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A Two-Stage Multi-Criteria Supplier Selection Model for Sustainable Automotive Supply Chain under Uncertainty

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Abstract: Sustainable supplier selection (SSS) is gaining popularity as a practical method to supply chain sustainability among academics and practitioners. However, in addition to balancing economic, social, and environmental factors, the emergence of the COVID-19 pandemic has affected the selection of long-term suppliers to ensure sustainable supply chains, recover better from the pandemic and effectively respond to any future unprecedented crises. The purpose of this study is to assess and choose a possible supplier based on their capability to adapt to the COVID-19 epidemic in a sustainable manner. For this assessment, a framework based on multi-criteria decision making (MCDM) is provided that integrates spherical fuzzy Analytical Hierarchical Process (SF-AHP) and grey Complex Proportional Assessment (G-COPRAS), in which spherical fuzzy sets and grey numbers are used to express the ambiguous linguistic evaluation statements of experts. In the first stage, the evaluation criteria system is identified through a literature review and experts' opinions. The SF-AHP is then used to determine the criteria weights. Finally, the G-COPRAS method is utilized to select sustainable suppliers. A case study in the automotive industry in Vietnam is presented to demonstrate the proposed approach's effectiveness. From the SF-AHP findings, "quality", "use of personal protective equipment", "cost/price", "safety and health practices and wellbeing of suppliers", and "economic recovery programs" have been ranked as the five most important criteria. From G-COPRAS analysis, THACO Parts (Supplier 02) is the best supplier. A sensitivity study was also conducted to verify the robustness of the proposed model, in which the priority rankings of the best suppliers are very similar. For long-term development and increased competitiveness, industrial businesses must stress the integration of response mechanisms during SSS implementation in the COVID-19 epidemic, according to the findings. This will result in significant cost and resource savings, as well as reduced environmental consequences and a long-term supply chain, independent of the crisis.

Keywords: COVID-19; supplier selection; automotive industry; MCDM; fuzzy theory; grey theory; SF-AHP model; G-COPRAS model; sustainability

MSC: 68U35; 90B50; 91B06; 20F10; 90C70; 68T35

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1. Introduction

The prevalence of the COVID-19 epidemic has shaken things up in all businesses around the world, particularly in the global freight sector, causing severe economic consequences. The pandemic has exposed the vulnerabilities of many companies, especially those that depend on global supply chains and are too dependent on production centers and large markets. The threat of the expanding COVID-19 outbreak has raised concerns worldwide about the damage and recovery of global supply chains [1,2]. To avert a large-scale infection, travel restrictions, temporary closures, and medical supplies such as gloves, face masks, ventilators, and other personal protective equipment have all been enforced by governments as preventive measures [3]. These constraints lead to shortages of labor and raw materials. As a result, the global supply chain has faced delays and inventory shortages. Supply chains and goods were disrupted across most sectors [4]. COVID-19 had a notably negative impact on all car manufacturers and the majority of industrial product makers, according to them. In light of this, most automakers are shutting down production at some of their plants. Global output for the automotive industry is expected to decline by 13% due to travel restrictions and spare parts shortages [5]. The COVID-19 problem has underlined the necessity of robust and sustainable supply chains. To elevate global competitiveness, any business must incorporate sustainability objectives into their underlying supply chain networks, particularly response tactics in the COVID-19 pandemic; such measures can be considered a crucial aspect of the pandemic's influence on supply chains [6–8].

Southeast Asia has emerged as an important player in global supply chains over the past few decades, where Vietnam is among the countries becoming major manufacturing hubs. The region is now an important producer of automobiles, computers, electronics and apparel, among other products, for the world. However, the massive production disruption caused by the current Covid pandemic threatens to cause a shift in value chains [9]. In particular, the automotive industry was hardest hit by supply chain disruptions during the pandemic. The crisis spurred a wave of production cuts at auto suppliers, resulting in assembly plant closures extending outside the area, posing a slew of issues for automakers. Procurement is crucial in the automotive industry since many components are assembled, and a company cannot make all those components. There are also numerous sellers for each component, with fierce rivalry. The frequent introduction of new models and shorter product lifecycles, along with quick order fulfillment, demand a high level of agility and flexibility on suppliers, compounding supply chain complexity even more. With the increasing complexity of the supply chain, selecting a sustainable supplier becomes an arduous task yet vital strategic decision [10–14].

In recent years, there has been a growing awareness of sustainability trends in emerging economies such as Vietnam, one of the Southeast Asian countries most distinguished by inefficient technologies and unsustainable production of goods and services, which are revealed in high pollution rates, human and environmental hazards [15]. This has increased the demand for manufacturing enterprises to incorporate sustainability measures to meet stakeholders' needs while minimizing negative environmental consequences. Vietnam is increasingly aware of a sustainable supply chain's role and importance in recovering more effectively after the pandemic. However, studies on the COVID-19 pandemic's impact on supply chain sustainability decisions such as the SSS problem are still meager [1,4,7,8,16–21], at least in the context of the automotive industry in Vietnam. Therefore, our study focused on the influence of the COVID-19 pandemic on sustainable supplier selection (SSS) in the automotive industry in Vietnam, examining the relative importance of green strategies and pandemic response methods in SSS. The present study is believed to give related businesses significant insights into achieving supply chain sustainability in the post-pandemic era and prevent perceptual reactions to any unprecedented crisis.

In order to achieve the objectives mentioned earlier, this research is focused on evaluating suppliers' performance on the basis of sustainability triple bottom line attributes (economic, environmental, and social) and the attributes of COVID-19 pandemic response strategies into their supply chain activities. Thus, it can be concluded that the selection of a potential sustainable supplier is a complex multi-criteria decision making (MCDM) problem, in which MCDM techniques are necessary for reducing the preliminary set of suppliers to the final choices [22]. Furthermore, in real-world applications and many real-world circumstances, uncertainty is an inescapable aspect due to the fuzziness of human judgements and the imprecise nature of information. Imprecise sources include unquantifiable, incomplete, and inaccessible data, as well as partial ignorance, and experts may be unwilling or unable to give precise numerical values to comparison judgments [23]. Fuzzy sets theory [24] and grey systems theory [25] are two main approaches for introducing uncertainty and ambiguity into the assessment process in this way. When dealing with imprecision or ambiguity, crisp or conventional procedures are less effective, but fuzzy sets theory and grey systems theory provide an appropriate paradigm for assessing systems with imprecise data and successfully managing uncertainty. As a result, in this study, we used an integrated MCDM framework that combines spherical fuzzy Analytical Hierarchical Process (SF-AHP) with grey Complex Proportional Assessment (G-COPRAS) to rank and select the best potential supplier. The assessment criteria system is initially identified by a literature research and expert recommendations. The criteria weights are then determined using the SF-AHP. Finally, the G-COPRAS approach is used to choose the best suppliers.

Our research's contributions can be summarized as follows.

- In practice, this is the first research in Vietnam to perform a comprehensive sustainable supplier selection (SSS) inside the automotive sector. A major feature of the COVID-19 pandemic's impact is evaluated, as are general sustainability requirements based on three pillars (economic, environmental, and social); this is a significant benefit of the proposed work.
- To the best of our knowledge, this work is the first to design an integrated SF-AHP and G-COPRAS methodology in the existing supplier selection literature. The MCDM method is implemented with the aid of experts' inputs.
- For managerial implications, our suggested method and results can help enterprises achieve supply chain sustainability in the post-pandemic period, respond to risks/threats from future pandemics, identify opportunities, and preserve competitiveness by reconfiguring resources. The approach can be applied not just to SSS, but also to other comparable industries in Asian developing markets and even industrialized ones.

The rest of the paper is organized as follows. Section 2 includes a literature review on SSS and criteria. The approach utilized to perform the case study covered in this research is discussed in Section 3. Section 4 addresses case studies. Section 5 offers a sensitivity analysis to assess the feasibility of the proposed model. Section 6 delves more into the managerial implications of the planned task. Section 7 contains concluding remarks as well as suggestions for further research.

