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Mask Design for Life in the Midst of COVID-19

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Abstract: Existing medical masks have various disadvantages, such as the environmental damage caused by disposable masks, the discomfort and poor ventilation caused by prolonged mask wearing, and the lack of aesthetic design in mass-produced masks. Thus, this study used quality function deployment, the fuzzy analytic hierarchy process, and fuzzy comprehensive evaluation to research, develop, and design masks. The aforementioned methods were also used to determine the ranking of design requirements. The following priority ranking of design requirements from most to least important was obtained: reducing discomfort at the contact between the mask and the skin (0.265), avoiding foul odor inside the mask (0.187), convenient cleaning and portability (0.166), good air-tightness (0.152), suitable aesthetic design for wearing in public and on social occasions (0.130), and reducing waste (0.100). Experts evaluated mask designs, and their opinions were subject to fuzzy analysis. Specifically, 50% of the experts evaluated the designs to be "good" or "very good". Only 29% of the experts rated the design results as "average". Thus, the innovative mask designed in this study can meet the needs of users, overcome the drawbacks of existing masks, and provide a feasible solution for the current COVID-19 pandemic.

Keywords: COVID-19; mask design; quality function deployment (QFD); fuzzy analytic hierarchy process (FAHP); fuzzy comprehensive evaluation (FCE)

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1. Introduction

In 2019, coronavirus disease 2019 (COVID-19) triggered global panic [1]. The global pandemic has not only caused many deaths but also affected the economy of all countries. The ongoing pandemic of COVID-19 affects the medical system and public facilities' operation on the social aspect and impacts the emotional, work, and mental health between families [2]. Recent studies have shown that patients with COVID-19 often sustain bacterial and fungal co-infection situations in addition to the primary infection of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) [3]. Moreover, the pathogenesis of SARS-CoV-2 itself with a co-infection situation will cause the prognosis of COVID-19 and the difficulty of treatment or even increase the severity of disease symptoms and increase the probability of death [4]. It also shows the horror of COVID-19 and the complexity of treatment. Recently, in India, there was an outbreak of a deadly fungal infection, mucormycosis, in addition to the pandemic of COVID-19. Patients with COVID-19 have a vulnerable infection due to immunocompromised conditions and cause a 50% death rate [5]. Most of the cases worldwide come from India (72%), and most patients are male (78%) and have diabetes (85%) [6]. People cannot work due to the severe pandemic which forces a considerable number of Indians to return to their hometown, facing famine, suffering, and death on the way home [7]. Currently, countries worldwide are actively investing lots of resources to develop vaccines to reduce the public health damage from SARS-CoV-2, and many vaccines are undergoing clinical trials [8]. At present, stopping the spread of the pandemic has become an urgent task. SARS-CoV-2 is a highly contagious virus and has three main methods of transmission: droplet, contact, and aerosol transmission. When a carrier of SARS-CoV-2 coughs or sneezes, droplets containing the virus may be inhaled by people nearby or may mix with the air to form aerosols, which propagates the virus [9]. Studies have indicated that wearing masks can effectively reduce the transmission of coronavirus and influenza virus among humans [9–11]. Thus, mask wearing is regarded as an effective method for controlling the spread of SARS-CoV-2 [12]. Consequently, the demand for masks has increased rapidly, which has resulted in a global shortage of disposable masks and panic among people [13–16].

Mask wearing is an effective method for preventing the spread of SARS-CoV-2 [15]. Considering the health and safety of users, masks must be replaced regularly to ensure maximum protection; however, discarded masks also cause considerable harm to the environment. OceansAsia, an environmental protection organization, conducted a study on beach garbage in the Soko Islands and found a large amount of disposable mask waste on the islands. This waste has destroyed the marine and wildlife habitats of the islands and caused massive ecological pollution [17]. Saadat et al. [18] indicated that the pandemic has resulted in the generation of large quantities of untreatable medical waste globally. Due to their water resistance, disposable masks do not decompose naturally and are ultimately buried in landfills. Thus, irreversible environmental pollution is eventually caused when disposable masks are discarded. Existing masks are difficult to recycle because of their composition and because doing so is costly and unhygienic. Therefore, the reduction of mask waste is an important issue.

The COVID-19 pandemic has profoundly changed people's life patterns in education, work, life, etc. In order to prevent people from getting together and causing the spread of the virus, people's social activities are restricted; in terms of education, many schools have switched to online cores; in terms of work, lots of companies allow employees to work from home or diversion of work schedule; in terms of life, many restaurants changed to take-away only instead of dine-in. Future human civilization must adopt contingency measures in the face of unknown infectious diseases. Humans must also find new methods of living, socializing, and working. Wearing masks on social occasions could become a new lifestyle and trend in the future. Therefore, new masks must be developed in line with the new normal to solve the drawbacks of existing masks. Moreover, the amount of mask waste should be reduced to make masks more pleasant to wear and friendlier to the environment.

2. Literature Review

2.1. Correlational Research on Masks' Reduction

Developments in mask design can focus on sustainability (such as ensuring reusability or prolonging mask service life) to reduce the shortage of masks [19,20]. Focusing on this issue, some scholars have proposed that removing the one-way valve of the cardiopulmonary resuscitation (CPR) mask and covering the front opening of the mask with a small piece of cut surgical face mask can be reusable and reduce the number of masks used [21]. However, the comfort of wearing a CPR mask may be far worse than ordinary masks. Meanwhile, a CPR mask is a medical assistive device for first aid, which may cause psychological rejection from the user. Nonetheless, the concept proposed by Phan and Ching [21] provides considerable inspiration to the innovative design of masks. If the problem mentioned above can be improved, it could increase the willingness to wear the mask and reduce the waste generated by using the mask.

2.2. Enhance the Wearing Experience of Masks

Existing masks in the market have many limitations. For example, wearing a mask often causes discomfort, such as increased respiratory resistance and skin irritation on the contact surface between the face and the mask [22]. The elastic straps of the masks will cause pressure and friction constantly in the posterior auricular region and cause pain and discomfort to the user [23]. The upper border of the mask is not sealed with the face causing the exhaled exhaust gas to flow upward while wearing a mask. The condensed moisture will adhere to the lenses and affect the user's vision if they wear glasses [24]. It also increases the chance of people's ocular surface inflammation by wearing a face mask for a long time. For a patient with dry eye disease, wearing a mask regularly every day can also damage the ocular surface [25]. Most of the masks sold on the market are designed for one-time use with almost no inhibition of the growth of bacteria in the mask [26]. However, it is easy to breed bacteria if people wear the face mask for a long time or even create an additional risk of infection [27]. Therefore, the mask needs to be replaced regularly or disinfected. In addition, the outer and middle layers of common medical and surgical masks shield the human respiratory tract from external disease sources. Therefore, these layers should closely fit the user's face. However, when masks are worn for a long time, the air inside the mask does not circulate, which results in a stuffy and often intolerable smell. Thus, the user cannot breathe fresh air, and their mask-wearing intention and usage experience are affected.

Balachandar et al. [28] successfully injected active compounds of natural medicinal plants into mask fibers to eliminate viruses. These plants also emit a pleasant scent. Thus, applying the compounds of natural medicinal plants to masks constitutes a feasible and innovative research direction to make mask wearing more pleasant. In addition, mask effectiveness is affected by the design of the exhalation valve, nose clip, and peek flaps as well as the material used for the mask edge contacting the face [29]. Therefore, the mask design process in this study applied and emphasized the design guidelines proposed by Faridi et al. [29], selecting suitable material and feasible engineering techniques to ensure the mask can effectively resist the virus and provide a more comprehensive wearing experience.

3. Methodology

In this study, quality function deployment (QFD), the fuzzy analytic hierarchy process (FAHP), and fuzzy comprehensive evaluation (FCE) were used to research, develop, and design masks. The steps of this research are shown in Figure 1.

