sustainability

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The Sustainability Evaluation of Masks Based on the Integrated Rank Sum Ratio and Entropy Weight Method

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Abstract: Due to the seriousness of COVID-19, masks are considered to be as a key and effective device to cut off the spread of viruses and are widely used by people, such as doctors and patients. Hundreds of millions of masks used worldwide in daily life will inevitably cause huge pollution and damage to the environment. However, existing research has not yet provided a method to simultaneously evaluate the economic, environmental, and social aspects of sustainable design of masks, which brings great barriers and challenges for designers to make sustainability decisions on masks and consumers' behavioral decisions on mask purchases. Consequently, on the basis of principles of sustainability evaluation of masks, this work evaluates ten masks of different materials (including two newly designed masks) by using a novel hybrid of rank-sum ratio and entropy weight method. The results indicate that some disposable masks also show better sustainability than reusable masks, and in addition, the integrated rank-sum ratio and entropy weight method can effectively realize the sustainability evaluation of masks. The main contribution is to furnish an effective decision-making reference for sustainability evaluation of masks while greatly reducing the negative impacts of masks on the environment during the epidemic.

Keywords: product design; sustainability evaluation; rank-sum-ratio method; entropy weight method

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1. Introduction

COVID-19 is highly contagious and can be spread through the following three main ways: droplet, contact, and aerosol transmission [1]. Studies have already shown that mask is a solid physical barrier that prevents particles from spreading and blocking viruses, and wearing masks can effectively reduce the spread of COVID-19 and influenza viruses in the population [2]. According to the report from World Health Organization (WHO), approximately 1.6 million tons of masks have been used globally since the outbreak of COVID-19. Among them, the consumption of medical masks alone requires 89 million pieces per month [3]. The production of masks requires plenty of chemical raw materials, which may lead to serious environmental problems. Due to the lack of in-depth research on the sustainability evaluation of masks, mask designers and consumers are more casual in making decisions on mask sustainability design and purchasing behavior, which causes a huge burden on the environment, especially when unsustainable masks get widely used. As a result, it is of great significance to research the sustainability evaluation of masks [4].

Currently, most research in the field of mask sustainability evaluation gets environmental pollution reduced through two approaches: designing new masks by ecological design methods and reusing masks to prolong their service life [5–7]. In the research of new mask design, Furukawa et al. designed a new type of surgical mask which could effectively reduce the risk of virus spread to doctors during surgery, thereby improving the use cycle of the mask [8]. Fang-Lin et al. analyzed and improved the design process of previous masks and then proposed three improved mask design styles to reduce virus exposure and extend the use cycle of the mask [9]. Liu et al. applied a fuzzy comprehensive evaluation method to the masks research, development, and design and considered the prioritization of mask design requirements. The experimental results presented that their innovative masks could meet the long-term needs of users and provide a sustainable solution for the COVID-19 [1]. In the research on mask reuse, Allison et al. conducted a sustainability comparison of single-use and reusable masks and found that the use of reusable masks could reduce unnecessary exposure to viruses [10]. Phan et al. proposed a novel method of removing CPR masks to redesign and reuse masks, which effectively reduces the number of used masks [11]. Núria Boix et al. formulated an action guide for mask design and found that reusable masks, such as 3D printed masks and washable masks, were the most sustainable from the perspective of products' life cycle [12]. Monzamodeth et al. conducted further research on 3D printed masks and explored the feasibility of different printing materials to prevent flow diffusion of human sneezing. They also considered the utilization of ethanol or commercial disinfectants to sterilize 3D printed masks [13]. The above studies provide considerable inspiration for the innovative design of masks. Especially, the research on mask reuse gives remarkable insights into the sustainability evaluation of 3D printed masks and washable masks. For example, Núria Boix et al. even conducted a comparison of five different models of masks on the global market. These studies focused on reducing the impact of industrial products on the environment and played a positive role in reducing mask waste and environmental pollution.