2. Literature Review

2.1. Literature Review on SSS and Criteria

There have been astronomically increasing discussions in supplier selection studies related to the enhancement of supplier capabilities towards green and sustainable practices. A range of studies on SSS suggested by various researchers is reviewed in this section, in which numerous MCDM techniques are presented. Using an integrated MCDM approach combining AHP and VIKOR (VIseKriterijumska Optimizacija I Kompromisno Resenje) methods, Luthra et al. [26] created a scientific model that provides comprehensive information on supplier selection for sustainability based on the essential variables, including product quality, pricing, environmental costs, occupational health and safety systems, and environmental skills. Awasthi et al. [27] employed the fuzzy AHP-VIKOR framework for the extended global sustainable supplier selection towards sustainability risks under five sustainability criteria (economic, quality, environment, social, and global risk). Proposing a hybrid MCDM model of AHP and TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) methods, Jain et al. [28] solved a supplier selection problem in a case study in the Indian automotive industry, considering eight criteria: quality, price/cost, environmental performance relationship, warranty, delivery time, manufacturing capability and brand name. Gupta et al. [29] also considered a case study in the automobile sector supplier selection based on green parameters such as resource consumption, environmental training for employees, quality, service level, eco-design, green image, environmental management system, price/cost, and pollution control. Along with AHP and TOPSIS, the authors used some new MCDM methods, namely MABAC (Multi-Attributive Border Approximation Area Comparison), WASPAS (Weighted Aggregated Sum-Product Assessment). Memari et al. [30] presented an intuitionistic fuzzy TOPSIS method for SSS that concerns nine criteria (cost, quality, service, green image, green competencies, safety and health, environmental efficiency, pollution reduction, and employment practices), as well as thirty sub-criteria for an automobile spare parts manufacturing. Hendiani et al. [11] used the fuzzy best-worst method (BWM) to prioritize the supplier based on their performance of sustainable development under 20 criteria of social, economic, and environment.

Since the COVID-19 crisis, some SSS studies have included pandemic response strategies in their research. For example, Orji and Ojadi [3] examined the COVID-19 pandemic's impact on SSS in the Nigerian manufacturing sector based on fuzzy set theory, AHP and MULTIMOORA (Multi-Objective Optimization based on Ratio Analysis with full multiplicative form). According to the authors, the most important factors in SSS implementation in the post-pandemic era were quality, affordability, personal protective equipment usage, and information technology use for consumer demand forecast. Wang and Chen [31] proposed a bi-objective AHP–mixed integer nonlinear programming (MINLP)–genetic algorithm (GA) approach for supplier selection amid the COVID-19 pandemic according to five following criteria: level of buyer–supplier cooperation, delivery speed, company reputation, pandemic severity, and pandemic containment performance. Petrudi et al. [32] evaluated suppliers considering social sustainability innovation factors during the COVID-19 disaster with the BWM method and grey relational analysis (GRA). During COVID-19, the authors recommended paying attention to safety and health practices, distant working circumstances, and localization while selecting suppliers. In addition to the above-mentioned MCDM techniques used in supplier selection problem, there are many other effective and novel methods that have been widely applied in multiple industries, such as SWOT analysis [33], Analytic Network Process (ANP) [34], Evaluation Based on Distance from Average Solution (EDAS) [35], Decision Making Trial and Evaluation Laboratory (DEMATEL) [36], COmbined COmpromise SOlution (CoCoSo) [37,38], Multi-Attribute Utility Theory (MAUT) [39], Measurement Alternatives and Ranking according to the Compromise Solution (MARCOS) [40], Simple Weighted Sum Product (WISP) [41], Simultaneous Evaluation of Criteria and Alternatives (SECA) [42], to name a few. Table 1 summarizes the methodologies taken by researchers in the realm of supplier and SSS green practices.

Table 1. Summary of SSS studies' approaches.

Authors	Approaches	Issues Addressed
Luthra et al. [26]	AHP and VIKOR	SSS for the Indian automobile industry
Azimifard et al. [43]	AHP and TOPSIS	SSS for Iran's Steel Industry
Awasthi et al. [27]	Fuzzy AHP and Fuzzy VIKOR	Multi-tier SSS for electronic goods manufacturing
Jain et al. [28]	AHP and TOPSIS	SSS in the Indian automotive industry
Abdel-Basset et al. [34]	Neutrosophic Group ANP and TOPSIS	SSS in a dairy company in Egypt
Mohammed et al. [44]	MCDM-FMOO	SSS in a metal factory in Saudi Arabia
Gupta et al. [29]	Fuzzy AHP, TOPSIS, MABAC and WASPAS	Green supplier selection in the automotive industry in India
Memari et al. [30]	Intuitionistic fuzzy TOPSIS	SSS for the manufacturer of catalytic converters
Wong [45]	Fuzzy goal programming	Green supplier selection with risk management
Hendiani et al. [11]	Fuzzy BWM	SSS for refineries in Iran
Zhang et al. [36]	DEMATEL and fuzzy VIKOR	Numerical analysis
Thanh and Lan [37]	Fuzzy AHP and CoCoSo	SSS in the food processing industry
Çalık [46]	Pythagorean fuzzy AHP and fuzzy TOPSIS	Green supplier selection in the industry 4.0 era
Orji and Ojadi [3]	AHP and MULTIMOORA	SSS in the Nigerian manufacturing sector with COVID-19 impacts
Wang and Chen [31]	AHP-MINLP-GA	SSS with COVID-19 impacts
Nguyen et al. [47]	Fuzzy AHP and VIKOR	Supplier selection in coffee bean supply chain with COVID-19 impacts
Petrudi et al. [32]	BWM and GRA	SSS with COVID-19 impacts in Iran
Salimian et al. [40]	VIKOR and MARCOS	SSS in the healthcare sector

2.2. Literature Review on Proposed Methodology

The Analytic Hierarchy Process (AHP) was developed by Saaty [48], which is an effective MCDM approach with several advantages. The approach is used for evaluating, ranking, and selecting criteria, which results in optimum and projected judgments. It is one of the most often used modeling tools for supplier selection. While the technique gets data from experts, the expressed perspectives may not be correctly reflected. As a result, fuzzy sets theory and AHP have been merged, and several types of fuzzy AHP have been developed to capture preference ambiguity. The usefulness of fuzzy AHP approaches has been shown, and researchers and practitioners are becoming more interested. Such approaches have been used on many extensions of fuzzy set theory that are dependent on the determination of linguistic assertions, such as traditional fuzzy sets [3,27–29,47,49], type-2 fuzzy sets [50–52], interval-valued fuzzy sets [53], intuitionistic fuzzy sets [30], neutrosophic sets [54], Pythagorean fuzzy sets (PSF) [46], and spherical fuzzy sets [55–57]. The spherical fuzzy set (SFS) is the novel set introduced in 2018 by Kutlu Gündoğdu and Kahraman [58–61]. It is a three-dimensional fuzzy set of Pythagorean and neutrosophic fuzzy sets combined. SFS may also be used to create criteria for coping with ambiguity and fuzziness in linguistic expressions, giving decision-makers a new viewpoint in a hazy situation. Regardless of the membership and nonmembership levels of the components in these sets, the decision maker's indeterminacy level is established. In SFS, decision-makers specify the membership function on a spherical surface in order to infer additional fuzzy sets from which the parameters of this membership function can be allowed in a broader domain.

COPRAS offers the advantage of having fewer computation steps and a lower calculation time when compared to the AHP approach [62]. COPRAS does not require a typical sample distribution to calculate the values to be maximized and minimized independently among the criteria. Compared to previous MCDM approaches [63], the calculated utility degree reflects how much better the optimal choice is than the other in percentage terms. The COPRAS approach was used by Rani et al. [64] to solve the SSS for a trading organization in India. Masoomi et al. [65] devised a fuzzy COPRAS strategy for strategic supplier selection in the renewable energy supply chain based on green capabilities. Kumari and Mishra [66] proposed a multi-criteria COPRAS technique for intuitionistic fuzzy sets based on parametric measures: application of green supplier selection. G-COPRAS is a useful tool for expressing the genuine state of a decision-making situation using grey values. Kannan [67] utilized G-COPRAS to solve the challenge of SSS in a real-world textile business in India's growing economy. Kayapinar Kaya and Aycin [51] introduced a hybrid interval type-2 fuzzy AHP and G-COPRAS methodologies for supplier selection in the era of industry 4.0. Rajesh and Malliga [68] presented a structured model using G-COPRAS for the evaluation and selection of strategic suppliers. Malaga and Vinodh [69] identified and analyzed drivers of smart manufacturing using the G-COPRAS approach.