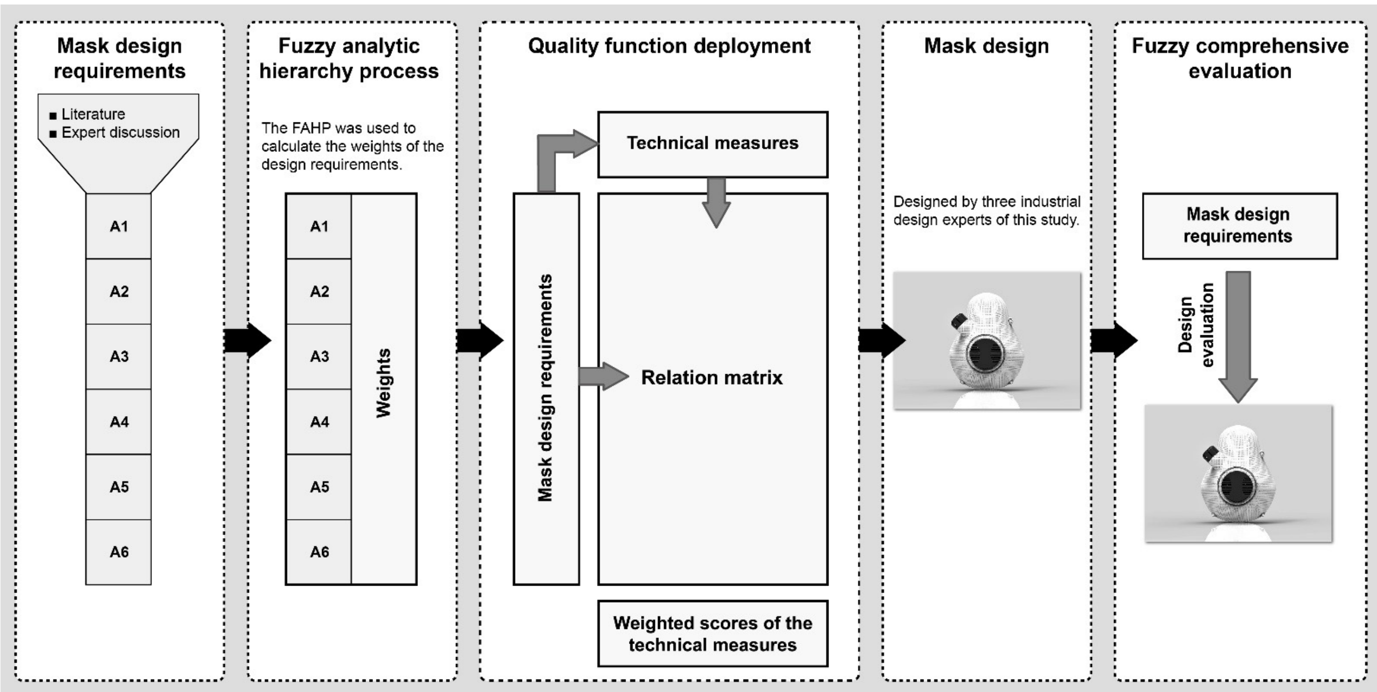


Figure 1. Research flow chart.

3.1. Quality Function Deployment

QFD, which is a systematic development tool, is used to consider users' requirements to improve product development [30]. Matrix, qualitative, and quantitative technology can be used to define a development strategy based on customer demand [31]. QDF has been applied by many scholars in related research fields of product innovation so far [32–38], and we illustrate the applicability of this method in this study. In addition, there have been 100 articles (98 articles and two reviews) in the area of manufacturing, supply chain, higher education, strategy, service, sustainability, marketing, and energy that integrated QFD and analytic hierarchy process (AHP) to conduct the research, illustrating that these methods have been developed to a mature level. At the same time, the method and tools of QFD–AHP have evolved many variants and extensions. Many articles combine QFD with FAHP as a research tool on product design topics as well [39]. Therefore, this study conducted FAHP when operating the QFD method. In this study, an innovative mask was designed by three industrial design experts by using QFD, and the experience in professional fields of the 3 experts was: 6 years, 9 years, and 41 years.

3.2. Fuzzy Analytic Hierarchy Process

The FAHP is based on the analytic hierarchy process (AHP). Moreover, it involves using the fuzzy theory, which was proposed by Zadeh in 1965, to analyze decision-making problems with fuzzy properties. Csutora and Buckle [40] proposed the Lambda-Max method for conducting fuzzy hierarchical analysis. This method can be easily conducted to calculate any type of fuzzy number with high precision. The Lambda-Max method has also been adopted by various scholars. In this study, the Lambda-Max method was employed in the FAHP. Therefore, the FAHP was used to calculate the weights of design requirements in the house of quality. Meanwhile, we will invite experts with more than two years of design or medical experience to fill in the experts' questionnaire.

3.3. Fuzzy Comprehensive Evaluation

Fuzzy comprehensive evaluation (FCE) is an evaluation method based on fuzzy theory. This method can be used to comprehensively evaluate various fuzzy object attributes. The membership function in fuzzy mathematics can be used to quantify qualitative evaluations [41]. FCE is widely used in engineering, design and development, development planning, and other fields of design evaluation to solve evaluation problems with fuzzy and complex attributes [42–44]. Therefore, FCE was used to calculate and obtain a comprehensive evaluation result of mask design. What is more, we will invite another expert who is different from the previous experiment and has more than two years of design or medical experience to fill in the questionnaire.

The evaluation questionnaire was conducted through an online questionnaire. Six design requirements were used as the evaluation criteria, and the level of each design requirement was evaluated separately after the expert had read the design drawing and description (function, mechanism) of the innovative mask. The evaluation included five levels of scale which were "very bad": very inadequate to meet the design requirement; "bad": cannot meet the design requirement; "average": generally meet the design requirement; "good": closely satisfy the design requirement; and "very good": very closely satisfy the design requirement. Experts rated each evaluation aspect according to their professional judgment. Finally, we applied the FCE to calculate the experts' evaluation results of the innovative mask to receive a comprehensive evaluation.

4. Research Execution and Analysis

4.1. Mask Design Requirements

By reviewing the relevant literature and expert discussion, the problems of existing masks and the requirements had by mask users were summarized and used as design requirements in QFD (Table 1).

Table 1. Design requirements.

No.	Design Requirements
A1	Good airtightness
A2	Convenient cleaning and portability
A3	Reducing discomfort at the contact between the mask and the skin
A4	Avoiding foul odor inside the mask
A5	Reducing mask waste
A6	Suitable aesthetic design for wearing in public and on social occasions

4.2. Weight of Each Design Requirement

The FAHP was used to calculate the weights of the design requirements. In this study, 16 experts (Table 2) were invited to fill in questionnaires. The content of the questionnaire combined the six design requirements in Table 1 into an AHP questionnaire, and the FAHP calculation process was divided into the following five steps.

Table 2. Experts' background.

No.	Years of Experience in Professional Field	Professional Field
1	12	visual design, industrial design
2	5	industrial design
3	30	art, design education, industrial design
4	6	medical product design, industrial design
5	3	design of health care industry
6	8	industrial design
7	10	industrial design, mechanism design
8	4	industrial design, consumer behavior
9	5	product design
10	12	visual design, industrial design
11	10	human factor engineering, product design, chromatics
12	2	industrial design
13	3	industrial design
14	3	industrial design
15	5	industrial design
16	4	industrial design

4.2.1. Step 1: Establishment of a Fuzzy Positive Reciprocal Matrix

In this step, according to Table 3, the questionnaire results filled out by 16 experts are transformed into a fuzzy positive reciprocal matrix. The results of the transformation are shown in Table 4. Fuzzy positive reciprocal matrix is expressed as:

$$\widetilde{A} = [\widetilde{a}_{ij}]_{n\times n} = \begin{bmatrix} 1 & (l_{12}, m_{12}, u_{12}) & \cdots & (l_{1n}, m_{1n}, u_{1n}) \\ \left(\frac{1}{u_{12}}, \frac{1}{m_{12}}, \frac{1}{l_{12}}\right) & 1 & \cdots & (l_{2n}, m_{2n}, u_{2n}) \\ \vdots & \vdots & 1 & \vdots \\ \left(\frac{1}{u_{1n}}, \frac{1}{m_{1n}}, \frac{1}{l_{1n}}\right) & \left(\frac{1}{u_{2n}}, \frac{1}{m_{2n}}, \frac{1}{l_{2n}}\right) & \cdots & 1 \end{bmatrix} \quad (1)$$

4.2.2. Step 2: The α-Cut Method Is Used to Calculate the Fuzzy Weight Vector

Equation (2): Normalization of the Geometric Mean of the Rows is used in this study to calculate the approximate solution of the eigenvector.

$$Z_i = (a_{i1} \times a_{i2} \times \cdots a_{in})^{\frac{1}{n}}: \forall i = 1, 2, \cdots, n;\ W_i = Z_i \times (Z_1 + Z_2 + \cdots Z_n)^{-1} \quad (2)$$

Table 3. Translating linguistic terms into triangular fuzzy numbers.