However, research on the sustainable design of masks is mainly employed to improve the environmental aspects of products, and there exist few methods for sustainability evaluation of masks that simultaneously evaluate the economic, environmental, and social aspects [14]. On the other hand, the effectiveness of integrating the advantages of rank-sum ratio and entropy weight method for sustainability evaluation of masks has not been adopted and verified. As a matter of fact, the sustainability evaluation of products not only considers impacts on the environment but also pays attention to the economic aspect and social issues aspect [15]. The study conducted by Piergiuseppe et al. found that the main impact of disposable masks on the environment was related to raw material consumption, energy demand, and waste disposal, while the use stage and raw material consumption contributed the most to the reusable type. In other words, reusable masks had the least impact on the environment during the use phase but still caused a greater burden on the environment during the recycling phase [16]. Thus, it is worthwhile to construct a complete evaluation index system of masks and apply a scientific method for comprehensive sustainability evaluation [17]. In addition, although Núria Boix et al. compared five different types of masks in the global market, whether these five types of masks cover all basic types of masks is still worth considering.

Based on the above description, the main goal of this work is to verify the effectiveness of the novel hybrid of rank-sum ratio and entropy weight method in the sustainability evaluation of masks so as to provide guidance for designers in the development process of masks and consumers in purchasing products of masks as well as to reduce masks' negative impact on the environment during COVID-19. To handle this issue, a seven-index evaluation system of masks including the factors of life cycle cost (material consumption, energy consumption, discount rate, and waste treatment recycling cost), material environmental friendliness, waste generation amount, recyclable value, worker friendliness, aesthetic appearance, and functionality is established, and the rank-sum ratio and entropy weight method are combined to evaluate the sustainability of masks comprehensively [18]. This work is based on actual research data from China, but the research results are also applicable to other countries. The main innovation of this research is to break through the bottleneck of reuse and ecological design in traditional mask sustainability research. On the basis of considering the principles of economy and sociality, an integrated rank-sum ratio and entropy weight method is proposed to realize the comprehensive evaluation of the sustainability of masks. The findings also promote the development of decision making on the sustainability of masks.

The rest of this paper is organized as follows: Section 2 introduces the sustainability evaluation materials, sustainability evaluation principles, and the hybrid of rank-sum ratio and entropy weight method. Section 3 presents the evaluation process for ten masks, and experimental results are then analyzed and discussed. Section 4 illustrates the validation process of the validity of the mask sustainability evaluation method. Section 4 concludes this work and draws the future outlines.

2. Materials and Methods

In this work, a count of ten images of different types of masks were selected, and the sustainability evaluation principles were formulated by literature review and user research. The scoring of indexes was carried out by consulting relevant experts. The rank-sum ratio method was utilized for data calculation and comprehensive evaluation, and the entropy weight method was employed to compensate for the evaluation results to obtain the final results. The following text introduces the sustainable evaluation materials, sustainable evaluation principles, sustainable evaluation methods, and data compensatory evaluation methods in detail.

2.1. Sustainable Evaluation Materials

The sustainable evaluation materials were selected from the images of 10 different types of masks. Through online research and on-the-spot investigation, we selected 10 different types of masks for the study, including 3 disposable masks and 7 reusable masks. The three disposable masks contained a nasal connector made of EVA, a nasal connector made of aluminum, and no nasal connector. Among them, masks were either with breathing valves or without breathing valves; masks were also either with or without mask straps. The seven reusable masks contained nasal connectors made of ABS, PP, and NR, and meanwhile, their mask bands, nasal connectors, and breathing valve materials are different from each other [12]. In this work, the new green masks designed by project members are evaluated and compared with the same type of masks in the market, and those new self-designed green masks were randomly assigned to ten mask images. The appearance images and materials of all masks are presented in Table 1.

Table 1. Different types of 10 kinds of masks appearance images and material parameters.

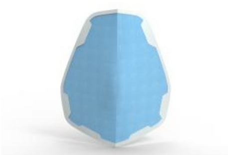
Items	Content				
Number	1	2	3	4	5
Image					
Materials	Filter: pp Mask strap: None Nose joint: EVA Breathing valve: None	Filter: PP Mask strap: PP Nose joint: None Breathing valve: None	Filter: PS Mask strap: ABS Nose joint: ABS Breathing valve: None	Filter: PP Mask strap: PP Nose joint: None Breathing valve: ABS	Filter: PP Mask strap: PE Nose joint: aluminum Breathing valve: PU

Table 1. *Cont.*

Items	Content				
Number	6	7	8	9	10
Image					
Materials	Filter: PP Mask strap: PE Nose joint: PP Breathing valve: ABS	Filter: PP Mask strap: PP Nose joint: None Breathing valve: None	Filter: PP Mask strap: PE Nose joint: None Breathing valve: PU	Filter: PP Mask strap: PE Nose joint: NR Breathing valve: PU	Filter: PP Mask strap: PE Nose joint: None Breathing valve: None

