A Choquet Integral-based Environmental Performance Evaluation Framework for New Manufacturing and Remanufacturing: Emission Reduction, Energy Saving, and Scenario Analysis

Siqi Wu[1,a], Yijie Li[1,b], Sihai Zhao[2,c*]

[1]Business School, Sichuan University, Chengdu, Sichuan, 610065, China
[2]College of Management Science, Chengdu University of Technology, Chengdu, Sichuan, 610059, China
[a]siqiwu@scu.edu.cn, [b]liyijie@stu.scu.edu.cn, [c*]shzhao@cdut.edu.cn

Abstract. With the rapid development of green manufacturing and circular economy practices, evaluating the environmental performance differences between new manufacturing and remanufacturing has become an increasingly important research issue. This study examines a manufacturing system characterized by the co-existence of new and remanufactured products, and develops a Choquet integral-based environmental performance evaluation framework. This framework evaluates environmental performance along two dimensions: pollution emission and energy consumption. Based on these two dimensions, an integrated pollution and energy reduction coefficient is constructed through Choquet integral to compare the overall environmental performance of new manufacturing and remanufacturing. Different from traditional additive weighting approach, the proposed framework can capture the possible interactions between pollution reduction and energy saving. Finally, an illustrative example is designed to illustrate the applicability of the proposed framework, and the results suggest that the framework can effectively capture differences in environmental performance arising from resource inputs and process configurations.

Keywords: Remanufacturing, Environmental Performance Evaluation, Green Manufacturing, Sustainable Development, Choquet Integral.

1 Introduction

With the continued advancement of industrialization and the ongoing expansion of manufacturing scale, the problems of intensive resource consumption and environmental pollution have become increasingly prominent, making emission reduction, energy saving, and green transformation central issues in the pursuit of high-quality manufacturing development. Against the background of the dual-carbon agenda, the circular economy, and sustainable development, a critical challenge for both academia and industry is how to reduce resource consumption and pollutant emissions while maintaining product supply and operational efficiency[1]. From this perspective, pollution and

L. W. Koon et al. (eds.), *Proceedings of the 2026 7th International Conference on Management Science and Engineering Management (ICMSEM 2026)*, Advances in Economics, Business and Management Research 399,
https://doi.org/10.2991/978-94-6239-758-3_60

energy reduction should be understood not merely as an end-of-pipe environmental issue, but as a systemic managerial problem embedded in product manufacturing, resource input, process organization, and circular utilization.

Among the various pathways toward green manufacturing, remanufacturing is widely recognized as an effective approach to extending product life cycles, recovering residual value, and alleviating resource and environmental constraints[2]. Compared with new manufacturing, remanufacturing typically requires fewer virgin resources and lower energy input, and can reduce environmental burdens by restoring used products or components to functional use. In this sense, remanufacturing is relevant not only to end-of-life product recovery, but also to the broader question of whether manufacturing systems can achieve closed-loop resource utilization and sustainable operational improvement.

Existing research on remanufacturing has primarily developed along two related lines. One stream focuses on operational decisions, such as acquisition, pricing, and platform-based remanufacturing strategies[3-4]. The other examines environmental and sustainability effects, showing that remanufacturing may create synergies between economic and environmental performance, while also emphasizing that its environmental benefits depend on specific operating conditions[5-7]. However, two limitations remain. First, much of the literature evaluates the environmental value of remanufacturing at a relatively aggregate level, with limited decomposition of pollution emission and energy consumption within the manufacturing process. Second, existing analyses often rely on single indicators or case-specific assessments and therefore lack a unified framework for directly comparing the environmental performance of new manufacturing and remanufacturing.

This study develops an environmental performance evaluation framework for a setting in which new and remanufactured products coexist. Specifically, the framework evaluates environmental performance along two dimensions—pollution emission and energy consumption—and further constructs an integrated pollution and energy reduction coefficient to compare the environmental performance of new manufacturing and remanufacturing. An illustrative example is then used to illustrate the applicability of the proposed framework. The results show that remanufacturing achieves lower pollution emission and lower energy consumption, thereby demonstrating a clear overall environmental advantage. This study contributes by shifting environmental analysis from broad qualitative judgment to quantitative comparison and by providing a unified indicator system for evaluating the environmental performance of remanufacturing.

2 Methodology

In this section, we develop the environmental performance evaluation framework used to compare new manufacturing and remanufacturing. Notably, the pollution emission and energy consumption calculation in this study adopts a process-level system boundary rather than a full life-cycle assessment boundary. The calculation focuses on the major resource inputs consumed during the core production processes.