Saaty Scale	Fuzzy Triangular Scale	Definition
1	(1, 1, 1)	Equally important
2	(1, 2, 3)	In between "equally important" and "weakly important"
3	(2, 3, 4)	Weakly important
4	(3, 4, 5)	In between "weakly important" and "fairly important"
5	(4, 5, 6)	Fairly important
6	(5, 6, 7)	In between "fairly important" and "strongly important"
7	(6, 7, 8)	Strongly important
8	(7, 8, 9)	In between "strongly important" and "absolutely important"
9	(9, 9, 9)	Absolutely important

Table 4. The fuzzy positive reciprocal matrix of 16 experts' questionnaires.

Experts		A1	A2	A3	A4	A5	A6
1	A1	(1, 1, 1)	(1, 1, 1)	(1/8, 1/7, 1/6)	(1/8, 1/7, 1/6)	(2, 3, 4)	(1, 1, 1)
	A2	(1, 1, 1)	(1, 1, 1)	(1/6, 1/5, 1/4)	(1/8, 1/7, 1/6)	(2, 3, 4)	(1/4, 1/3, 1/2)
	A3	(6, 7, 8)	(4, 5, 6)	(1, 1, 1)	(1, 1, 1)	(6, 7, 8)	(6, 7, 8)
	A4	(6, 7, 8)	(6, 7, 8)	(1, 1, 1)	(1, 1, 1)	(6, 7, 8)	(2, 3, 4)
	A5	(1/4, 1/3, 1/2)	(1/4, 1/3, 1/2)	(1/8, 1/7, 1/6)	(1/8, 1/7, 1/6)	(1, 1, 1)	(1, 1, 1)
	A6	(1, 1, 1)	(2, 3, 4)	(1/8, 1/7, 1/6)	(1/4, 1/3, 1/2)	(1, 1, 1)	(1, 1, 1)
2	A1	(1, 1, 1)	(1/9, 1/9, 1/9)	(1, 1, 1)	(1/9, 1/9, 1/9)	(1, 1, 1)	(2, 3, 4)
	A2	(9, 9, 9)	(1, 1, 1)	(9, 9, 9)	(1/4, 1/3, 1/2)	(4, 5, 6)	(9, 9, 9)
	A3	(1, 1, 1)	(1/9, 1/9, 1/9)	(1, 1, 1)	(1/9, 1/9, 1/9)	(1, 1, 1)	(1, 1, 1)
	A4	(9, 9, 9)	(2, 3, 4)	(9, 9, 9)	(1, 1, 1)	(6, 7, 8)	(6, 7, 8)
	A5	(1, 1, 1)	(1/6, 1/5, 1/4)	(1, 1, 1)	(1/8, 1/7, 1/6)	(1, 1, 1)	(6, 7, 8)
	A6	(1/4, 1/3, 1/2)	(1/9, 1/9, 1/9)	(1, 1, 1)	(1/8, 1/7, 1/6)	(1/8, 1/7, 1/6)	(1, 1, 1)
3	A1	(1, 1, 1)	(1, 1, 1)	(2, 3, 4)	(2, 3, 4)	(1, 1, 1)	(1, 1, 1)
	A2	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	(1/4, 1/3, 1/2)	(1/4, 1/3, 1/2)
	A3	(1/4, 1/3, 1/2)	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	(1/6, 1/5, 1/4)	(1/8, 1/7, 1/6)
	A4	(1/4, 1/3, 1/2)	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	(1/6, 1/5, 1/4)	(1/6, 1/5, 1/4)
	A5	(1, 1, 1)	(2, 3, 4)	(4, 5, 6)	(4, 5, 6)	(1, 1, 1)	(1, 1, 1)
	A6	(1, 1, 1)	(2, 3, 4)	(6, 7, 8)	(4, 5, 6)	(1, 1, 1)	(1, 1, 1)
4	A1	(1, 1, 1)	(1/6, 1/5, 1/4)	(1/6, 1/5, 1/4)	(1, 1, 1)	(1/8, 1/7, 1/6)	(1/6, 1/5, 1/4)
	A2	(4, 5, 6)	(1, 1, 1)	(1, 1, 1)	(2, 3, 4)	(1, 1, 1)	(1/4, 1/3, 1/2)
	A3	(4, 5, 6)	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	(2, 3, 4)	(1, 1, 1)
	A4	(1, 1, 1)	(1/4, 1/3, 1/2)	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	(1/4, 1/3, 1/2)
	A5	(6, 7, 8)	(1, 1, 1)	(1/4, 1/3, 1/2)	(1, 1, 1)	(1, 1, 1)	(1/4, 1/3, 1/2)
	A6	(4, 5, 6)	(2, 3, 4)	(1, 1, 1)	(2, 3, 4)	(2, 3, 4)	(1, 1, 1)
5	A1	(1, 1, 1)	(2, 3, 4)	(1, 1, 1)	(2, 3, 4)	(6, 7, 8)	(4, 5, 6)
	A2	(1/4, 1/3, 1/2)	(1, 1, 1)	(1/4, 1/3, 1/2)	(1, 1, 1)	(6, 7, 8)	(4, 5, 6)
	A3	(1, 1, 1)	(2, 3, 4)	(1, 1, 1)	(6, 7, 8)	(6, 7, 8)	(4, 5, 6)
	A4	(1/4, 1/3, 1/2)	(1, 1, 1)	(1/8, 1/7, 1/6)	(1, 1, 1)	(6, 7, 8)	(1, 1, 1)
	A5	(1/8, 1/7, 1/6)	(1/8, 1/7, 1/6)	(1/8, 1/7, 1/6)	(1/8, 1/7, 1/6)	(1, 1, 1)	(1/6, 1/5, 1/4)
	A6	(1/6, 1/5, 1/4)	(1/6, 1/5, 1/4)	(1/6, 1/5, 1/4)	(1, 1, 1)	(4, 5, 6)	(1, 1, 1)
6	A1	(1, 1, 1)	(2, 3, 4)	(1, 1, 1)	(4, 5, 6)	(6, 7, 8)	(4, 5, 6)
	A2	(1/4, 1/3, 1/2)	(1, 1, 1)	(1/6, 1/5, 1/4)	(2, 3, 4)	(2, 3, 4)	(2, 3, 4)
	A3	(1, 1, 1)	(4, 5, 6)	(1, 1, 1)	(4, 5, 6)	(4, 5, 6)	(6, 7, 8)
	A4	(1/6, 1/5, 1/4)	(1/4, 1/3, 1/2)	(1/6, 1/5, 1/4)	(1, 1, 1)	(2, 3, 4)	(2, 3, 4)
	A5	(1/8, 1/7, 1/6)	(1/4, 1/3, 1/2)	(1/6, 1/5, 1/4)	(1/4, 1/3, 1/2)	(1, 1, 1)	(1/4, 1/3, 1/2)
	A6	(1/6, 1/5, 1/4)	(1/4, 1/3, 1/2)	(1/8, 1/7, 1/6)	(1/4, 1/3, 1/2)	(2, 3, 4)	(1, 1, 1)
7	A1	(1, 1, 1)	(6, 7, 8)	(1, 1, 1)	(1, 1, 1)	(1/4, 1/3, 1/2)	(1, 1, 1)
	A2	(1/8, 1/7, 1/6)	(1, 1, 1)	(1/9, 1/9, 1/9)	(1/6, 1/5, 1/4)	(1/8, 1/7, 1/6)	(1/8, 1/7, 1/6)
	A3	(1, 1, 1)	(9, 9, 9)	(1, 1, 1)	(2, 3, 4)	(2, 3, 4)	(1, 1, 1)
	A4	(1, 1, 1)	(4, 5, 6)	(1/4, 1/3, 1/2)	(1, 1, 1)	(1/4, 1/3, 1/2)	(1/4, 1/3, 1/2)
	A5	(2, 3, 4)	(6, 7, 8)	(1/4, 1/3, 1/2)	(2, 3, 4)	(1, 1, 1)	(2, 3, 4)
	A6	(1, 1, 1)	(6, 7, 8)	(1, 1, 1)	(2, 3, 4)	(1/4, 1/3, 1/2)	(1, 1, 1)
8	A1	(1, 1, 1)	(2, 3, 4)	(6, 7, 8)	(1, 1, 1)	(6, 7, 8)	(2, 3, 4)
	A2	(1/4, 1/3, 1/2)	(1, 1, 1)	(1/4, 1/3, 1/2)	(1/8, 1/7, 1/6)	(1/4, 1/3, 1/2)	(1/8, 1/7, 1/6)
	A3	(1/8, 1/7, 1/6)	(2, 3, 4)	(1, 1, 1)	(1/6, 1/5, 1/4)	(2, 3, 4)	(1, 1, 1)
	A4	(1, 1, 1)	(6, 7, 8)	(4, 5, 6)	(1, 1, 1)	(6, 7, 8)	(2, 3, 4)
	A5	(1/8, 1/7, 1/6)	(2, 3, 4)	(1/4, 1/3, 1/2)	(1/8, 1/7, 1/6)	(1, 1, 1)	(1/4, 1/3, 1/2)
	A6	(1/4, 1/3, 1/2)	(6, 7, 8)	(1, 1, 1)	(1/4, 1/3, 1/2)	(2, 3, 4)	(1, 1, 1)