3. Materials and Methods

This paper proposes a two-stage MCDM model-based approach for analyzing supplier selection in the automotive market in this research. Literature and expert views were used to create the criterion list. The framework's applicability was proved in a real-world case study of the Vietnamese automobile sector. First, the substantial degree of criterion was determined using the SF-AHP model. G-COPRAS then ranked the options in order of importance. The spherical fuzzy set and grey theory were combined to minimize uncertainty in the decision-making process. The consistency test was conducted to check for consistency in the expert evaluation process and a sensitivity analysis was performed to illustrate the robustness of the proposed MCDM model. Figure 1 depicts the suggested MCDM framework that was used in this study.

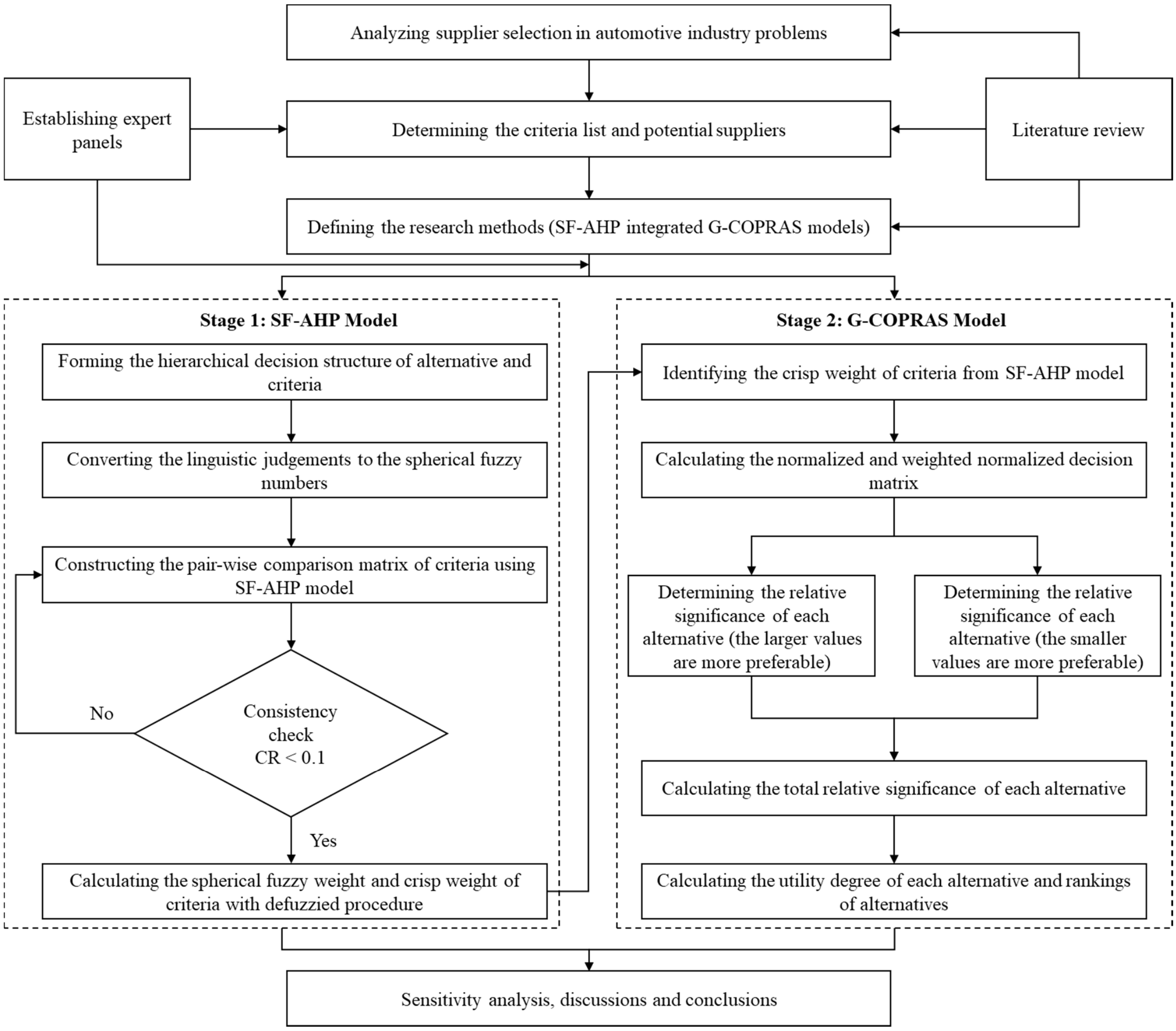

Figure 1. The proposed MCDM framework.

3.1. Spherical Fuzzy Analytical Hierarchy Process (SF-AHP)

As the most recent expansion of the fuzzy sets, Kutlu Gündoudu and Kahraman [70] created a spherical fuzzy set (SFS), which can better manage uncertainties and ambiguities in decision-making. Each spherical fuzzy number comprises the membership, non-membership, and hesitancy functions from the interval [0,1] [71].

Definition 1. *Singer value SFS $\widetilde{F}_S$ of the universe of discourse X is presented by Equations (1)–(3).*

$$\widetilde{F}_S = \left\{ x, (\alpha_{\widetilde{F}_S}(x),\ \beta_{\widetilde{F}_S}(x),\ \gamma_{\widetilde{F}_S}(x)) | x \in X \right\} \tag{1}$$

$$\alpha_{\widetilde{F}_S}(x) :\ X \to [0,1], \beta_{\widetilde{F}_S}(x) : X \to [0,1], \gamma_{\widetilde{F}_S}(x) : X \to [0,1] \tag{2}$$

$$0 \leq \alpha^2_{\widetilde{F}_S}(x) + \beta^2_{\widetilde{F}_S}(x) + \gamma^2_{\widetilde{F}_S}(x) \leq 1 \tag{3}$$

with $\forall x \in X$, for each x, $\alpha_{\widetilde{F}_S}(x)$, $\beta_{\widetilde{F}_S}(x)$ and $\gamma_{\widetilde{F}_S}(x)$ denote for membership, non-membership, and hesitancy levels of x to $\widetilde{F}_S$, respectively.

Definition 2. *For convenience, let $\widetilde{F}_S = (\alpha_{\widetilde{F}_S}, \beta_{\widetilde{F}_S}, \gamma_{\widetilde{F}_S})$ and $\widetilde{E}_S = (\alpha_{\widetilde{E}_S}, \beta_{\widetilde{E}_S}, \gamma_{\widetilde{E}_S})$ be two SFSs. Some arithmetic operations of SFS are presented in Equations (4)–(9).*

- Union operation

$$\begin{aligned} \widetilde{F}_S \cup \widetilde{E}_S = & \{max\{\alpha_{\widetilde{F}_S}, \alpha_{\widetilde{E}_S}\}, min\{\beta_{\widetilde{F}_S}, \beta_{\widetilde{E}_S}\}, min\{(1 \\ - & ((max\{\alpha_{\widetilde{F}_S}, \alpha_{\widetilde{E}_S}\})^2 + (min\{\beta_{\widetilde{F}_S}, \beta_{\widetilde{E}_S}\})^2))^{1/2}, max\{\gamma_{\widetilde{F}_S}, \gamma_{\widetilde{E}_S}\}\}\} \end{aligned} \quad (4)$$

- Intersection operation

$$\begin{aligned} \widetilde{F}_S \cap \widetilde{E}_S = & \{min\{\alpha_{\widetilde{F}_S}, \alpha_{\widetilde{E}_S}\}, max\{\beta_{\widetilde{F}_S}, \beta_{\widetilde{E}_S}\}, max\{(1 \\ - & ((min\{\alpha_{\widetilde{F}_S}, \alpha_{\widetilde{E}_S}\})^2 + (max\{\beta_{\widetilde{F}_S}, \beta_{\widetilde{E}_S}\})^2))^{1/2}, min\{\gamma_{\widetilde{F}_S}, \gamma_{\widetilde{E}_S}\}\}\} \end{aligned} \quad (5)$$