2.1 Standardization of the Pollution Emission Coefficient

In reality, different types of resources generate substantially different forms of environmental impact during consumption; therefore, a direct comparison of their original consumption amounts cannot accurately reflect the environmental burden of different manufacturing modes. To improve the consistency and comparability of the evaluation results, this study adopts carbon dioxide emissions as a unified benchmark and standardizes the pollution emission induced by various resource inputs by converting them into equivalent CO_2 emissions from standard coal combustion[6]. Considering actual resource inputs in the manufacturing process, coal, water, electricity, gasoline, and diesel are selected as the major resource categories. Corresponding standard-coal conversion coefficients and carbon emission factors are introduced to complete the conversion from resource consumption to standard-coal equivalent and then to CO_2 emissions, thereby providing a basis for subsequent pollution assessment and energy consumption measurement. The standard-coal conversion coefficients for the major energy sources are reported in Table 1, and the corresponding carbon emission factors are presented in Table 2[6].

Table 1. Standard-coal conversion coefficients for major energy sources.

Energy	**Raw Coal**	**Water**	**Electricity**	**Gasoline**	**Diesel**
Unit	kg	t	kWh	kg	kg
Coefficient(kgce)	0.7143	0.1229	0.2429	1.4714	1.4571

Table 2. Carbon emission factors for major energy sources.

Energy	**Raw Coal**	**Water**	**Electricity**	**Gasoline**	**Diesel**
Unit	kg	t	kWh	kg	kg
Coefficient(kgco2/kgce)	1.90	0.194	0.80	2.93	3.01

Let PE_{np} and PE_{rp} denote the pollution emission generated in new manufacturing and remanufacturing, respectively. Let θ_i and v_i be the standard-coal conversion coefficient and the carbon emission factor of the i-th resource type, respectively. Let M_i^n and M_i^r denote the consumption of the i-th resource type in new manufacturing and remanufacturing, respectively, and q be the number of resource categories. Then, the pollution emission associated with new manufacturing and remanufacturing can be respectively calculated as follows:

$$PE_{np} = \sum_{i=1}^{q} \theta_i v_i M_i^n \tag{1}$$

$$PE_{rp} = \sum_{i=1}^{q} \theta_i v_i M_i^r \tag{2}$$

Let X_p be the pollution emission coefficient, then it can be derived from the ratio of the two emission levels:

$$X_P = \frac{PE_{rp}}{PE_{np}} \tag{3}$$

If $X_p < 1$, then remanufacturing is more environmentally friendly than new manufacturing; If $X_p = 1$, then new manufacturing and remanufacturing has equal amount of pollution emission; Otherwise, new manufacturing is a better way.

2.2 Standardization of the Energy Consumption Coefficient

In addition to pollution emission, energy consumption is another important dimension for evaluating the environmental friendliness of manufacturing activities. In essence, the manufacturing process is a multi-stage system involving multiple processes and heterogeneous resource inputs. Differences in resource-input intensity and processing methods across stages lead to different levels of energy consumption in new manufacturing and remanufacturing. Therefore, this study evaluates energy consumption at the process level. Based on the resource-input intensity and mass variation in each process, the total energy consumption of new manufacturing and remanufacturing is calculated [5].

Let EC_n and EC_r denote the total energy consumption of new manufacturing and remanufacturing, respectively. Let e_k be the specific energy consumption in process k, r_k be the material removal rate in process k, m_{k-1} and m_k be the component mass before and after process k, respectively, and n be the number of manufacturing processes. Then, the total energy consumption can be calculated as follows:

$$EC = \sum_{k=1}^{n} e_k \, r_k (m_k - m_{k-1}) \tag{4}$$

Let X_e be the energy consumption coefficient, then it can be derived from the ratio of the two emission levels:

$$X_E = \frac{EC_r}{EC_n} \tag{5}$$

Similarly, if $X_e < 1$, then remanufacturing is more environmentally friendly than new manufacturing; If $X_e = 1$, then new manufacturing and remanufacturing has equal energy consumption; Otherwise, new manufacturing is a better way.