Table 4. *Cont.*

Experts		A1	A2	A3	A4	A5	A6
9	A1	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	(6, 7, 8)	(4, 5, 6)
	A2	(1, 1, 1)	(1, 1, 1)	(1/6, 1/5, 1/4)	(4, 5, 6)	(4, 5, 6)	(4, 5, 6)
	A3	(1, 1, 1)	(4, 5, 6)	(1, 1, 1)	(4, 5, 6)	(4, 5, 6)	(9, 9, 9)
	A4	(1, 1, 1)	(1/6, 1/5, 1/4)	(1/6, 1/5, 1/4)	(1, 1, 1)	(2, 3, 4)	(2, 3, 4)
	A5	(1/8, 1/7, 1/6)	(1/6, 1/5, 1/4)	(1/6, 1/5, 1/4)	(1/4, 1/3, 1/2)	(1, 1, 1)	(1, 1, 1)
	A6	(1/6, 1/5, 1/4)	(1/6, 1/5, 1/4)	(1/9, 1/9, 1/9)	(1/4, 1/3, 1/2)	(1, 1, 1)	(1, 1, 1)
10	A1	(1, 1, 1)	(1/4, 1/3, 1/2)	(1/9, 1/9, 1/9)	(2, 3, 4)	(1, 1, 1)	(1/8, 1/7, 1/6)
	A2	(2, 3, 4)	(1, 1, 1)	(1/6, 1/5, 1/4)	(2, 3, 4)	(4, 5, 6)	(1, 1, 1)
	A3	(9, 9, 9)	(4, 5, 6)	(1, 1, 1)	(6, 7, 8)	(6, 7, 8)	(6, 7, 8)
	A4	(1/4, 1/3, 1/2)	(1/4, 1/3, 1/2)	(1/8, 1/7, 1/6)	(1, 1, 1)	(1, 1, 1)	(1/8, 1/7, 1/6)
	A5	(1, 1, 1)	(1/6, 1/5, 1/4)	(1/8, 1/7, 1/6)	(1, 1, 1)	(1, 1, 1)	(1/6, 1/5, 1/4)
	A6	(6, 7, 8)	(1, 1, 1)	(1/8, 1/7, 1/6)	(6, 7, 8)	(4, 5, 6)	(1, 1, 1)
11	A1	(1, 1, 1)	(1/9, 1/9, 1/9)	(1/9, 1/9, 1/9)	(1/9, 1/9, 1/9)	(1, 1, 1)	(1, 1, 1)
	A2	(9, 9, 9)	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	(9, 9, 9)	(4, 5, 6)
	A3	(9, 9, 9)	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	(4, 5, 6)	(1, 1, 1)
	A4	(9, 9, 9)	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	(4, 5, 6)	(1, 1, 1)
	A5	(1, 1, 1)	(1/9, 1/9, 1/9)	(1/6, 1/5, 1/4)	(1/6, 1/5, 1/4)	(1, 1, 1)	(1/6, 1/5, 1/4)
	A6	(1, 1, 1)	(1/6, 1/5, 1/4)	(1, 1, 1)	(1, 1, 1)	(4, 5, 6)	(1, 1, 1)
12	A1	(1, 1, 1)	(1/9, 1/9, 1/9)	(1/9, 1/9, 1/9)	(1/9, 1/9, 1/9)	(1/9, 1/9, 1/9)	(1, 1, 1)
	A2	(9, 9, 9)	(1, 1, 1)	(2, 3, 4)	(1, 1, 1)	(2, 3, 4)	(2, 3, 4)
	A3	(9, 9, 9)	(1/4, 1/3, 1/2)	(1, 1, 1)	(1, 1, 1)	(2, 3, 4)	(9, 9, 9)
	A4	(9, 9, 9)	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	(9, 9, 9)
	A5	(9, 9, 9)	(1/4, 1/3, 1/2)	(1/4, 1/3, 1/2)	(1, 1, 1)	(1, 1, 1)	(6, 7, 8)
	A6	(1, 1, 1)	(1/4, 1/3, 1/2)	(1/9, 1/9, 1/9)	(1/9, 1/9, 1/9)	(1/8, 1/7, 1/6)	(1, 1, 1)
13	A1	(1, 1, 1)	(1, 1, 1)	(1/4, 1/3, 1/2)	(1/8, 1/7, 1/6)	(4, 5, 6)	(2, 3, 4)
	A2	(1, 1, 1)	(1, 1, 1)	(1/6, 1/5, 1/4)	(1/8, 1/7, 1/6)	(2, 3, 4)	(1/4, 1/3, 1/2)
	A3	(2, 3, 4)	(4, 5, 6)	(1, 1, 1)	(1, 1, 1)	(4, 5, 6)	(6, 7, 8)
	A4	(6, 7, 8)	(6, 7, 8)	(1, 1, 1)	(1, 1, 1)	(1, 2, 3)	(2, 3, 4)
	A5	(1/6, 1/5, 1/4)	(1/4, 1/3, 1/2)	(1/6, 1/5, 1/4)	(1/3, 1/2, 1/1)	(1, 1, 1)	(1/4, 1/3, 1/2)
	A6	(1/4, 1/3, 1/2)	(2, 3, 4)	(1/8, 1/7, 1/6)	(1/4, 1/3, 1/2)	(2, 3, 4)	(1, 1, 1)
14	A1	(1, 1, 1)	(1/9, 1/9, 1/9)	(1, 1, 1)	(1/9, 1/9, 1/9)	(1, 1, 1)	(2, 3, 4)
	A2	(9, 9, 9)	(1, 1, 1)	(9, 9, 9)	(1/5, 1/4, 1/3)	(1, 2, 3)	(9, 9, 9)
	A3	(1, 1, 1)	(1/9, 1/9, 1/9)	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	(4, 5, 6)
	A4	(9, 9, 9)	(3, 4, 5)	(1, 1, 1)	(1, 1, 1)	(6, 7, 8)	(7, 8, 9)
	A5	(1, 1, 1)	(1/3, 1/2, 1/1)	(1, 1, 1)	(1/8, 1/7, 1/6)	(1, 1, 1)	(6, 7, 8)
	A6	(1/4, 1/3, 1/2)	(1/9, 1/9, 1/9)	(1/6, 1/5, 1/4)	(1/9, 1/8, 1/7)	(1/8, 1/7, 1/6)	(1, 1, 1)
15	A1	(1, 1, 1)	(2, 3, 4)	(1/3, 1/2, 1/1)	(2, 3, 4)	(2, 3, 4)	(1, 2, 3)
	A2	(1/4, 1/3, 1/2)	(1, 1, 1)	(1, 1, 1)	(2, 3, 4)	(1/7, 1/6, 1/5)	(1/4, 1/3, 1/2)
	A3	(1, 2, 3)	(1, 1, 1)	(1, 1, 1)	(4, 5, 6)	(1/6, 1/5, 1/4)	(1/8, 1/7, 1/6)
	A4	(1/4, 1/3, 1/2)	(1/4, 1/3, 1/2)	(1/6, 1/5, 1/4)	(1, 1, 1)	(1/6, 1/5, 1/4)	(1/8, 1/7, 1/6)
	A5	(1/4, 1/3, 1/2)	(5, 6, 7)	(4, 5, 6)	(4, 5, 6)	(1, 1, 1)	(2, 3, 4)
	A6	(1/3, 1/2, 1/1)	(2, 3, 4)	(6, 7, 8)	(6, 7, 8)	(1/4, 1/3, 1/2)	(1, 1, 1)
16	A1	(1, 1, 1)	(1/8, 1/7, 1/6)	(1/3, 1/2, 1/1)	(1, 2, 3)	(1/8, 1/7, 1/6)	(1/6, 1/5, 1/4)
	A2	(6, 7, 8)	(1, 1, 1)	(1, 1, 1)	(2, 3, 4)	(1, 1, 1)	(1/6, 1/5, 1/4)
	A3	(1, 2, 3)	(1, 1, 1)	(1, 1, 1)	(1, 2, 3)	(4, 5, 6)	(2, 3, 4)
	A4	(1/3, 1/2, 1/1)	(1/4, 1/3, 1/2)	(1/3, 1/2, 1/1)	(1, 1, 1)	(2, 3, 4)	(1/6, 1/5, 1/4)
	A5	(6, 7, 8)	(1, 1, 1)	(1/6, 1/5, 1/4)	(1/4, 1/3, 1/2)	(1, 1, 1)	(1/4, 1/3, 1/2)
	A6	(4, 5, 6)	(4, 5, 6)	(1/4, 1/3, 1/2)	(4, 5, 6)	(2, 3, 4)	(1, 1, 1)