2.2. Sustainable Evaluation Principles

The principles of product sustainability evaluation used in this work are listed as follows: economic competitiveness, environmental friendliness, and social desirability [19]. The product sustainability evaluation should not only consider the negative impact on the environment but also focus on several dimensions such as economic aspects and social issues [14,15]. Economic competitiveness takes the life cycle cost (LCC) as the evaluation index, where the LCC includes the material cost, manufacturing cost, transportation cost, service life, maintenance cost, and mask scrap recycling cost of masks [20]. Environmental friendliness regards material environmental friendliness, waste yield, and recyclable value as its evaluation indexes [14,21]. Social desirability takes mask ergonomics, aesthetics, and functionality as its evaluation indexes, where the functionality contains several aspects such as droplet blocking ability, facial fit, and smooth breathing [1,22]. It has difficulties in investigating social desirability due to the fact that it is closely concerned with how masks affect human well-being, including human equality, social justice, and people's happiness [23]. Regarding this difficulty, this work focuses only on the impact of masks on the quality of consumers' daily lives and, crucially, on the users themselves.

The sustainability evaluation principles of masks and the specific scores of each indicator are shown in Table 2. The sustainability evaluation indicators of masks in Table 2 are divided into the following three parts. The first part is mainly related to the production cost, manufacturing cost, transportation cost, maintenance cost, and recycling cost of masks, among which the production cost, manufacturing cost, and transportation cost data mainly come from the survey of enterprise employees in China Anhui Yufa Environmental Protection Technology Co., Ltd. (Hefei, China) and Anhui Hailitron Labor Protection Hardware Co., Ltd. The maintenance cost is from the subjective questionnaire survey of users, and the recycling cost is mainly from the survey of enterprise employees in Hefei Honest Waste Material Recycling Co., Ltd. (Hefei, China). The second part is mainly related to the materials used in the production stage, the waste yield in the manufacturing stage, and the recyclable values in the recycling stage; among them, the data on the environmental friendliness of the materials used and the amount of waste come from the unique identification database of medical devices in the webpage of the State Drug Administration of China, while the data on recyclable values in the recycling stage come from the study on the disassembly of mask components and materials in the published research results of scholars Boix Rodríguez and Lepelletier [12,24,25]. The third part is mainly related to the ergonomics, aesthetics, and functionality of the user's use process, which determines the scores of various evaluation indicators through user research and consultation with relevant experts.

Table 2. Principles of sustainable evaluation of masks and scoring of each index.

Sustainability Evaluation Principles	Economic Competitiveness	Environmental Friendliness			Social Desirability		
Evaluation Indicators	1	2	3	4	5	6	7
	Whole Lifecycle Costs	Material Environmental Friendliness	Waste Production	Recyclable Value	Use of Man-Machine Sex	Aesthetics	Functionality
	(Yuan/Day)	(Percentage)	(Percentage)	(Percentage)	(Percentage)	(Percentage)	(Percentage)
No. 1	12	100	3	85	75	98	80
No. 2	0.4	90	0	40	60	85	85
No. 3	6	80	5	80	71	70	75
No. 4	4	80	2	98	76	90	70
No. 5	60	80	10	95	70	95	85
No. 6	1	95	0	20	95	60	73
No. 7	5	80	5	70	60	87	92
No. 8	7	100	2	95	80	50	90
No. 9	8	80	10	90	30	80	95
No. 10	10	80	10	80	20	85	100

2.3. Rank-Sum Ratio–Entropy Method Evaluation Model

In this work, an integrated rank-sum ratio–entropy weight evaluation model is proposed to evaluate the sustainability of masks. Rank-sum ratio (RSR) is a statistical analysis method that combines the advantages of classical parametric statistics and modern nonparametric statistics [26]. The general process of the RSR is as follows: rank benefit indexes and cost indexes in ascending order and descending order, respectively, then calculate the rank-sum-ratio values, and finally perform statistical regression and binning. RSR obtains the dimensionless statistic RSR through rank conversion; on this basis, the concepts and methods of parametric statistical analysis are applied to study the distribution of RSR; the RSR value is used to directly rank the pros and cons of evaluation objects or rank them in different grades, so as to make a comprehensive evaluation of the evaluation objects [27]. RSR is based on the nonparametric method and does not requires special requirements for the index selection, which makes it applicable to various evaluation objects. Since values used in the calculation process are rank order, i.e., relative size relationship of data rather than data themselves, RSR is a comprehensive method that can tell minor changes, sort, and classify each evaluation object to find out the advantages and disadvantages. RSR can also find out whether the evaluation indexes are independent [28]. As a result, RSR is often taken as an effective approach to make comparisons and find relationships.