- Addition operation

$$\widetilde{F}_S \oplus \widetilde{E}_S = \{(\alpha^2_{\widetilde{F}_S} + \alpha^2_{\widetilde{E}_S} - \alpha^2_{\widetilde{F}_S}\alpha^2_{\widetilde{E}_S})^{1/2}, \beta_{\widetilde{F}_S}\beta_{\widetilde{E}_S}, ((1-\alpha^2_{\widetilde{E}_S})\gamma^2_{\widetilde{F}_S} + (1-\alpha^2_{\widetilde{F}_S})\gamma^2_{\widetilde{E}_S} - \gamma^2_{\widetilde{F}_S}\gamma^2_{\widetilde{E}_S})^{1/2}\} \quad (6)$$

- Multiplication operation

$$\widetilde{F}_S \otimes \widetilde{E}_S = \{\alpha^2_{\widetilde{F}_S}\alpha^2_{\widetilde{E}_S}, (\beta^2_{\widetilde{F}_S} + \beta^2_{\widetilde{E}_S} - \beta^2_{\widetilde{F}_S}\beta^2_{\widetilde{E}_S})^{1/2}, ((1-\beta^2_{\widetilde{E}_S})\gamma^2_{\widetilde{F}_S} + (1-\beta^2_{\widetilde{F}_S})\gamma^2_{\widetilde{E}_S} - \gamma^2_{\widetilde{F}_S}\gamma^2_{\widetilde{E}_S})^{1/2}\} \quad (7)$$

- Multiplication by a scalar; $\sigma > 0$

$$\sigma . \widetilde{F}_S = \{(1-(1-\alpha^2_{\widetilde{F}_S})^{\sigma})^{1/2}, \beta^{\sigma}_{\widetilde{F}_S}, ((1-\alpha^2_{\widetilde{F}_S})^{\sigma} - (1-\alpha^2_{\widetilde{F}_S} - \gamma^2_{\widetilde{F}_S})^{\sigma})^{1/2}\} \quad (8)$$

- Power of F_S; $\sigma > 0$

$$\widetilde{F}^{\sigma}_S = \{\alpha^{\sigma}_{\widetilde{F}_S}, (1-(1-\beta^2_{\widetilde{F}_S})^{\sigma})^{1/2}, ((1-\beta^2_{\widetilde{F}_S})^{\sigma} - (1-\beta^2_{\widetilde{F}_S} - \gamma^2_{\widetilde{F}_S})^{\sigma})^{1/2}\} \quad (9)$$

Definition 3. *For these SFSs $\widetilde{F}_S = (\alpha_{\widetilde{F}_S}, \beta_{\widetilde{F}_S}, \gamma_{\widetilde{F}_S})$ and $\widetilde{E}_S = (\alpha_{\widetilde{E}_S}, \beta_{\widetilde{E}_S}, \gamma_{\widetilde{E}_S})$, the followings are valid under the condition $\sigma, \sigma_1, \sigma_2 > 0$, Equations (10)–(15).*

$$\widetilde{F}_S \oplus \widetilde{E}_S = \widetilde{E}_S \oplus \widetilde{F}_S \quad (10)$$

$$\widetilde{F}_S \otimes \widetilde{E}_S = \widetilde{E}_S \otimes \widetilde{F}_S \quad (11)$$

$$\sigma\left(\widetilde{F}_S \oplus \widetilde{E}_S\right) = \sigma\widetilde{F}_S \oplus \sigma\widetilde{E}_S \quad (12)$$

$$\sigma_1\widetilde{F}_S \oplus \sigma_2\widetilde{F}_S = (\sigma_1 + \sigma_2)\widetilde{F}_S \quad (13)$$

$$(\widetilde{F}_S \otimes \widetilde{E}_S)^{\sigma} = \widetilde{F}^{\sigma}_S \otimes \widetilde{E}^{\sigma}_S \quad (14)$$

$$\widetilde{F}^{\sigma_1}_S \otimes \widetilde{F}^{\sigma_2}_S = \widetilde{F}^{\sigma_1+\sigma_2}_S \quad (15)$$

Definition 4. *Spherical weighted arithmetic mean (SWAM) with respect to $w = (w_1, w_2, \ldots, w_n)$; $w_i \in [0,1]$; $\sum_{i=1}^{n} w_i = 1$, SWAM is defined by Equation (16).*

$$\begin{aligned} SWAM_w(\widetilde{F}_{S1},\ldots,\widetilde{F}_{Sn}) &= w_1\widetilde{F}_{S1} + w_2\widetilde{F}_{S2} + \ldots + w_n\widetilde{F}_{Sn} \\ &= \left\{ \left[1 - \prod_{i=1}^{n}(1-\alpha^2_{\widetilde{F}_{Si}})^{w_i} \right]^{1/2}, \right. \\ &\left. \prod_{i=1}^{n}\beta^{w_i}_{\widetilde{F}_{Si}} \left[\prod_{i=1}^{n}\left(1-\alpha^2_{\widetilde{F}_{Si}}\right)^{w_i} - \prod_{i=1}^{n}\left(1-\alpha^2_{\widetilde{F}_{Si}} - \gamma^2_{\widetilde{F}_{Si}}\right)^{w_i} \right]^{1/2} \right\} \end{aligned} \tag{16}$$

The SF-AHP model has several advantages over the classic AHP approach. While the strategy gets data from experts, the expressed viewpoints may not be correctly reflected. Consequently, SF-AHP may easily reduce the uncertainty in the comparison matrix induced by expert opinion. In this study, the SF-AHP model was utilized to compute the weights of the criterion. The SF-AHP procedure is divided into six stages, which are as follows [72].

Step 1: The hierarchical structure is organized with the research goal (level 1) and the list of criteria $C = \{C_1,\ C_2, \ldots C_n\}$ (level 2) $within\ n \geq 2$.

Step 2: The pairwise comparison matrices are constructed with respect to spherical fuzzy linguistic scales, as shown in Table 2. It is noted that this paper used the linguistics scales as a heuristics reference [72]. The score indices (SI) are determined by Equations (17) and (18).

$$SI = \sqrt{\left|100 * \left[(\alpha_{\widetilde{F}_S} - \gamma_{\widetilde{F}_S})^2 - (\beta_{\widetilde{F}_S} - \gamma_{\widetilde{F}_S})^2 \right] \right|} \tag{17}$$

for the AMI, VHI, HI, SMI, and EI.

$$\frac{1}{SI} = \frac{1}{\sqrt{|100 * [(\alpha_{\widetilde{F}_S} - \gamma_{\widetilde{F}_S})^2 - (\beta_{\widetilde{F}_S} - \gamma_{\widetilde{F}_S})^2]|}} \tag{18}$$

for the EI, SLI, LI, VLI, and ALI.

Table 2. SF-AHP linguistic scales used for the pairwise comparisons [72].

Linguistics Scale	Fuzzy Number (α,β,γ)	Score Index (SI)
Absolutely high importance (AMI)	(0.9, 0.1, 0.0)	9
Very high importance (VHI)	(0.8, 0.2, 0.1)	7
High importance (HI)	(0.7, 0.3, 0.2)	5
Slightly high importance (SMI)	(0.6, 0.4, 0.3)	3
Equal importance (EI)	(0.5, 0.4, 0.4)	1
Slightly low importance (SLI)	(0.4, 0.6, 0.3)	1/3
Low importance (LI)	(0.3, 0.7, 0.2)	1/5
Very low importance (VLI)	(0.2, 0.8, 0.1)	1/7
Absolutely low importance (ALI)	(0.1, 0.9, 0.0)	1/9

Step 3: The linguistics scales are converted to the corresponding SI. Then, the consistency ratio (CR) is checked for the pairwise comparison matrices, where the CR must be less than 10%.

Step 4: Determine the weight of each criterion using the SWAM operator, as in Equation (19).

$$\begin{aligned} SWAM_w(\widetilde{F}_{S1},\ldots,\widetilde{F}_{Sn}) &= w_1\widetilde{F}_{S1} + w_2\widetilde{F}_{S2} + \ldots + w_n\widetilde{F}_{Sn} \\ &= \left\{ \left[1 - \prod_{i=1}^{n}(1-\alpha^2_{\widetilde{F}_{Si}})^{w_i} \right]^{1/2}, \right. \\ &\left. \prod_{i=1}^{n}\beta^{w_i}_{\widetilde{F}_{Si}} \left[\prod_{i=1}^{n}(1-\alpha^2_{\widetilde{F}_{Si}})^{w_i} - \prod_{i=1}^{n}(1-\alpha^2_{\widetilde{F}_{Si}} - \gamma^2_{\widetilde{F}_{Si}})^{w_i} \right]^{1/2} \right\} \end{aligned} \tag{19}$$

where $w = 1/n$.