When α = 1, Equation (2) is used to calculate the matrix $A_m = [a_{ijm}]_{n\times n}$ to obtain the weight $W_m = [w_{im}], i = 1, 2, \cdots, n$. When α = 0, Equation (2) is used to calculate the matrix $A_l = [a_{ijl}]_{n\times n}$ and matrix $A_u = [a_{iju}]_{n\times n}$ to obtain the weight $W_l = [w_{il}], i = 1, 2, \cdots, n$ and weight $W_u = [w_{iu}], i = 1, 2, \cdots, n$. The results are shown in Table 5.

Table 5. Fuzzy weight vector (rounded to the third decimal place).

Experts	W_l	W_m	W_u
1	(0.072, 0.060, 0.395, 0.352, 0.040, 0.081)	(0.071, 0.062, 0.389, 0.357, 0.041, 0.081)	(0.069, 0.066, 0.381, 0.356, 0.044, 0.083)
2	(0.058, 0.324, 0.052, 0.459, 0.076, 0.030)	(0.057, 0.321, 0.047, 0.470, 0.075, 0.030)	(0.055, 0.324, 0.043, 0.472, 0.075, 0.031)
3	(0.196, 0.098, 0.065, 0.068, 0.277, 0.296)	(0.197, 0.095, 0.063, 0.067, 0.281, 0.297)	(0.195, 0.097, 0.064, 0.069, 0.281, 0.294)

Table 5. *Cont.*

Experts	W_l	W_m	W_u
4	(0.047, 0.184, 0.232, 0.104, 0.140, 0.293)	(0.045, 0.184, 0.221, 0.097, 0.135, 0.318)	(0.045, 0.185, 0.207, 0.097, 0.137, 0.329)
5	(0.296, 0.148, 0.355, 0.105, 0.026, 0.071)	(0.307, 0.148, 0.354, 0.098, 0.025, 0.069)	(0.309, 0.155, 0.347, 0.096, 0.025, 0.069)
6	(0.338, 0.117, 0.379, 0.077, 0.037, 0.052)	(0.333, 0.129, 0.363, 0.082, 0.037, 0.054)	(0.323, 0.141, 0.346, 0.089, 0.042, 0.059)
7	(0.167, 0.028, 0.283, 0.098, 0.236, 0.187)	(0.152, 0.026, 0.275, 0.100, 0.264, 0.183)	(0.143, 0.025, 0.259, 0.108, 0.285, 0.180)
8	(0.324, 0.035, 0.093, 0.363, 0.050, 0.135)	(0.327, 0.036, 0.094, 0.356, 0.052, 0.136)	(0.322, 0.039, 0.095, 0.345, 0.056, 0.143)
9	(0.230, 0.201, 0.391, 0.094, 0.042, 0.041)	(0.219, 0.207, 0.390, 0.102, 0.043, 0.041)	(0.207, 0.212, 0.384, 0.109, 0.045, 0.042)
10	(0.052, 0.140, 0.531, 0.038, 0.046, 0.193)	(0.053, 0.151, 0.524, 0.038, 0.044, 0.190)	(0.054, 0.159, 0.515, 0.041, 0.044, 0.187)
11	(0.043, 0.336, 0.233, 0.233, 0.036, 0.120)	(0.041, 0.334, 0.232, 0.232, 0.038, 0.123)	(0.039, 0.332, 0.230, 0.230, 0.041, 0.127)
12	(0.030, 0.265, 0.241, 0.270, 0.159, 0.035)	(0.027, 0.292, 0.243, 0.243, 0.162, 0.034)	(0.024, 0.305, 0.247, 0.220, 0.171, 0.034)
13	(0.121, 0.071, 0.367, 0.311, 0.044, 0.086)	(0.118, 0.069, 0.355, 0.322, 0.045, 0.090)	(0.118, 0.070, 0.341, 0.319, 0.053, 0.099)
14	(0.068, 0.289, 0.110, 0.407, 0.100, 0.025)	(0.065, 0.303, 0.103, 0.403, 0.101, 0.026)	(0.062, 0.309, 0.096, 0.397, 0.108, 0.027)
15	(0.203, 0.088, 0.114, 0.042, 0.319, 0.233)	(0.232, 0.083, 0.109, 0.039, 0.309, 0.228)	(0.251, 0.080, 0.100, 0.039, 0.295, 0.235)
16	(0.054, 0.196, 0.247, 0.080, 0.110, 0.312)	(0.055, 0.176, 0.274, 0.084, 0.102, 0.309)	(0.059, 0.159, 0.275, 0.100, 0.100, 0.308)

4.2.3. Step 3: Adjustment of the Triangular Fuzzy Weight

In order to make the weight value conform to the definition of a fuzzy number: $W_{il} \leq W_{im} \leq W_{iu}$, the weight value obtained in step 2 needs to be re-adjusted by the algorithms in Equations (3) and (4) (K_l is used to adjust W_l, while K_u is used to adjust W_u), and then Equation (5) is used to calculate the adjusted triangular fuzzy weight vector. The calculation results are shown in Table 6.

$$K_l = min\left\{ \frac{w_{im}}{w_{il}} \middle| 1 \leq i \leq n \right\} = min\left\{ \frac{w_{1m}}{w_{1l}}, \frac{w_{2m}}{w_{2l}}, \cdots, \frac{w_{nm}}{w_{nl}} \right\} \tag{3}$$

$$K_u = max\left\{ \frac{w_{im}}{w_{iu}} \middle| 1 \leq i \leq n \right\} = max\left\{ \frac{w_{1m}}{w_{1u}}, \frac{w_{2m}}{w_{2u}}, \cdots, \frac{w_{nm}}{w_{nu}} \right\} \tag{4}$$

$$\begin{cases} W_l^* = K_l \times W_l \\ W_u^* = K_u \times W_u \end{cases} \tag{5}$$

Table 6. Adjustment of the triangular fuzzy weight vector (rounded to the third decimal place).

Experts	K_l	W_l^*	K_u	W_u^*
1	0.981	(0.071, 0.059, 0.388, 0.345, 0.040, 0.079)	1.019	(0.071, 0.067, 0.389, 0.363, 0.045, 0.085)
2	0.909	(0.053, 0.295, 0.047, 0.417, 0.070, 0.027)	1.092	(0.060, 0.354, 0.047, 0.515, 0.082, 0.033)
3	0.969	(0.190, 0.095, 0.063, 0.066, 0.268, 0.287)	1.014	(0.197, 0.099, 0.065, 0.070, 0.285, 0.299)
4	0.941	(0.045, 0.174, 0.219, 0.097, 0.131, 0.275)	1.064	(0.048, 0.197, 0.221, 0.103, 0.146, 0.350)
5	0.938	(0.277, 0.139, 0.333, 0.098, 0.024, 0.067)	1.026	(0.317, 0.159, 0.356, 0.098, 0.025, 0.071)
6	0.958	(0.323, 0.112, 0.363, 0.074, 0.035, 0.050)	1.049	(0.339, 0.148, 0.363, 0.093, 0.044, 0.062)
7	0.912	(0.152, 0.026, 0.259, 0.090, 0.215, 0.171)	1.067	(0.152, 0.027, 0.277, 0.115, 0.304, 0.192)
8	0.979	(0.317, 0.035, 0.091, 0.356, 0.049, 0.132)	1.032	(0.332, 0.041, 0.098, 0.356, 0.058, 0.148)
9	0.948	(0.219, 0.191, 0.371, 0.089, 0.040, 0.039)	1.053	(0.219, 0.223, 0.405, 0.115, 0.048, 0.045)
10	0.957	(0.050, 0.134, 0.508, 0.036, 0.044, 0.185)	1.017	(0.055, 0.162, 0.524, 0.042, 0.045, 0.190)
11	0.960	(0.041, 0.322, 0.223, 0.223, 0.035, 0.115)	1.038	(0.041, 0.345, 0.239, 0.239, 0.043, 0.132)
12	0.899	(0.027, 0.238, 0.216, 0.243, 0.143, 0.032)	1.106	(0.027, 0.337, 0.273, 0.243, 0.189, 0.037)
13	0.968	(0.117, 0.069, 0.355, 0.301, 0.043, 0.083)	1.040	(0.123, 0.072, 0.355, 0.332, 0.055, 0.102)
14	0.932	(0.063, 0.270, 0.103, 0.380, 0.093, 0.024)	1.066	(0.067, 0.330, 0.103, 0.423, 0.115, 0.029)
15	0.928	(0.189, 0.082, 0.106, 0.039, 0.296, 0.216)	1.090	(0.274, 0.087, 0.109, 0.042, 0.322, 0.256)
16	0.895	(0.048, 0.176, 0.222, 0.072, 0.099, 0.279)	1.109	(0.065, 0.176, 0.305, 0.111, 0.111, 0.342)