2.3 Calculation of the Integrated Pollution and Energy Reduction Coefficient

To comprehensively evaluate the overall environmental performance of remanufacturing relative to new manufacturing, it is necessary to aggregate the pollution emission coefficient and the energy consumption coefficient into an integrated indicator. In real new manufacturing and remanufacturing systems, for example, a remanufacturing process may achieve substantial energy saving while only producing limited pollution reduction, or vice versa. Moreover, simultaneous improvements in both dimensions may generate a stronger environmental advantage than that implied by a simple additive aggregation. Therefore, this study introduces the Choquet integral to construct a non-additive integrated pollution and energy reduction coefficient[8].

To capture the possible interaction between pollution emission and energy consumption, let X_P and X_E be as before. Let $N = \{P, E\}$ be the set of environmental evaluation dimensions, i.e., pollution emission and energy consumption. Then, we define a fuzzy measure on N is a function:

$$\mu: 2^N \to [0,1] \tag{6}$$

which satisfies the following conditions:

$$\begin{gathered} \mu(\emptyset) = 0, \mu(N) = 1 \\ 0 \le \mu(\{P\}) \le 1, 0 \le \mu(\{E\}) \le 1 \\ A \subseteq B \subseteq N \Rightarrow \mu(A) \le \mu(B) \end{gathered} \tag{7}$$

In Eq.(7), $\mu(\{P\})$ and $\mu(\{E\})$ represent the individual importance of pollution emission and energy consumption, respectively; while $\mu(\{P, E\})$ represents the joint importance of the two dimensions. Therefore, it is able to characterize the interaction between the two environmental dimensions.

Specifically, if $\mu(\{P\}) + \mu(\{E\}) < \mu(\{P, E\})$, then the two dimensions have a complementary relationship, indicating that simultaneous improvement in pollution reduction and energy saving is particularly valued; On the contrary, if $\mu(\{P\}) + \mu(\{E\}) > \mu(\{P, E\})$, then the two dimensions have a substitutive relationship, indicating that improvement in one dimension can partially compensate for weaker performance in the other.

For a general set of environmental criteria $N = \{1,2, \dots, m\}$, let x_i denote the normalized assessment coefficient of criterion i. Let $\sigma(\cdot)$ be a permutation on N such that $x_{\sigma(1)} \le \cdots \le x_{\sigma(n)}$, and $A_{\sigma(i)} = \{\sigma(i), \dots, \sigma(n)\}, A_{\sigma(n+1)} = \emptyset$. Then, the Choquet integral of $x = (x_1, \dots, x_n)$ with respect to the fuzzy measure μ is given by

$$C_\mu(x_1, \dots, x_n) = \sum_{i=1}^{n} x_{\sigma(i)} \left[\mu\left(A_{\sigma(i)}\right) - \mu\left(A_{\sigma(i+1)}\right)\right] \tag{8}$$

Based on Eqs.(6)-(8), this study considers two environmental dimensions, let the integrated pollution and energy reduction coefficient be as the Choquet integral in the following form:

$$C_\mu(X_P, X_E) = \begin{cases} X_P + (X_E - X_P)\mu(\{E\}), & \text{if } X_P \le X_E \\ X_E + (X_P - X_E)\mu(\{P\}), & \text{if } X_E \le X_P \end{cases} \tag{9}$$

The Choquet-integral-based coefficient can capture not only the individual importance of pollution emission and energy consumption, but also their interaction in determining the overall environmental performance of manufacturing.

3 An Illustrative Example

To verify the applicability of the proposed evaluation framework, this study develops a numerical example of a typical mechanical product with reference to the real-world machinery remanufacturing data reported in Gong et al [6]. One unit of the product is taken as the functional unit. Based on the typical resource-input characteristics of the two production modes, the consumption data of major resources, including coal, water, electricity, gasoline, and diesel, are specified. Process-level energy consumption is then measured for both new manufacturing and remanufacturing. On this basis, the pollution emission coefficient, the energy consumption coefficient, and the integrated pollution and energy reduction coefficient are calculated to compare the environmental performance of the two manufacturing modes.

3.1 Example Setting and Data Description

Table 3 reports the major resource consumption of new manufacturing and remanufacturing for the representative mechanical product. Compared with new manufacturing, remanufacturing consumes substantially less coal and electricity, mainly because it avoids part of the raw material preparation and front-end machining processes. By contrast, water consumption is slightly higher under remanufacturing, reflecting the additional requirements of cleaning, inspection, and surface treatment. The differences in gasoline and diesel consumption are relatively limited, suggesting that both production modes require comparable energy inputs for transportation, disassembly, and auxiliary processing.