Step 5: The criteria weights are defuzzified using Equation (20). Then, they are normalized using Equation (21). The multiplication operator in Equation (22) is applied to aggregate the final ranking scores.

$$S\left(\widetilde{w}_j^s\right) = \sqrt{\left|100 * \left[\left(3\alpha_{\widetilde{F}_S} - \frac{\gamma_{\widetilde{F}_S}}{2}\right)^2 - \left(\frac{\beta_{\widetilde{F}_S}}{2} - \gamma_{\widetilde{F}_S}\right)^2\right]\right|} \tag{20}$$

$$\overline{w}_j^s = \frac{S\left(\widetilde{w}_j^s\right)}{\sum_{j=1}^n S\left(\widetilde{w}_j^s\right)} \tag{21}$$

$$\widetilde{F}_{S_{ij}} = \overline{w}_j^s.\ \widetilde{F}_{S_i} = \left\{\left(1 - (1 - \alpha_{\widetilde{F}_S}^2)^{\overline{w}_j^s}\right)^{1/2},\ \beta_{\widetilde{F}_S}^{\overline{w}_j^s},\ \left((1 - \alpha_{\widetilde{F}_S}^2)^{\overline{w}_j^s} - (1 - \alpha_{\widetilde{F}_S}^2 - \gamma_{\widetilde{F}_S}^2)^{\overline{w}_j^s}\right)^{1/2}\right\},\ \forall i \tag{22}$$

The final SF-AHP score ($\widetilde{F}$) is calculated by carrying out spherical fuzzy arithmetic addition over global weights, as given in Equation (23).

$$\begin{gathered}\widetilde{F} = \sum_{j=1}^{n} \widetilde{F}_{S_{ij}} = \widetilde{F}_{S_{i1}} \oplus \widetilde{F}_{S_{i2}} \oplus \ldots \oplus \widetilde{F}_{S_{in}}, \forall i \\ \text{i.e., } \widetilde{F}_{S_{11}} \oplus \widetilde{F}_{S_{12}} = \{(\alpha_{\widetilde{F}_{S_{11}}}^2 + \alpha_{\widetilde{F}_{S_{12}}}^2 - \alpha_{\widetilde{F}_{S_{11}}}^2 \alpha_{\widetilde{F}_{S_{12}}}^2)^{1/2}, \beta_{\widetilde{F}_{S_{11}}} \beta_{\widetilde{F}_{S_{12}}}, ((1 - \alpha_{\widetilde{F}_{S_{12}}}^2)\gamma_{\widetilde{F}_{S_{11}}}^2 + (1 - \alpha_{\widetilde{F}_{S_{11}}}^2)\gamma_{\widetilde{F}_{S_{12}}}^2 - \gamma_{\widetilde{F}_{S_{11}}}^2 \gamma_{\widetilde{F}_{S_{12}}}^2)^{1/2}\}\end{gathered} \tag{23}$$

Step 6: Defuzzify the final score of each criterion. Sort the list of criteria according to their defuzzified final ranking, which are the larger, the better. The criteria weights are used for the G-COPRAS model in the next phase.

3.2. Grey Complex Proportional Assessment (G-COPRAS)

Julong [73] introduced the grey theory to investigate uncertainty with ambiguous information. According to the degree of knowledge, the grey theory is divided into three types: "white system," "black system," and "grey system" for information that is "totally known," "unknown," and "partially known," respectively [74].

Let $\otimes x = [\underline{x}, \overline{x}]$ represents a grey number with $\underline{x}$ denotes the lower limit, and $\overline{x}$ denotes the upper limit of the membership function.

Let $\otimes x_1 = [\underline{x}_1, \overline{x}_1]$ and $\otimes x_2 = [\underline{x}_2, \overline{x}_2]$ are two grey numbers; ε denotes a positive real number, and L denotes the length of the grey number. The basic grey number arithmetic operations are presented in Equations (24)–(29).

$$\otimes x_1 + \otimes x_2 = [\underline{x}_1 + \underline{x}_2, \overline{x}_1 + \overline{x}_2] \tag{24}$$

$$\otimes x_1 - \otimes x_2 = [\underline{x}_1 - \overline{x}_2, \overline{x}_1 - \underline{x}_2] \tag{25}$$

$$\otimes x_1 * \otimes x_2 = [\min(\underline{x}_1\underline{x}_2, \underline{x}_1\overline{x}_2, \overline{x}_1\underline{x}_2, \overline{x}_1\overline{x}_2), \max(\underline{x}_1\underline{x}_2, \underline{x}_1\overline{x}_2, \overline{x}_1\underline{x}_2, \overline{x}_1\overline{x}_2)] \tag{26}$$

$$\otimes x_1 / \otimes x_2 = [\min(\underline{x}_1/\underline{x}_2, \underline{x}_1/\overline{x}_2, \overline{x}_1/\underline{x}_2, \overline{x}_1/\overline{x}_2), \max(\underline{x}_1/\underline{x}_2, \underline{x}_1/\overline{x}_2, \overline{x}_1/\underline{x}_2, \overline{x}_1/\overline{x}_2)] \tag{27}$$

$$\varepsilon \otimes x_1 = \varepsilon[\underline{x}_1, \overline{x}_1] = [\varepsilon\underline{x}_1, \varepsilon\overline{x}_1] \tag{28}$$

$$L(\otimes x_1) = [\overline{x}_1 - \underline{x}_1] \tag{29}$$

Zavadskas et al. [75] first proposed grey complex proportional assessment (G-COPRAS) to reduce subjective judgments using grey numbers in the decision-making process. The G-COPRAS method priority the alternative based on the calculation of the utility degree. The G-COPRAS's procedure consists of six steps as follows [76].

Step 1: Suppose that $A = \{A_1, A_2, \ldots, A_m\}$ is a discrete set of m *alternatives*, which are ranked by a discrete set $C = \{C_1, C_2, \ldots, C_n\}$ of n criteria.

Step 2: Use the linguistic scale with grey numbers in Table 3 to evaluate the performance ratings of the options in terms of the criteria. Noted that this paper used the linguistics scales as a heuristics reference by [76]. Suppose that there are k experts, and the value of alternative h in the criterion g is calculated using Equation (30). Following that, the grey decision matrix is built, as can be seen in Equation (31).

$$\otimes G_{hg} = \frac{1}{k}(\otimes G_{hg}^1 + \otimes G_{hg}^2 + \ldots + \otimes G_{hg}^k) \tag{30}$$

$$\otimes G = \begin{bmatrix} \otimes G_{11} & \otimes G_{12} & \cdots & \otimes G_{1n} \\ \otimes G_{21} & \otimes G_{22} & \cdots & \otimes G_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ \otimes G_{m1} & \otimes G_{m2} & \cdots & \otimes G_{mn} \end{bmatrix} \tag{31}$$

where $\otimes G_{hg}$ is the importance of alternative h in the criterion g.

Table 3. The linguistics scale with grey numbers [76].

Linguistics Scale	Grey Number $[\underline{x}, \overline{x}]$
Very Poor (VP)	[0, 1]
Poor (P)	[1, 3]
Medium Poor (MP)	[3, 4]
Fair (F)	[4, 5]
Medium Good (MG)	[5, 6]
Good (G)	[6, 9]
Very Good (VG)	[9, 10]

Step 3: In this study, the relative importance of each criterion is calculated by the SF-AHP method.