4.2.4. Step 4: Consistency Test

When the AHP method is used for calculation, it is necessary to check whether the questionnaires filled out by the experts are consistent to determine their validity. Buckley [45] defined a fuzzy pair matrix $\widetilde{A} = [\widetilde{a}_{ij}]$ as follows: if it is consistent, it must satisfy $\widetilde{A} = [\widetilde{a}_{ij}] \langle = \rangle \widetilde{a}_{ik} \odot \widetilde{a}_{kj} \approx \widetilde{a}_{ij}$. At the same time, Buckley [45] also proved that supposing $\widetilde{A} = [\widetilde{a}_{ij}], \widetilde{a}_{ij} = (\alpha_{ij}/\beta_{ij}, \gamma_{ij}/\delta_{ij})$, you can find an a_{ij} to make $\beta_{ij} \leq a_{ij} \leq \gamma_{ij}, \forall i, j$;

if the paired comparison matrix $A = [a_{ij}]$ is consistent, then the fuzzy positive reciprocal matrix $\widetilde{A}$ will also be consistent. As the triangular fuzzy number used in this study is a special case of the trapezoidal fuzzy number, the questionnaire filled out by the experts can be accepted when the matrix $A_m = [a_{ijm}]_{n\times n}$ passes the consistency test.

Equation (6) is the algorithm for the consistency test in this study. Table 7 reveals that the random index (R.I.) value is 1.24 (n = 6). After calculation, the data show that 12 of the 16 questionnaires passed the consistency test (CR ≤ 1) (Table 8 below). Four of the experts failed the consistency test, and thus their data are not included in the calculation in Step 5.

$$\text{C.I.} = \frac{\lambda_{max} - n}{n-1}, \lambda_{max} = \frac{1}{n}\left[\left(\frac{w'_1}{w_1}\right) + \left(\frac{w'_2}{w_2}\right) + \cdots + \left(\frac{w'_n}{w_n}\right)\right],\ W' = \lambda W \quad (6)$$

Table 7. Random index.

N	1	2	3	4	5	6	7	8	9	10	11	12
R.I.	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.58

Table 8. Results of the consistency test of questionnaires completed by 16 experts (rounded to the third decimal place).

Experts' Number	λ_{max}	CI	CR
1	6.458	0.092	0.074
2	6.586	0.117	0.094
3	6.229	0.046	0.037
4	6.601	0.120	0.097
5	6.553	0.111	0.089
6	6.438	0.088	0.071
7	6.563	0.113	0.091
8	6.591	0.118	0.095
9	6.583	0.117	0.094
10	6.566	0.113	0.091
11	6.591	0.118	0.095
12	6.598	0.120	0.096
13	7.065	0.213	0.172 *
14	7.226	0.245	0.198 *
15	7.563	0.313	0.252 *
16	7.857	0.371	0.299 *

* Not consistent.

4.2.5. Step 5: Integration of Fuzzy Weights and Defuzzification

Next, Equation (7) is used to integrate the fuzzy weights of 12 experts: $(\widetilde{W}_i = (W^*_{il}, W_{im}, W^*_{iu}), i = 1, 2, \cdots, n)$. The final steps need to defuzzify the triangular fuzzy weight value. The process of defuzzification transforms the triangular fuzzy number to the best crisp value. There are many ways to defuzzify, and the center-of-gravity method proposed by Tzeng and Teng [46] has been widely used. Therefore, this study applies the center-of-gravity method to obtain a crisp value and the formula calculated as in Equation (8). After calculation, the weights of the six design requirements are shown in Table 9 below.

$$\widetilde{W}_i = \frac{\left(\widetilde{W}^1_i + \widetilde{W}^1_i + \cdots + \widetilde{W}^P_i\right)}{P}, i = 1, 2 \cdots, n \quad (7)$$

$$\text{DF}_i = \frac{(m_i - l_i) + (u_i - l_i)}{3} + l_i \approx \frac{l_i + m_i + u_i}{3}, \forall i = 1, 2, \cdots, n \quad (8)$$

Table 9. Weights of the design requirements (rounded to the third decimal place).

Design Requirements	Triangular Fuzzy Weight Value $\widetilde{W}_i$	Defuzzification Weight Value	Normalized Fuzzy Weight Value	Weight Ranking
A1	(0.147, 0.152, 0.155)	0.151	0.152	4
A2	(0.152, 0.165, 0.180)	0.166	0.166	3
A3	(0.257, 0.266, 0.271)	0.265	0.265	1
A4	(0.178, 0.187, 0.196)	0.187	0.187	2
A5	(0.091, 0.100, 0.109)	0.100	0.100	6
A6	(0.122, 0.130, 0.137)	0.129	0.130	5

The order of importance for the six mask design requirements, from most to least important, is as follows: reducing discomfort at the contact between the mask and the skin (0.265), avoiding foul odor inside the mask (0.187), convenient cleaning and portability (0.166), good airtightness (0.152), suitable aesthetic design for wearing in public and on social occasions (0.130), and reducing waste (0.100).

4.3. Technical Measures for Product Development

In this study, existing mask patents as well as the related literature and technical reports were examined to determine the feasible technology for mask design. The feasible technology was used as the engineering technology in the QFD process. A total of 13 design solutions were proposed for mask production (Table 10).

Table 10. Proposed technical measures.

No.	Technical Measures
B1	Ergonomic contact surface for the mask
B2	No dead-ends and easy cleaning
B3	Contact surface made of cloth material
B4	Contact surface made of silicone material
B5	Exhalation valve with a spheroidal sealing element
B6	Exhalation valve with a round-slice sealing element
B7	Replaceable cotton sheet with natural plant aroma
B8	Drop in natural aromatic essential oil
B9	Repeated use, with only the local filter layer having to be replaced
B10	Use of a small-area filter layer
B11	Washable mask body
B12	Streamline body modeling
B13	Customized replaceable mask shell

4.4. Establishment of the Relation Matrix and Priority of Technical Measures

Three industrial design experts discussed the correlation of mask design requirements with technical measures and established a relation matrix (Equation (9)). The value t_{mn} in the matrix represents the correlation value between m-th design requirement and n-th technical measure. The relation matrix data obtained after expert discussion are shown in Table 11. "Highly relevant" was assigned a score of 9, "relevant" was assigned a score of 3, "generally relevant" was assigned a score of 1, and "not relevant" was assigned a score of 0.

$$T = \begin{pmatrix} t_{11} & \cdots & t_{1n} \\ \vdots & \ddots & \vdots \\ t_{m1} & \cdots & t_{mn} \end{pmatrix}, (m = 1, 2, \cdots, 6; n = 1, 2, \cdots, 13) \quad (9)$$

$T:$ relation matrix

Table 11. Relation matrix.

T	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	B13
A1	9	0	1	3	9	9	0	0	0	0	0	0	0
A2	0	9	0	3	3	0	3	0	3	3	9	3	0
A3	3	0	9	9	0	0	0	0	0	0	0	0	0
A4	0	3	0	0	9	9	9	9	0	3	0	0	0
A5	0	1	1	9	0	0	0	0	9	9	9	0	0
A6	0	0	0	0	0	0	0	0	0	0	0	3	9

A: design requirements, B: technical measures.