Table 3. Major resource consumption data in new product manufacturing and remanufacturing processes

Resource Type	Unit	New Product	Remanufactured Product
Raw Coal	kg	58.00	32.00
Water	t	18.00	21.53
Electricity	kWh	34.00	19.02
Gasoline	kg	12.00	11.84
Diesel	kg	8.00	9.86

At the process level, remanufacturing exhibits lower energy consumption in raw material preparation or recovery, disassembly, rough machining or cleaning, and finish machining or inspection, whereas its energy consumption is relatively higher in the reprocessing and repair stage.

3.2 Comparative Analysis of Pollution Emission

Using the pollution emission standardization method developed in Section 2, together with the standard-coal conversion coefficients in Table 1 and the carbon emission factors in Table 2, the carbon emissions associated with new manufacturing and remanufacturing can be calculated, as shown in Table 4.

Table 4. Calculated CO_2 emissions of new product manufacturing and remanufacturing

Resource Type	New Manufacturing ($kgCO_2$)	Remanufacturing ($kgCO_2$)
Coal	78.72	43.43
Water	0.43	0.51
Electricity	6.61	3.70
Gasoline	51.73	51.04
Diesel	35.09	43.24
Total	172.57	141.93

Based on Eq. (3) and Table 4, the pollution emission coefficient is obtained as follows:

$$X_p = \frac{141.93}{172.57} = 0.8224 \tag{10}$$

The results show that total pollution emissions are 172.57 $kgCO_2$ for new manufacturing and 141.93 $kgCO_2$ for remanufacturing. Accordingly, the pollution emission coefficient is smaller than 1, indicating that remanufacturing performs better in the pollution dimension. Relative to new manufacturing, remanufacturing reduces pollution emission by approximately 17.76%.

3.3 Comparative Analysis of Energy Consumption

Table 5 further shows that total energy consumption is 430.02 MJ in new manufacturing and 270.10 MJ in remanufacturing. The corresponding energy consumption coefficient is therefore smaller than 1, indicating that remanufacturing is more energy-efficient than new manufacturing.

Table 5. Process-level energy consumption data for new manufacturing and remanufacturing

Process	Energy consumption of new manufacturing	Energy consumption of remanufacturing
Raw material preparation/recovery and disassembly	82.43	26.54
Rough machining/cleaning	96.72	38.01
Finish machining/inspection and sorting	104.26	22.51
Heat treatment or surface treatment/ reprocessing and repair	92.89	126.66
Assembly and testing	54.02	56.38
Total	430.02	270.10

Based on Eq. (5) and Table 5, the energy consumption coefficient is obtained as follows:

$$X_e = \frac{270.10}{430.02} = 0.6281 \tag{11}$$

The energy saving advantage of remanufacturing mainly arises from three factors. First, it avoids a substantial part of raw material preparation and initial forming, thereby significantly reducing front-end energy use. Second, part of the original product structure is retained during the rough and finish machining stages, which reduces processing intensity. Third, although the reprocessing and repair stage requires higher energy input under remanufacturing, this localized increase does not alter the overall energy-saving pattern. In total, remanufacturing reduces energy consumption by approximately 37.19%, a reduction that is larger than its decrease in pollution emission.

These results provide differentiated managerial guidance. Under high energy prices or energy-efficiency regulations, manufacturers may prioritize remanufacturing as an effective energy-saving strategy. Under stricter carbon-emission or pollution-control regulations, however, they should not only rely on remanufacturing, but should further improve transportation, cleaning, surface-treatment, and so on. In market settings where customers value green products, they can emphasize the energy-saving benefit of remanufacturing while combining it with additional emission-reduction measures.

3.4 Comprehensive Analysis of the Pollution and Emission Reduction Effect

To further obtain the overall environmental performance of remanufacturing, in this subsection, we conduct a scenario analysis that consists of two common scenarios. Specifically, in Scenario I, the two dimensions are mutually independent, and aggregation is performed using the weighted average method; while in Scenario II, the two dimensions have a complementary relationship, and aggregation is performed using the Choquet integral.

Scenario I: Weighted average method. We use a simple additive form with equal weights as a benchmark, i.e.,

$$C_\mu(X_P, X_E) = 0.5X_P + 0.5X_E \tag{12}$$

Then, the resulting integrated pollution and energy reduction coefficient is 0.7253.