However, RSR does not pay enough attention to the index weights. To address this problem, the entropy weight method (EWM) is introduced in this work. The EWM is a purely objective evaluation method and obeys the rule that the greater dispersion degree an index has, the lower the information entropy the index has and the greater the amount of information the index contains. If the values of an index are all equal, the index does not work in the comprehensive evaluation [29]. In the process of masks' sustainability evaluation, scores of each index are obtained through expert scoring or other forms, which contains some subjectivity. Embedding the EWM into the RSR evaluation process can gain an effective integration of subjective and objective factors, avoid distortion in the information process, and make an effective evaluation of mask design. Based on the rank and ratio-entropy method evaluation model, this study conducts the sustainability evaluation of mask design. The specific evaluation process is organized as follows:

1. Put raw evaluation data into a matrix. Suppose that there are m kinds of masks as evaluation objects and n evaluation indexes, then obtain the raw data matrix of m rows and n columns $X = (X_{ij})_{m \times n}$, where X_{ij} denotes the score of the *j*-th index of the *i*-th mask.
2. Forward standardized scores for each index. For benefit indexes (the higher, the better principle), their standardization process is expressed in Equation (1); For cost indexes (the lower, the better principle), their standardization process is expressed in Equation (2).

$$Z_{ij} = \frac{X_{ij} - \min(X_{1j}, X_{2j} \cdots X_{mj})}{\max(X_{1j}, X_{2j} \cdots X_{mj}) - \min(X_{1j}, X_{2j} \cdots X_{mj})} \tag{1}$$

$$Z_{ij} = \frac{\max(X_{1j}, X_{2j} \cdots X_{mj}) - X_{ij}}{\max(X_{1j}, X_{2j} \cdots X_{mj}) - \min(X_{1j}, X_{2j} \cdots X_{mj})} \tag{2}$$

3. Calculate the rank value for each index. In order to overcome the drawback that RSR tends to lose the quantitative information of the original index value when performing ranking, this work does not directly compare the index scores but adopts a method similar to linear interpolation. There exists a quantitative linear correspondence between the compiled rank and the original index value, which is calculated by:

$$R_{ij} = 1 + (m-1)Z_{ij} \tag{3}$$

4. The weights of each index are calculated by EWM, and the calculation procedure contains the following three steps:
   Step 1. Work out the weight of the *i*-th evaluation object under the *j*-th index p_{ij}. p_{ij} is regarded as the probability used in the relative entropy calculation process, and its formula is presented in Equation (4).
   Step 2. Calculate the information entropy of each index e_j; the information entropy calculation formula is shown in Equation (5).
   Step 3. Normalize the information entropy to determine the entropy weight of each indicator W_j, as presented in Equation (6).

$$p_{ij} = Z_{ij} / \sum_{i=1}^{m} Z_{ij} \tag{4}$$

$$e_j = -\frac{1}{\ln m} \sum_{i=1}^{m} p_{ij} \ln(p_{ij}), \quad j = 1, 2, 3, \cdots n \tag{5}$$

$$W_j = (1 - e_j) / \sum_{j=1}^{n} (1 - e_j) \tag{6}$$

5. Calculate the weighted *RSR* values and rank them. The weighted rank-sum ratio is calculated by Equation (7):

$$WRSR_i = \frac{1}{mn} \sum_{j=1}^{n} W_j R_{ij} \tag{7}$$

6. Determine the distribution of $WRSR_i$ (transformed into probability units). The distribution of $WRSR_i$ is the cumulative frequency of the value specific expressed in probability units Probit. The Probit model is a generalized linear model that obeys a normal distribution, and its transformation process consists of the following five steps:

Step 1. Arrange the values of $WRSR_i$ in ascending order.
Step 2. List the frequency of each group f, and calculate the cumulative frequency of each group $\sum f$.
Step 3. Determine the average rank of each $\overline{R}_i$. For $WRSR_i$ values whose frequency equals 1, the value of $\overline{R}_i$ is the rank of $WRSR_i$. The higher the rank is, the better the evaluation object is. For $WRSR_i$ values whose frequency is not 1, the value of $\overline{R}_i$ is the average value of each rank.
Step 4. Calculate the downward cumulative frequency $\overline{R}/m \times 100\%$ and correct the last item with $(1 - 1/4m) \times 100\%$.
Step 5. Convert the downward cumulative frequencies to probability units Probit. Probit is the standard normal deviation μ plus 5 corresponding to the cumulative frequencies. Refer to reference [30] for the "comparison table of percentages and probability units".