To obtain the priority ranking of technical measures, the weight of each design requirement was multiplied by the value corresponding to the technical measures in the relation matrix. The products obtained for each technical measure were then summed to obtain its weighted score. The calculation formula for weighted scores of the thirteen technical measures is shown in Equation (10), and the calculation result is shown in Table 12.

$$B_n = \sum_{m=1}^{6} [\, A_m \times t_{mn}], (n = 1,\ 2, \cdots,\ 13)$$
$$B_n : nth\ weighted\ score\ of\ technical\ measure,\ A_m : mth\ weight\ of\ design\ requirement \quad (10)$$

Table 12. Weighted score of technical measures and priority ranking of technical measures.

No	Technical Measures	Weighted Scores	Ranking
B1	Ergonomic contact surface for the mask	2.163	7
B2	No dead-ends and easy cleaning	2.155	8
B3	Contact surface made of cloth material	2.637	4
B4	Contact surface made of silicone material	4.239	1
B5	Exhalation valve with a spheroidal sealing element	3.549	2
B6	Exhalation valve with a round-slice sealing element	3.051	3
B7	Replaceable cotton sheet with natural plant aroma	2.181	6
B8	Drop in natural aromatic essential oil	1.683	10
B9	Repeated use, with only the local filter layer having to be replaced	1.398	11
B10	Use of a small-area filter layer	1.959	9
B11	Washable mask body	2.394	5
B12	Streamline body modeling	0.888	13
B13	Customized replaceable mask shell	1.170	12

After ranking the weighted scores of the technical measures, the priority of implementing technical measures was determined. The following priority of technical measures was obtained through QFD, from most to least important: (1) contact surface made of silicone material; (2) exhalation valve with a spheroidal sealing element; (3) exhalation valve with a round-slice sealing element; (4) contact surface made of cloth material; (5) washable mask body; (6) replaceable cotton sheet with natural plant aroma; (7) ergonomic contact surface for the mask; (8) no dead-ends and easy cleaning; (9) use of a small-area filter layer; (10) infusion of natural aromatic essential oil; (11) repeated use, with only the local filter layer having to be replaced; (12) customized replaceable mask shell; and (13) streamline body modeling (House of Quality, Figure 2).

4.5. Designed Product

Based on the technical measures presented in the House of Quality, an innovative mask was designed by three industrial design experts of this study. The innovative mask has a reusable one-piece design, and only its local filter layer must be replaced (Figure 3). The characteristics of the designed mask are as follows:

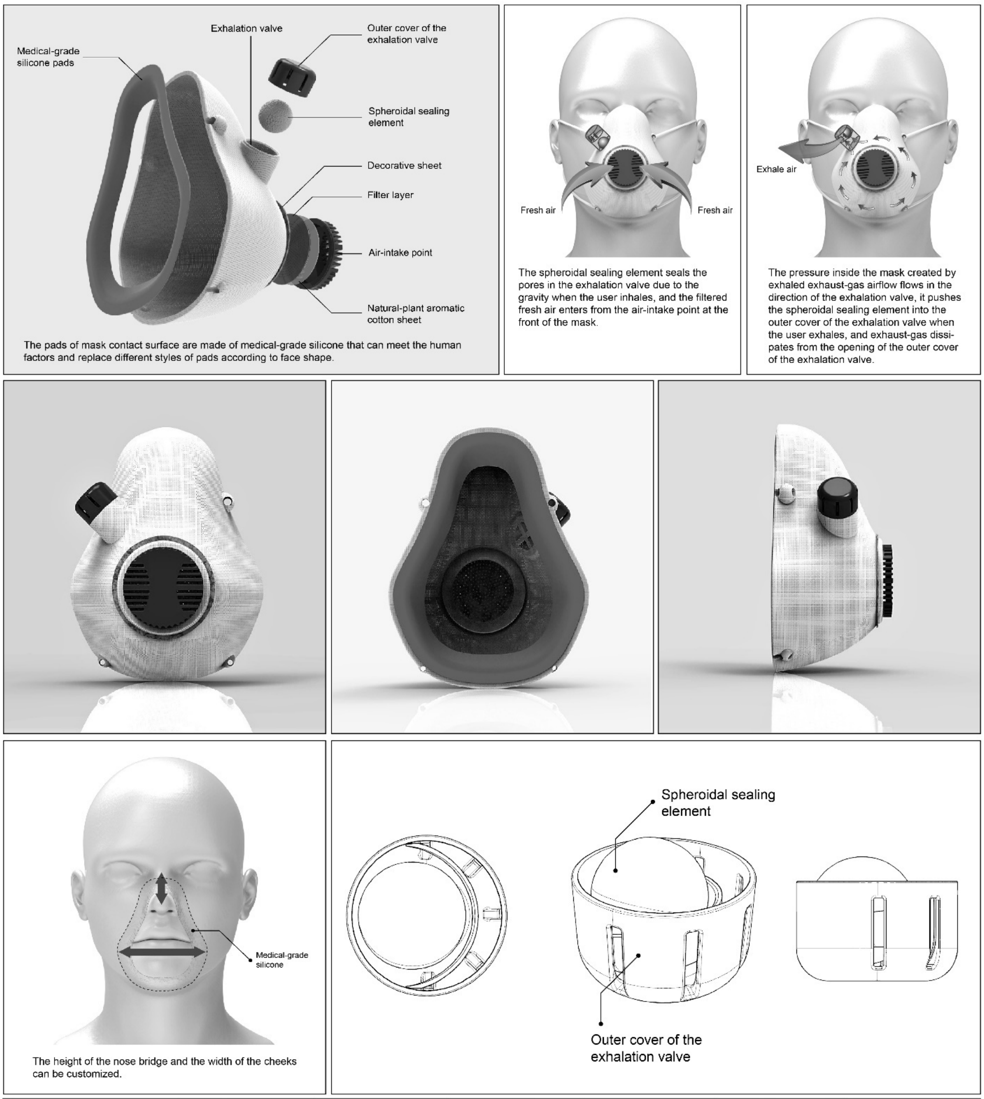
Design requirements	Weight	Technical measures B1 Ergonomic contact surface for the mask	B2 No dead-ends and easy cleaning	B3 Contact surface made of cloth material	B4 Contact surface made of silicone material	B5 Exhalation valve with a spheroidal sealing element	B6 Exhalation valve with a round-slice sealing element	B7 Replaceable cotton sheet with natural plant aroma	B8 Drop in natural aromatic essential oil	B9 Repeated use, with only the local filter layer having to be replaced	B10 Use of a small-area filter layer	B11 Washable mask body	B12 Streamline body modeling	B13 Customized replaceable mask shell
A1 Good airtightness	0.152	9		1	3	9	9							
A2 Convenient cleaning and portability	0.166		9		3	3		3		3	3	9	3	
A3 Reducing discomfort at the contact between the mask and the skin	0.265	3		9	9									
A4 Avoiding foul odor inside the mask	0.187		3			9	9	9	9		3			
A5 Reducing mask waste	0.100		1	1	9					9	9	9		
A6 Suitable aesthetic design for wearing in public and on social occasions	0.130												3	9
Weighted score of technical measures		2.163	2.155	2.637	4.239	3.549	3.051	2.181	1.683	1.398	1.959	2.394	0.888	1.170
The priority ranking of technical measures		7	8	4	1	2	3	6	10	11	9	5	13	12

Figure 2. House of Quality.

1. To achieve comfort and airtightness, medical-grade silicone pads were designed with consideration to human factors and customized replacement was conducted according to the user's face shape.
2. To solve the problem of a stuffy smell inside the mask, an exhalation valve with a spherical sealing element was used to effectively circulate the air inside the mask. An opening was designed on the side of the outer cover of the exhalation valve to reduce the inhalation of dust from the environment. A replacement filter screen with fragrance from natural ingredients was used at the air-intake point for the user to breathe well.
3. The mask had a streamlined design with round guide angles. Moreover, its components were easy to disassemble, clean, and maintain. Polylactic acid was used for environmental protection and to enhance durability. An exhalation valve with a spherical sealing element was used. This valve was convenient to clean and maintain.
4. To cope with the requirement to wear masks in the midst of the pandemic, a socially appropriate mask design was developed. A magnetic suction decorative sheet was adopted in the outer ring of the air inlet of the mask. To express themselves aesthetically, users can adopt one of many differently colored styles that they prefer.
5. To reduce the waste caused by the use of traditional masks, a small-area filter layer was installed at the air inlet. This layer can be changed according to the use case.