Scenario II: Choquet integral method. Since the pollution emission coefficient is larger than the energy consumption coefficient, namely, $X_E < X_P$, the integrated pollution and energy reduction coefficient can be calculated as:

$$C_\mu(X_P, X_E) = X_E + (X_P - X_E)\mu(\{P\}) \tag{13}$$

Here, the fuzzy measure is calibrated through a scenario-based procedure by experts, and we set $\mu(\{P\}) = 0.55, \mu(\{E\}) = 0.35, \mu(\{P, E\}) = 1$. This setting indicates that the overall environmental advantage of remanufacturing depends not only on the individual improvement in pollution emission or energy consumption, but also on their joint contribution. These values are not universal constants. They are used for the illustrative mechanical product and should be recalibrated for other product types. Based on Eq.(13) and the above values, the coefficient is calculated as:

$$C_\mu(X_P, X_E) = 0.6281 + (0.8224 - 0.6281) \times 0.55 = 0.7350.$$

Since $C_\mu(X_P, X_E) < 1$, remanufacturing exhibits an overall environmental advantage over new manufacturing. Compared with the conventional equal-weighted result of 0.7253, the Choquet-integral-based coefficient is slightly larger. This indicates that when the interaction between emission reduction and energy saving is considered, the environmental advantage of remanufacturing is evaluated more cautiously. Nevertheless, the conclusion remains unchanged: remanufacturing achieves better overall environmental performance than new manufacturing. The sensitivity analysis results are reported in Table 6.

Table 6. The sensitivity analysis results

Scenario	$\mu(\{P\})$	$\mu(\{E\})$	Relationship	$C_\mu(X_P, X_E)$
Additive case	0.50	0.50	$\mu(\{P\}) + \mu(\{E\}) = 1$	0.7253
Complementary case	0.55	0.35	$\mu(\{P\}) + \mu(\{E\}) < 1$	0.7350
Substitutive case	0.65	0.45	$\mu(\{P\}) + \mu(\{E\}) > 1$	0.7544

The results show that the composite coefficient remains smaller than 1 under all tested fuzzy measure specifications. Therefore, the result of this example that remanufacturing exhibits an overall environmental advantage over new manufacturing remains robust.

4 Conclusion

This study examines a manufacturing setting in which new and remanufactured products coexist and develops an environmental performance evaluation framework composed of a pollution emission coefficient, an energy consumption coefficient, and an integrated pollution and energy reduction coefficient. Specifically, pollution emission is standardized by converting heterogeneous resource inputs into equivalent carbon emissions, while energy consumption is evaluated from a process-level perspective. On this basis, a Choquet-integral-based integrated coefficient is introduced to aggregate the two environmental dimensions. Compared with a conventional weighted-average method, the proposed aggregation approach can capture the possible interaction between emission reduction and energy saving, thereby providing a more flexible and informative evaluation of the overall environmental performance of remanufacturing.

References

1. Kamal, M. M., Mamat, R., Mangla, S. K., et al. (2022). Immediate return in circular economy: Business to consumer product return information sharing framework to support sustainable manufacturing in small and medium enterprises. Journal of Business Research, 151, 379-396.
2. Liu, B., Song, Q., Zheng, H., et al. (2023). Remanufacturing production decisions considering product life cycle and green consumers' scale in the circular economy. Industrial Management & Data Systems, 123(4), 1122-1156.

3. Li, K., Liu, J., Fu, H., et al. (2020). Acquisition and pricing strategies in hybrid manufacturing-remanufacturing systems. Journal of Manufacturing Systems, 57, 217-230.
4. Xu, X. P., Yan, L. L., Choi, T. M., et al. (2023). When is it wise to use blockchain for platform operations with remanufacturing? European Journal of Operational Research, 309(3), 1073-1090.
5. Zhang, X. G., Zhang, M. Y., Zhang, H., et al. (2020). A review on energy, environment and economic assessment in remanufacturing based on life cycle assessment method. Journal of Cleaner Production, 255, 120160.
6. Gong, Q. S., Xiong, Y. R., Jiang, Z. G., et al. (2022). Economic, Environmental and Social Benefits Analysis of Remanufacturing Strategies for Used Products. Mathematics, 10(21), 3929.
7. Sun, X. C., Rajapakshe, T., & Oliva, R. (2024). Interplay between servicizing and remanufacturing: Economic and environmental implications. Manufacturing & Service Operations Management, 27(1), 114-126.
8. Aggarwal, M., & Tehrani, A. F. (2019) Modelling Human Decision Behaviour with Preference Learning. INFORMS Journal on Computing, 31(2), 318-334.