7. Take the probability unit Probit corresponding to the cumulative frequency as the independent variable and $WRSR_i$ as the dependent variable, calculate the linear regression equation shown in Equation (8), and test this regression equation.

$$WR\hat{S}R = a + b \times \text{Probit} \tag{8}$$

8. The binning process is performed according to the probability unit Probity and the correct rank-sum-ratio value $WR\hat{S}R$.

3. Results and Discussion

3.1. Mask Sustainability Evaluation Results

1. Based on the scores of the seven indicators of the ten masks presented in Table 2 and step "1" of the rank-sum ratio comprehensive evaluation method, an original evaluation matrix is constructed and presented as follows:

$$X = \begin{bmatrix} 12 & 100 & 3 & 85 & 75 & 98 & 80 \\ 0.4 & 90 & 0 & 40 & 60 & 85 & 85 \\ 6 & 80 & 5 & 80 & 71 & 70 & 75 \\ 4 & 80 & 2 & 98 & 76 & 90 & 70 \\ 60 & 80 & 10 & 95 & 70 & 95 & 85 \\ 1 & 95 & 0 & 20 & 95 & 60 & 73 \\ 5 & 80 & 5 & 70 & 60 & 87 & 92 \\ 7 & 100 & 2 & 95 & 80 & 50 & 90 \\ 8 & 80 & 10 & 90 & 30 & 80 & 95 \\ 10 & 80 & 10 & 80 & 20 & 85 & 100 \end{bmatrix}$$

2. Positive standardization on masks sustainability evaluation indexes. Scores of the indexes are standardized by Equations (1) and (2), and the obtained results are as follows:

$$Z = \begin{bmatrix} 0.805 & 1 & 0.75 & 0.833 & 0.733 & 1 & 0.333 \\ 1 & 0.5 & 1 & 0.256 & 0.533 & 0.729 & 0.5 \\ 0.906 & 0 & 0.583 & 0.769 & 0.68 & 0.417 & 0.167 \\ 0.940 & 0 & 0.833 & 1 & 0.747 & 0.833 & 0 \\ 0 & 0 & 0.167 & 0.962 & 0.667 & 0.938 & 0.5 \\ 0.990 & 0.75 & 1 & 0 & 1 & 0.208 & 0.1 \\ 0.923 & 0 & 0.583 & 0.641 & 0.533 & 0.771 & 0.733 \\ 0.889 & 1 & 0.833 & 0.962 & 0.8 & 0 & 0.667 \\ 0.872 & 0 & 0.167 & 0.897 & 0.133 & 0.625 & 0.833 \\ 0.839 & 0 & 0 & 0.769 & 0 & 0.729 & 1 \end{bmatrix}$$

3. Calculate the rank of each index for the sustainability evaluation of masks R_{ij}. Indexes 1 and 3 are cost indicators, while the other indexes are benefit indicators, which are calculated by Equation (3). The calculation results are as follows:

$$R = \begin{bmatrix} 8.25 & 10 & 7.75 & 8.8 & 7.6 & 10 & 4 \\ 10 & 5.5 & 10 & 3.4 & 5.8 & 7.56 & 5.5 \\ 9.15 & 1 & 6.25 & 8.2 & 7.12 & 4.75 & 2.5 \\ 9.46 & 1 & 8.5 & 10.36 & 7.72 & 8.5 & 1 \\ 1 & 1 & 2.5 & 10 & 7 & 9.44 & 5.5 \\ 9.91 & 7.75 & 10 & 1 & 10 & 2.88 & 1.9 \\ 9.31 & 1 & 6.25 & 7 & 5.8 & 7.94 & 7.6 \\ 9 & 10 & 8.5 & 10 & 8.2 & 1 & 7 \\ 8.85 & 1 & 2.5 & 9.4 & 2.2 & 6.63 & 8.5 \\ 8.55 & 1 & 1 & 8.2 & 1 & 7.56 & 10 \end{bmatrix}$$

4. Calculate weights by EWM. According to Equation (4), the information entropy e_j and entropy weight W_j of the seven evaluation indexes can be obtained, and the results are shown in Table 3. It can be seen from Table 3 that the information entropy of index 2 is obviously lower than other indexes, indicating that index 2 has the biggest weight. Meanwhile, it can also be found that various types of masks have the greatest difference in terms of material environmental friendliness and are most likely to attract more people's attention.