Step 4: First, the normalized grey decision matrix is built, as can be seen in Equations (32)–(34).

$$\otimes G^* = \begin{bmatrix} \otimes G^*_{11} & \otimes G^*_{12} & \cdots & \otimes G^*_{1n} \\ \otimes G^*_{21} & \otimes G^*_{22} & \cdots & \otimes G^*_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ \otimes G^*_{m1} & \otimes G^*_{m2} & \cdots & \otimes G^*_{mn} \end{bmatrix} \tag{32}$$

$$\underline{G}^*_{hg} = \frac{\underline{G}_{hg}}{\frac{1}{2}\left(\sum_{h=1}^{m} \underline{G}_{hg} + \sum_{h=1}^{m} \overline{G}_{hg}\right)} = \frac{2\underline{G}_{hg}}{\sum_{h=1}^{m} \underline{G}_{hg} + \sum_{h=1}^{m} \overline{G}_{hg}} \tag{33}$$

$$\overline{G}^*_{hg} = \frac{\overline{G}_{hg}}{\frac{1}{2}\left(\sum_{h=1}^{m} \underline{G}_{hg} + \sum_{h=1}^{m} \overline{G}_{hg}\right)} = \frac{2\overline{G}_{hg}}{\sum_{h=1}^{m} \underline{G}_{hg} + \sum_{h=1}^{m} \overline{G}_{hg}} \tag{34}$$

where $\otimes G_{hg}$ represent the pairwise comparison from a group of decision-makers with respect to the h^{th} alternative in the g^{th} criterion.

Following that, the weighted normalized grey decision matrix is developed, as can be seen in Equation (35).

$$\otimes X = \begin{bmatrix} \otimes X_{11} & \otimes X_{12} & \cdots & \otimes X_{1n} \\ \otimes X_{21} & \otimes X_{22} & \cdots & \otimes X_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ \otimes X_{m1} & \otimes X_{m2} & \cdots & \otimes X_{mn} \end{bmatrix} \text{ where } \otimes X_{hg} = \otimes G^*_{hg} \times w_g \tag{35}$$

where w_g is the important weight of each criterion.

Step 5: First, we compute the sums P_h of the criterion values (the larger values are more preferable) using Equation (36).

$$P_h = \frac{1}{2}\sum_{g=1}^{o}\left(\underline{X}_{hg} + \overline{X}_{hg}\right), h = 1, 2, \ldots, m; g = 1, 2, \ldots, o \tag{36}$$

Next, we compute the sums R_h of the criterion value (the smaller values are more preferable) using Equation (37).

$$R_h = \frac{1}{2}\sum_{g=o+1}^{n}\left(\underline{X}_{hg} + \overline{X}_{hg}\right), h = 1, 2, \ldots, m; g = o+1, o+2, \ldots, n \tag{37}$$

Then, the relative significance of each alternative is computed using Equation (38).

$$Q_h = P_h + \frac{\sum_{h=1}^{m} R_h}{R_h \sum_{h=1}^{m} \frac{1}{R_h}}, h = 1, 2, \ldots, m \tag{38}$$

Step 6: First, the optimality criterion K is determined using Equation (39). Then, the utility degree of each alternative N_h is calculated by comparing the alternatives under consideration with the best alternative (i.e., 100% for the best alternative), as can be seen in Equation (40).

$$K = Max_h Q_h, h = 1,\ 2, \ldots, m \tag{39}$$

$$N_h = \frac{Q_h}{Q_{max}} \times 100\%,\ h = 1,\ 2, \ldots, m \tag{40}$$

4. Empirical Analysis

4.1. A Case Study of the Automotive Industry in Vietnam

This work proposed a two-stage MCDM model by integrating SF-AHP and G-COPRAS models to evaluate and select the suitable suppliers in terms of sustainability aspects (compromised social, environmental, and economic during the COVID-19 pandemic. A case study of five automotive suppliers in Vietnam is used to test the proposed model, which is MARUEI Viet Nam Precision Company Limited (Supplier 01), THACO Parts (Supplier 02), GDC Viet Nam Joint Stock Company (Supplier 03), Hoang Dung Phat Production Trading Services Import and Export Company Limited (Supplier 04), and Dac Yen Company Limited (Supplier 05), as can be seen in Table 4. Out of the total number of possible suppliers, these five companies were selected, which have core business in automotive parts manufacturing in Vietnam and also based on experts' recommendations. Through literature review, the list of sustainable criteria systems was validated through interviews with specialists with at least ten years of logistics and supply chain management, especially in the procurement of the automotive industry. There was a session in which the committee discussed the criteria and potential alternatives in the automotive sector of Vietnam; many vital considerations were referenced and discussed between experts and specialists to determine critical factors for evaluating and selecting possible options. After discussions, the evaluation indicator system was constructed and finalized as the suitable and comprehensive set of criteria responsible for the feasible implementation of the SSS from a developing country's perspective. The list of criteria and their definition is shown in Table 5. The hierarchical structure of the MCDM model is presented in Figure 2. As can be seen from Figure 2, the inputs of the decision group of experts and a literature analysis are used to select the four main dimensions and 15 evaluation criteria of SSS for sustainability in the automotive supply chain. Further, five suppliers (Supplier 01, Supplier 02, Supplier 03, Supplier 04, and Supplier 05) were available as alternatives (from data available from the company) to select the most efficient sustainable supplier among them by using experts' inputs.

Table 4. The list of suppliers.

No	Suppliers	Name of Suppliers	Website (accessed on 30 March 2022)
1	Supplier 01	MARUEI Viet Nam Precision Company Limited	http://www.marueikogyo.jp/english/group/vietnam/
2	Supplier 02	THACO Parts	https://thacoparts.vn/en/home/
3	Supplier 03	GDC Viet Nam Joint Stock Company	http://gdcvietnam.vn/
4	Supplier 04	Hoang Dung Phat Production Trading Services Import and Export Company Limited	http://cokhihoangdungphat.com/
5	Supplier 05	Dac Yen Company Limited	https://phutungotovietnam.com.vn/en/

Table 5. The list of criteria and their objective.

Dimension	Criteria	Objective	References
Social (C1)	C11. Staff training programs	Maximum	[11,29,30,67,77]
	C12. Social responsibility	Maximum	[3,26]
	C13. Safety and health practices and wellbeing of suppliers	Maximum	[3,11,26,27,30,32]
Environmental (C2)	C21. Eco-design	Maximum	[3,26,29,30]
	C22. Environmental management and policies	Maximum	[3,26,29,30]
	C23. Waste and pollution	Minimum	[3,11,26,29,30]
Economic (C3)	C31. Supply capacity	Maximum	[11,29,78]
	C32. Quality	Maximum	[3,11,26,27,29,30,47]
	C33. Cost/Price	Minimum	[3,11,26,27,29,30,47]
	C34. Delivery reliability	Maximum	[11,26,27,29,30,47]
	C35. Financial capability	Maximum	[3,26]

Table 5. *Cont.*

Dimension	Criteria	Objective	References
COVID-19 pandemic response strategies (C4)	C41. Adherence to regulatory changes	Maximum	[3,11,27,30,79]
	C42. Economic recovery programs	Maximum	[1,3,4,80]
	C43. Use of personal protective equipment	Maximum	[3,81]
	C44. Use of IT for customer demand prediction	Maximum	[12,80]