4.6. Design Evaluation

In this study, to verify the suitability of the developed mask design, 64 experts were invited to fill in evaluation questionnaires, and the FCE method was used to analyze their evaluations. The group of 64 experts comprised 35 men and 29 women. In total, 14 experts (21.9%) were <20 years old, 27 experts (42.2%) were 21–30 years old, 21 experts (32.8%) were 31–40 years old, and two experts (3.1%) were >41 years old. In total, 21 experts (32.8%) had received university or college education, 37 experts (57.8%) had a master's degree, and six experts (9.4%) had a doctorate. In total, 43 experts (67.2%) specialized in industrial design, three experts (4.7%) specialized in medical care, and 18 experts (28.1%) specialized in design. In total, 41 experts (64.1%) had <5 years of work experience, 18 experts (28.1%) had 6–10 years of work experience, four experts (6.3%) had 11–15 years of work experience, and one expert (1.6%) had >15 years of work experience.



Design requirements / Product	Good airtightness	Convenient cleaning and portability	Reducing discomfort at the contact between the mask and the skin	Avoiding foul odor inside the mask	Reducing mask waste	Suitable aesthetic design for wearing in public and on social occasions
The innovative mask proposed by this study	✓	✓	✓	✓	✓	✓
Medical mask						
A resable mask (Phan and Ching [21])	✓	✓			✓	

Figure 3. Design of the innovative mask.

The evaluation indices constituted the six design requirements for QFD, and the weight of each evaluation index, indicating its importance, was determined through the FAHP (Table 9). The evaluation grades were "very bad", "bad", "average", "good", and "very good". The aforementioned five grades were mathematically expressed as follows: v = {V1, V2, V3, V4, V5} = {very bad, bad, average, good, very good}. The experts evaluated the proposed innovative mask according to the factors of each dimension. The evaluation results were arranged into a factor evaluation matrix $\widetilde{R}$ (Equation (11)). The value (r_{mn}) in the matrix represents the percentage of votes for the n^{th} evaluation grades in the m-th design requirement, and the data of the matrix are shown in Table 13.

$$\widetilde{R} = \begin{pmatrix} r_{11} & \cdots & r_{1n} \\ \vdots & \ddots & \vdots \\ r_{m1} & \cdots & r_{mn} \end{pmatrix}, (m = 1,\ 2, \cdots, 6; n = 1,\ 2, \cdots, 5) \quad (11)$$

Table 13. Evaluation metrics $\widetilde{R}$ (rounded to the second decimal place).

$\widetilde{R}$	V1	V2	V3	V4	V5
A1	0	0.03	0.16	0.59	0.22
A2	0.02	0.16	0.31	0.38	0.14
A3	0	0.03	0.28	0.50	0.19
A4	0	0.02	0.20	0.50	0.28
A5	0	0.05	0.08	0.55	0.33
A6	0.03	0.17	0.52	0.17	0.11

The result in the dimension of "good airtightness" shows that 22% of experts rated the innovative mask as "very good", 59% as "good", 16% as "average", 3% as "bad", and none as "very bad". The result in the dimension of "convenient cleaning and portability" shows that 14% of experts rated the innovative mask as "very good", 38% as "good", 31% as "average", 16% as "bad", and 2% as "very bad". The result in the dimension of "reducing discomfort at the contact between the mask and the skin" shows that 19% of experts rated the innovative mask as "very good", 50% as "good", 28% as "average", 3% as "bad", and none as "very bad". The result in the dimension of "avoiding foul odor inside the mask" shows that 28% of experts rated the innovative mask as "very good", 50% as "good", 20% as "average", 2% as "bad", and none as "very bad". The result in the dimension of "reducing mask waste" shows that 33% of experts rated the innovative mask as "very good", 55% as "good", 8% as "average", 5% as "bad", and none as "very bad" The result in the dimension of "suitable aesthetic design for wearing in public and on social occasions" shows that 11% of experts rated the innovative mask as "very good", 17% as "good", 52% as "average", 17% as "bad", and 3% as "very bad". According to the statistical results for various design requirements, 81% of the experts evaluated the design results as "good" or "very good" for the dimension of "good airtightness." A total of 52%, 69%, 78%, 88%, and 28% of the experts evaluated the design results as "good" or "very good" for the dimensions of "convenient cleaning and portability", "reducing discomfort at the contact between the mask and the skin", "avoiding foul odor inside the mask", "reducing mask waste", and "suitable aesthetic design for wearing in public and on social occasions", respectively. Displaying results from the data, the innovative mask receives the most positive evaluation from the experts in the dimensions of "good airtightness", "avoiding foul odor inside the mask", and "reducing mask waste". This also shows that most experts believe that this design can meet the needs of users mentioned above. On the other hand, the dimension of "suitable aesthetic design for wearing in public and on social occasions" received the lowest percentage of positive evaluation from the experts, which most experts rated as "average", and therefore we suggest exploring the aesthetic of mask design to improve the appearance in the future.

After obtaining the factor evaluation matrix, first-level FCE was conducted. The adopted calculation formula was:

$$\widetilde{B} = \widetilde{A}\,\widetilde{R} = (a_1, a_2, \ldots, a_m)\begin{pmatrix} r_{11} & \cdots & r_{1n} \\ \vdots & \ddots & \vdots \\ r_{m1} & \cdots & r_{mn} \end{pmatrix} = (b_1, b_2, \ldots, b_n)$$
$$b_j = \bigvee_{m}^{i=1} (a_i \wedge r_{ij}) \quad (\mathrm{j} = 1, 2, \ldots, n) \tag{12}$$

The vector $\widetilde{A}$ was the weight of each design requirement.

The FCE vector and standardized FCE vector were calculated (Table 14). A total of 21%, 29%, 29%, 18%, and 3% of the experts evaluated the innovative mask design as "very good", "good", "general", "bad", and "very bad", respectively. Thus, 50% of the experts evaluated the design results as "good" or "very good". From the perspective of the maximum degree of membership, the experts rated the design proposal as "good". In general, the experts believe that the innovative mask proposed in this study can meet the user's needs.

Table 14. FCE vector and standardized FCE vector (rounded to the second decimal place).

FCE Vector	0.03	0.16	0.27	0.27	0.19
Standardization	0.03	0.18	0.29	0.29	0.21

5. Conclusions, Limitations, and Future Work

A closely interconnected world demands caution in the face of unknown infectious diseases. Scholars also appeal that it is necessary to integrate experts in the fields of government, social work, science, medicine, and pharmaceuticals to avoid the pandemic's continued deterioration [47]. In this study, we developed an innovative face mask under the basis of industrial design. The mask accords with people's daily requirements, especially in reducing the problem of odors in mask wearing. Moreover, the issue of environmental sustainability was considered to cope with the new normal of mask wearing. In addition to technological breakthroughs, user demands are combined with engineering for product demand to be translated into practical technological innovation from the perspective of users. In this study, the FAHP was used to accurately analyze experts' opinions and fuzzy answers in response to the research topic. The experts who participated in this study believed that a suitably designed mask should primarily be highly comfortable and cause less skin irritation than traditional masks do. Improving the stuffy odor caused by the prolonged wearing of traditional masks is a secondary demand.

In this study, a reusable mask was designed through a systematic method based on a modular design concept. A customized medical silicone material pad, an exhalation valve, aromatic cotton sheets with natural plant fragrance, and a small-area filter layer were used to achieve user comfort, solve the problem of stuffy odors, and reduce waste. The developed mask design has a smooth and streamlined appearance. Moreover, the developed mask can be conveniently disassembled, which makes it easy to clean and maintain. Users can change the appearance and color of the designed mask according to their personal preferences and social occasion. Fuzzy decisions that may arise from expert opinions can be evaluated by comprehensively assessing design outputs through FCE. According to the evaluation results, 50% of the experts believed that the design results were "good" or "very good". Moreover, only 29% of the experts believed that the evaluation results were "average". The aforementioned results demonstrate that the proposed innovative mask design can meet the requirements of most users and can overcome the drawbacks of existing masks. Limited research has been conducted on the development of new masks. In this study, the demands for future mask development were explored through systematic methods, and feasible strategies were provided for mask development and design. This study also presented a feasible solution for controlling the spread of the SARS-CoV-2. There were some limitations to the study. A product needs to go through many stages of development before launching in the market, including front-end design (explore the user needs, related technology research, drafting design strategies, form, functionality, etc.), product sampling and testing, and mass production. Each stage needs to go through continuous testing and adjustment. Specifically, this research focused on the category of front-end design and visualized the mask based on the research result. Therefore, there were no samples manufactured for the actual wearing test. We suggest that future follow-up studies can further make samples of this mask, explore the susceptibility feedback of people wearing it from the perspective of ergonomics, and conduct experiments to verify the effectiveness of reducing the spread of SARS-CoV-2.

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