. A., Cochran Hameen, E. (2021) Life cycle assessment (LCA) of natural vs conventional building assemblies. *Renew. Sust. Energ. Rev.*, 144, 110951. https://doi.org/10.1016/j.rser.2021.110951.

[3] International Organization for Standardization. (2006) ISO 14040: 2006 environmental management – life cycle assessment – principles and guidelines. https://www.iso.org/standard/37456.html.

[4] International Organization for Standardization. (2006) ISO 14044: 2006 Environmental management – Life cycle assessment – Requirements and guidelines. https://www.iso.org/standard/38498.html.

[5] Jordaan, S. M., Combs, C., Guenther, E. (2021) Life cycle assessment of electricity generation: A systematic review of spatiotemporal methods. *Advances in Applied Energy*, 3, 100058. https://doi.org/10.1016/j.adapen.2021.100058.

[6] Pushkar, S., Ribakov, Y. (2021) ENVIRONMENTAL BENEFIT OF TWO-LAYER STEEL FIBERED HIGH-PERFORMANCE CONCRETE BEAMS [J]. *Journal of Green Building*, 16(3): 237-250. https://doi.org/10.3992/jgb.16.3.237.

[7] Wang, R., Wen, X., Wang, X., Fu, Y., Zhang, Y. (2022) Low carbon optimal operation of integrated energy system based on carbon capture technology, LCA carbon emissions and ladder-type carbon trading. *Appl. Energ.,* 311, 118664. https://doi.org/10.1016/j.apenergy.2022.118664.

[8] Yuan, X., Sheng, X., Chen, L., Tang, Y., Li, Y., Jia, Y., Qu, D., Wang, Q., Ma, Q., Zuo, J. (2022) Carbon footprint and embodied carbon transfer at the provincial level of the Yellow River Basin [J]. *Sci Total Environ.,* 803, 149993. https://doi.org/10.1016/j.scitotenv.2021.149993.

[9] Yuan, X., Zhang, M., Wang, Q., Wang, Y., Zuo, J. (2017) Evolution analysis of environmental standards: Effectiveness on air pollutant emissions reduction [J]. *J Clean. Prod.,* 149, 511-520. https://doi.org/10.1016/j.jclepro.2017.02.127.

[10] Ziout, A., Alkahtani, M., Elgawad, A. E. E. A., Salah, B. (2022) Environmental Inventory Analysis for Remanufacturing Initiative: Case Study of Air Conditioner Remanufacturing. *Appl. Sci.,* 12(12). https://doi.org/10.3390/app12126251.