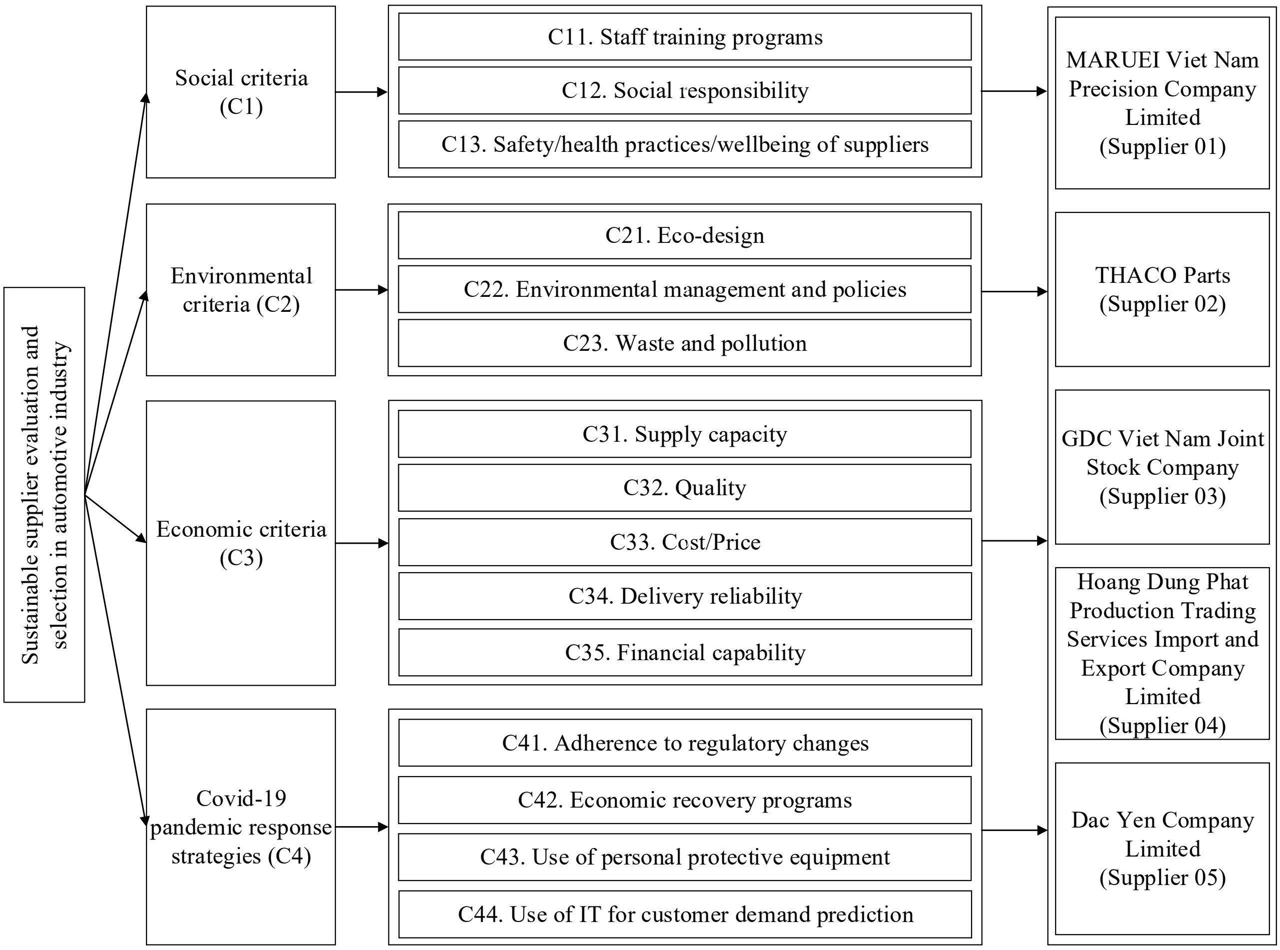

Figure 2. Hierarchical structure.

4.2. SF-AHP for Determination Criteria Weights

In this stage, the SF-AHP model was utilized for weighting the qualitative criteria for supplier selection with the case study of the automotive industry in Vietnam. Based on expert judgment and literature, four main dimensions include social criteria (C1), environmental criteria (C2), economic criteria (C3), and COVID-19 pandemic response strategies (C4), and their decomposition into 15 criteria were selected.

The SF-AHP model is step-by-step conducted by the following calculation process of the four main dimensions. The pairwise comparison matrix, the non-fuzzy comparison matrix and the normalized comparison matrix of the four main dimensions are presented in Tables 6–8. The consistency ratio of the pairwise comparison was calculated accordingly. Note that WSV is the weighted sum value, CV is the consistency vector, C is a considered criteria (or dimension in this example), SI is score index.

$$C_{12} = \frac{SI_{C_{12}}}{SUM_{C_2}} = \frac{1.000}{4.478} = 0.223$$

$$MEAN_{C_1} = \frac{0.171 + 0.223 + 0.135 + 0.182}{4} = 0.178$$

$$WSV = \begin{bmatrix} 1.000 & 1.000 & 0.436 & 0.637 \\ 1.000 & 1.000 & 0.904 & 0.729 \\ 2.293 & 1.107 & 1.000 & 1.132 \\ 1.571 & 1.372 & 0.883 & 1.000 \end{bmatrix} \times \begin{bmatrix} 0.178 \\ 0.221 \\ 0.318 \\ 0.284 \end{bmatrix} = \begin{bmatrix} 0.718 \\ 0.893 \\ 1.291 \\ 1.146 \end{bmatrix};$$

$$CV = \begin{bmatrix} 0.718 \\ 0.893 \\ 1.291 \\ 1.146 \end{bmatrix} / \begin{bmatrix} 0.178 \\ 0.221 \\ 0.318 \\ 0.284 \end{bmatrix} = \begin{bmatrix} 4.036 \\ 4.045 \\ 4.059 \\ 4.403 \end{bmatrix}$$

With the four main dimensions ($n = 4$), the largest eigenvector (λ_{max}) was calculated to identify the consistency index (CI), the random index (RI), and consistency ratio (CR) as follows:

$$\lambda_{max} = \frac{4.036 + 4.045 + 4.059 + 4.403}{4} = 4.046$$

$$CI = \frac{\lambda_{max} - n}{n - 1} = \frac{4.046 - 4}{4 - 1} = 0.015$$

Such that $n = 4$, $RI = 0.9$, and the CR value is calculated as follows:

$$CR = \frac{CI}{RI} = \frac{0.015}{0.9} = 0.017$$

As shown in $CR = 0.017 < 0.1$, the pairwise comparison matrix was consistent, and the result was satisfactory.

Table 6. The pairwise comparison matrix of SF-AHP.

Dimension	Left Criteria Is Greater					Right Criteria Is Greater				Dimension
	AMI	**VHI**	**HI**	**SMI**	**EI**	**SLI**	**LI**	**VLI**	**ALI**	
C1		1	3	3	2	1	3	1	1	C2
C1				3	2	2	6	2		C3
C1		2	1	2	1	2	4	3		C4
C2			3	3	3	2	1	3		C3
C2		1	2	3	1	2	2	4		C4
C3		1	4	3	1	1	3	2		C4

Table 7. The non-fuzzy comparison matrix of SF-AHP.

Dimension	C1	C2	C3	C4
C1	1.000	1.000	0.436	0.637
C2	1.000	1.000	0.904	0.729
C3	2.293	1.107	1.000	1.132
C4	1.571	1.372	0.883	1.000
SUM	5.864	4.478	3.223	3.498

Table 8. The normalized comparison matrix of SF-AHP.

Dimension	C1	C2	C3	C4	MEAN	WSV	CV
C1	0.171	0.223	0.135	0.182	0.178	0.718	4.036
C2	0.171	0.223	0.280	0.208	0.221	0.893	4.045
C3	0.391	0.247	0.310	0.324	0.318	1.291	4.059
C4	0.268	0.306	0.274	0.286	0.284	1.146	4.043

Note: WSV is the weighted sum value, CV is the consistency vector.

Table 9 shows the calculated integrated spherical fuzzy comparison matrix. Following that, the obtained spherical fuzzy weights of each dimension were calculated and are presented in Table 10. For more understanding, the following calculation was presented for the spherical fuzzy weights of criteria social criteria (C1), with spherical fuzzy weights $(\alpha, \beta, \gamma) = (0.426,\ 0.553,\ 0.292)$, as follows:

$$\alpha_{C1} = \left[1 - \prod_{i=1}^{n} (1 - \alpha^2_{\widetilde{F}_{Si}})^{w_i}\right]^{1/2} = \left[1 - \left(1 - 0.500^2\right)^{\frac{1}{4}} * \left(1 - 0.430^2\right)^{\frac{1}{4}} * \left(1 - 0.363^2\right)^{\frac{1}{4}} * \left(1 - 0.393^2\right)^{\frac{1}{4}}\right]^{1/2} = 0.426$$

$$\beta_{C1} = \prod_{i=1}^{n} \beta^{w_i}_{\widetilde{F}_{Si}} = 0.400^{\frac{1}{4}} * 0.857^{\frac{1}{4}} * 0.638^{\frac{1}{4}} * 0.622^{\frac{1}{4}} = 0.553$$

$$\begin{aligned}\gamma_{C1} &= \left[\prod_{i=1}^{n}(1 - \alpha^2_{\widetilde{F}_{Si}})^{w_i} - \prod_{i=1}^{n}(1 - \alpha^2_{\widetilde{F}_{Si}} - \gamma^2_{\widetilde{F}_{Si}})^{w_i}\right]^{1/2} \\ &= \left[(1 - 0.500^2)^{\frac{1}{4}} * (1 - 0.430^2)^{\frac{1}{4}} * (1 - 0.363^2)^{\frac{1}{4}} * (1 - 0.393^2)^{\frac{1}{4}} - (1 - 0.500^2 - 0.400^2)^{\frac{1}{4}} \right. \\ &\quad \left. * (1 - 0.430^2 - 0.236^2)^{\frac{1}{4}} * (1 - 0.363^2 - 0.246^2)^{\frac{1}{4}} * (1 - 0.393^2 - 0.219^2)^{\frac{1}{4}}\right]^{1/2} = 0.292\end{aligned}$$

$$S\left(\widetilde{w}^s_{C1}\right) = \sqrt{\left|100 * \left[\left(3\alpha_{\widetilde{F}_S} - \frac{\gamma_{\widetilde{F}_S}}{2}\right)^2 - \left(\frac{\beta_{\widetilde{F}_S}}{2} - \gamma_{\widetilde{F}_S}\right)^2\right]\right|} = \sqrt{\left|100 * \left[\left(3 * 0.426 - \frac{0.292}{2}\right)^2 - \left(\frac{0.553}{2} - 0.292\right)^2\right]\right|} = 11.324$$

$$\overline{w}^s_{C1} = \frac{S\left(\widetilde{w}^s_j\right)}{\sum_{j=1}^{n} S\left(\widetilde{w}^s_j\right)} = \frac{11.324}{11.324 + 11.993 + 13.679 + 13.217} = 0.226$$