Table 3. Information entropy and weights of the seven indexes in sustainability evaluation of masks.

	Index 1	Index 2	Index 3	Index 4	Index 5	Index 6	Index 7
Information entropy	0.95	0.59	0.90	0.93	0.92	0.93	0.89
Weights	0.05	0.46	0.11	0.08	0.09	0.08	0.13

5. Determine the value of the weighted rank-sum ratio WRSR. Calculate the weighted rank-sum ratio for the ten masks by Equation (7) in step (5), and experimental results are shown below. It can be figured out that the values of the weighted rank-sum ratio of masks numbered 1 and 8 are significantly better than other masks.

$$WRSR = \begin{bmatrix} 0.123 & 0.090 & 0.051 & 0.060 & 0.052 & 0.095 & 0.062 & 0.121 & 0.054 & 0.052 \end{bmatrix}$$

6. Statistics on the distribution of WRSR. According to step "6", the frequency, cumulative frequency, average rank, downward cumulative rating, and probability unit are listed in Table 4. As Table 4 demonstrates, the two masks with a WRSR value of 0.52 jointly occupy the second and third place in the ranking; thus, the average rank $\overline{R}_i$ is 2.5. The probability unit is obtained from the "Comparison table of percentages and probability units". It should be emphasized that in terms of the rank-sum-ratio evaluation method used in this work, a higher ranking indicates a better evaluation object.
7. Linear regression calculation and test. Calculation results are obtained by IBM SPSS Statistics 26 software, and they are reported in Table 5 since SPSS Statistics 26 can provide more scientific support for data processing [31]. It can be seen that Sig ≤ 0.05 in Table 5, and thus the regression results pass the confidence test. The regression equation is formulated in Equation (9).

$$WR\hat{S}R = -0.066 + 0.027\text{Probit} \tag{9}$$

Table 4. Distribution condition of statistical WRSR.

Mask Number	*WRSR*	*f*	$\sum f$	Ranking	$\overline{R_i}$	$\overline{R}/m \times 100\%$	Probit
3	0.051	1	1	1	1	10%	3.71
5, 10	0.052	2	3	2, 3	2.5	25%	4.33
9	0.054	1	4	4	4	40%	4.75
4	0.060	1	5	5	5	50%	5
7	0.062	1	6	6	6	60%	5.25
2	0.090	1	7	7	7	70%	5.52
6	0.095	1	8	8	8	80%	5.84
8	0.121	1	9	9	9	90%	6.28
1	0.123	1	10	10	10	97.5%	6.96

Table 5. Linear regression results.

	Non-Standardized Coefficient		Standard Coefficient	Sig
	B	Standard Error	β	
Constants	−0.066	0.022	0.928	0.021
Probit	0.027	0.004		0.000

8. Grading ranking. The sustainability of ten masks is ranked according to Probit and $WR\hat{S}R$, and the results are reported in Table 6. The radar plots of scores of the seven indexes for the sustainability evaluation of ten masks are drawn in Figure 1.

Table 6. Sustainability ranking results for ten different types of masks.

Grade	Probit	$WR\hat{S}R$	Mask Number
Excellent	≥6	≥0.121	1, 8
Moderate	4~6	0.052~0.095	2, 4, 5, 6, 7, 9, 10
Poor	<4	<0.051	3

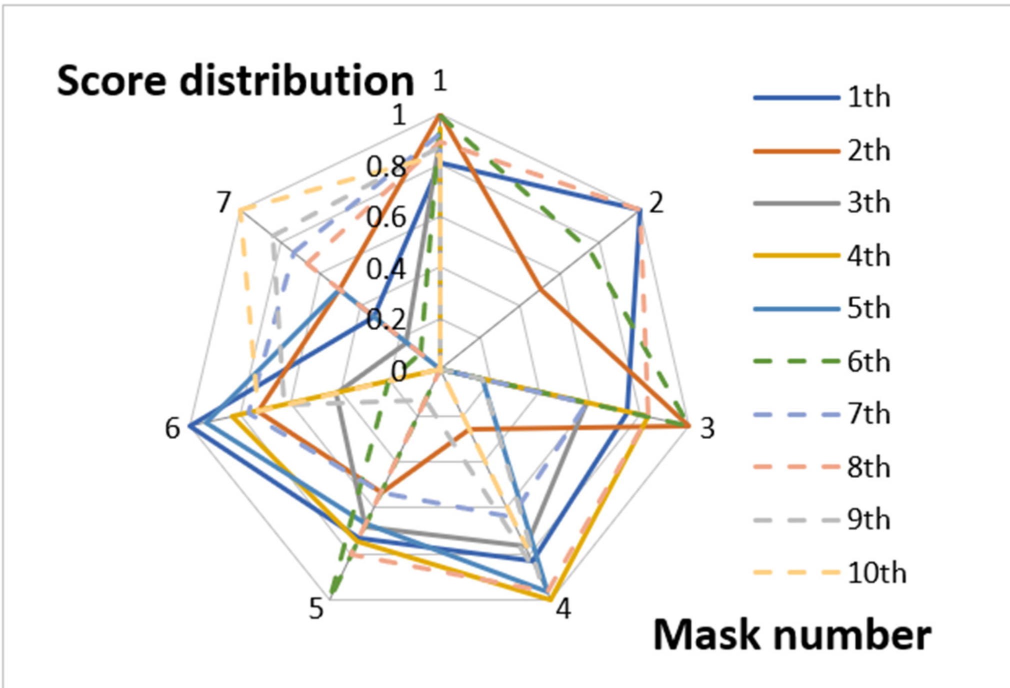


Figure 1. Distribution of sustainability evaluation scores of ten masks.

3.2. Discussion of Sustainable Evaluation of Masks

As Figure 1 shows, although the mask with number 3 can reach a medium level in terms of recyclable value and aesthetic appearance, its materials are not environmentally friendly and can generate plenty of waste. Those two indexes have bigger entropy weights, which makes the evaluation result of the mask with number 3 poor. Mask with number 4 has poor performance in environmental protection, but its scores of other indexes are quite high, so it gains a satisfying result. The masks with numbers 1 and 8 have low lifecycle costs and good environmentally friendly materials, and most of their index scores are ranked in the forefront; the scores of individual indexes are low, but their corresponding weights are also small. Regarding the mask with number 1, it has the highest aesthetic appearance index score, therefore gaining an excellent comprehensive performance.

From Table 6, it can be observed that the sustainability grades of the masks numbered 1 and 8 are excellent, the sustainability grade of the mask numbered 3 is poor, while the other eight masks belong to a general level. It is worth mentioning that the two newly designed masks in this work are both rated as excellent, of which the reusable mask numbered 8 validates the study by Núria Boix et al. (reusable masks are the most sustainable), while enriching the comparative study by Núria Boix et al., for five different types of masks.

However, the disposable mask numbered 2 is also rated as excellent, which shows that reusable masks are more sustainable in terms of economic and social issues. At the same time, experimental results also verify the study of Piergiuseppe et al., namely, the main impact of disposable masks on the environment is related to raw material consumption, energy demand, and waste disposal, while the use stage and raw material consumption contribute to the most to the reusable type. In other words, reusable masks have the least impact on the environment during the use phase but still cause a greater burden on the environment during the recycling phase [16]. Therefore, a scientific and comprehensive sustainability evaluation must be carried out according to multiple index parameters of masks.

3.3. Verification

To verify the effectiveness and reliability of the comprehensive rank-sum ratio–entropy weight method evaluation model for the sustainable evaluation of masks, we obtained subjective evaluation data by recording the sustainability scores of masks from 60 users. Those users aged between 18 and 50 came from different industries, 33 of whom are men (55%) and 27 of whom are women (45%). By combining their personal experience of using masks, the 60 people were asked to select four mask numbers that they considered are the most sustainable among the ten mask products, and the statistical results are shown in Figure 2. In Figure 2, by referring to the subjective data, masks numbered 1, 8, 9, and 10 own higher scores, while other schemes are with relatively lower scores. Among the masks with higher scores, masks numbered 1 and 8 have the highest scores, which is exactly the same as the previous calculation results; among the lower schemes, the slight difference is that mask numbered 5 gains a higher score than the mask numbered 6, which may be due to people's subjective preference for masks with significantly more environmentally friendly materials and lower waste production. In summary, by comparing the subjective rating data of 60 users with the previously calculated results, the results are basically consistent, which verifies the validity and reliability of the sustainable evaluation method of masks based on the rank and ratio and the entropy weight method.

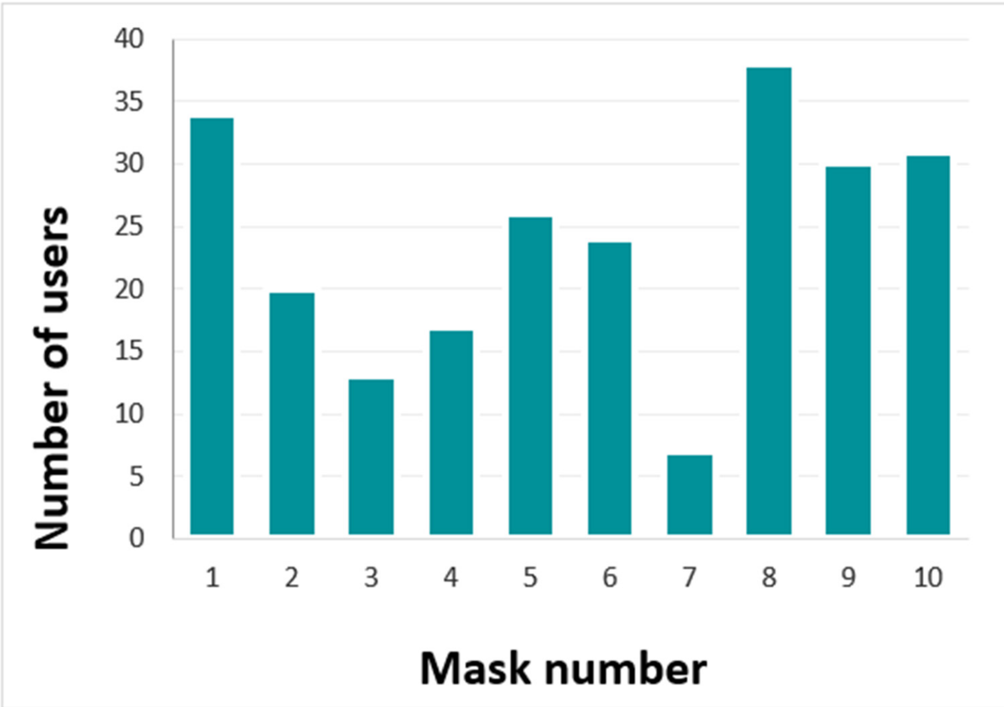


Figure 2. Summary of subjective questionnaires in the experiment.

4. Conclusions

Sustainability evaluation of masks is an important task to improve the sustainable design and decision making of masks. The accuracy of evaluation results directly affects the sustainability of masks and has an essential impact on the environment. This work aims to provide a sustainability evaluation method of masks simultaneously considering economic, environmental, and social aspects. Motivated by the virtues of existing methods, this work proposes an integrated rank and ratio–entropy weight method evaluation model, and its feasibility and effectiveness are tested through a real case. In summary, this work makes the following findings:

1. The environmental, economic, and social sustainability of the masks are evaluated simultaneously, and it is found that some disposable masks show better sustainability than reusable masks.
2. The integrated rank-sum ratio and entropy weight method can effectively realize the sustainability evaluation of masks, and its reliability is also tested and verified.

The integrated rank-sum ratio and entropy weight method evaluation model proposed in this work provides a more scientific basis for the sustainability evaluation of masks. Compared with previous studies, the sustainability evaluation indexes of masks in this work are more comprehensive. More importantly, the integrated rank-sum ratio and entropy weight method has an excellent and reliable performance in the sustainability evaluation of masks. Although the rank-sum ratio method adopted in this work cannot further answer the specific differences in the degree of sustainability grading of masks, the integrated rank-sum ratio and entropy weight method has excellent performance in rapid classification, especially when faced with a large number of masks. This work is of great significance for improving the sustainability evaluation of masks, guiding consumers to choose masks reasonably and to reduce the negative impacts on the environment during COVID-19.

In the future work, we plan to focus on the exploration of the integration of more sustainability evaluation methods for products so as to provide a more comprehensive reference for the sustainable design of products.

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