Table 9. The integrated spherical fuzzy comparison matrix.

Dimension	C1			C2			C3			C4		
	α	β	γ	α	β	γ	α	β	γ	α	β	γ
C1	0.500	0.400	0.400	0.430	0.587	0.236	0.363	0.638	0.246	0.393	0.622	0.219
C2	0.458	0.553	0.254	0.500	0.400	0.400	0.433	0.573	0.259	0.397	0.619	0.220
C3	0.579	0.420	0.276	0.475	0.523	0.281	0.500	0.400	0.400	0.461	0.559	0.229
C4	0.504	0.521	0.229	0.503	0.518	0.241	0.446	0.569	0.238	0.500	0.400	0.400

Table 10. The spherical weights from SF-AHP.

Dimension	SF-AHP Weight			Crisp Weight
	α	β	γ	$\overline{w}^s_j$
C1	0.426	0.553	0.292	0.226
C2	0.450	0.529	0.298	0.239
C3	0.507	0.471	0.306	0.272
C4	0.489	0.498	0.290	0.263

The SF-AHP weights consist of three parameters, which are the membership function (α), non-membership function (β), and hesitancy function (γ) of the element $x \in X$. The crisp weights were calculated based on the abovementioned calculation. The most significant dimension is Economic criteria (C3) with a value of 0.272, followed by COVID-19 pandemic response strategies (C4) with a value of 0.263. Meanwhile, Environmental criteria (C2) with a value of 0.239, and social criteria (C1) with a value of 0.226 was the last significant dimension. The relevance level of 15 criteria was then calculated using the same procedures as before. Table A1 shows the integrated spherical fuzzy comparison matrix with 15 criteria (Appendix A). Then, the significant level of investigated criteria is discussed.

The spherical fuzzy weights and crisp weights of SF-AHP are presented in Table 11. The geometrical mean is applied to calculate the significant level of each criterion [82]. From the results, for example, the spherical fuzzy weights of the criteria C11. Staff training programs have a membership function (α) at 0.503, non-membership function (β) at 0.494, and hesitancy function (γ) at 0.328. Similar to the procedure, the spherical fuzzy weights of the criteria C12. Social responsibility has a membership function (α), non-membership function (β), and hesitancy function (γ) of 0.475, 0.511, and 0.317, respectively. The significance levels of 15 criteria of the SF-AHP model are visualized in Figure 3. The results show that the five most significant criteria for qualitative performance evaluation of CSCs are C32. Quality, C43. Use of personal protective equipment, C33. Cost/Price, C13. Safety and health practices and wellbeing of suppliers, and C42. Economic recovery programs, with significance levels of 7.75%, 7.44%, 7.27%, 7.17%, and 6.98%, respectively. Meanwhile, C44. The use of IT for customer demand prediction is specified as the least significant criterion, with a value of 4.81% compared to other considered criteria. The findings suggest that decision-makers focus on "C32", "C43", "C33", "C13", and "C42" for improving the performance of suppliers in the automotive industry.

Table 11. Spherical fuzzy weights and crisp weights 15 criteria of SF-AHP.

Criteria	Geometric Mean			Spherical Fuzzy Weights			Crisp Weights
	α	β	γ	α	β	γ	
C11. Staff training programs	0.747	0.494	0.108	0.503	0.494	0.328	0.070
C12. Social responsibility	0.775	0.511	0.100	0.475	0.511	0.317	0.066
C13. Safety and health practices and wellbeing of suppliers	0.733	0.476	0.110	0.517	0.476	0.331	0.072
C21. Eco-design	0.770	0.513	0.100	0.479	0.513	0.315	0.066
C22. Environmental management and policies	0.766	0.512	0.100	0.484	0.512	0.316	0.067
C23. Waste and pollution	0.753	0.493	0.109	0.497	0.493	0.331	0.069
C31. Supply capacity	0.756	0.492	0.104	0.494	0.492	0.322	0.068
C32. Quality	0.693	0.430	0.107	0.554	0.430	0.328	0.077
C33. Cost/Price	0.726	0.471	0.111	0.524	0.471	0.334	0.073
C34. Delivery reliability	0.813	0.562	0.089	0.432	0.562	0.298	0.060
C35. Financial capability	0.829	0.588	0.080	0.414	0.588	0.284	0.057
C41. Adherence to regulatory changes	0.787	0.526	0.103	0.462	0.526	0.320	0.063
C42. Economic recovery programs	0.749	0.489	0.095	0.501	0.489	0.309	0.070
C43. Use of personal protective equipment	0.715	0.449	0.107	0.534	0.449	0.328	0.074
C44. Use of IT for customer demand prediction	0.876	0.654	0.066	0.353	0.654	0.257	0.048

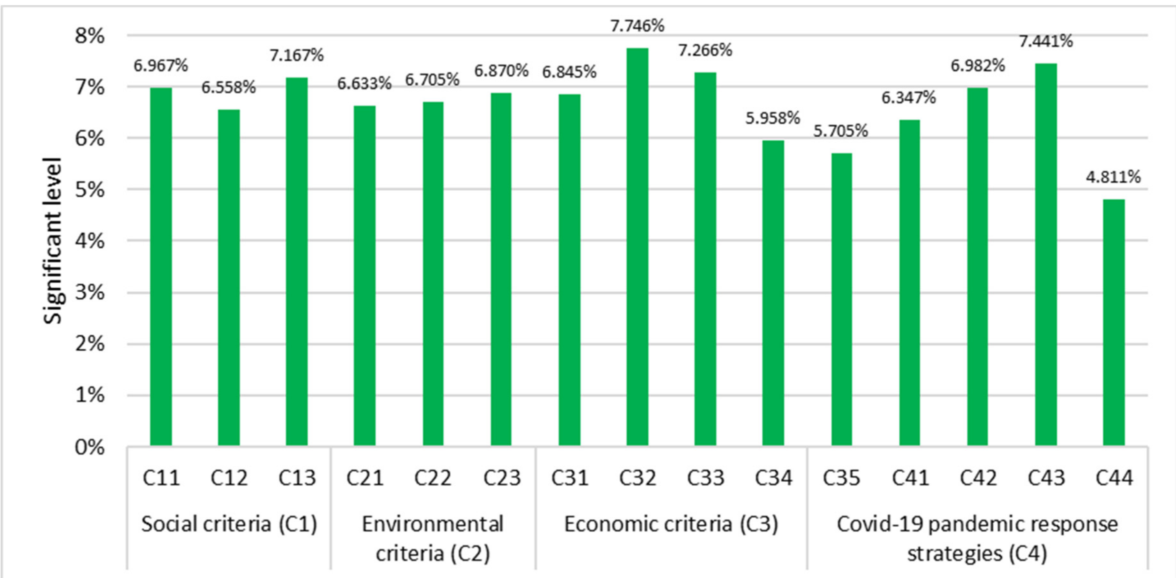

Figure 3. The significant level of 15 criteria of SF-AHP.

4.3. G-COPRAS for Ranking Suppliers

In this step, G-COPRAS is applied to rank the suppliers. The preference weight of each criterion is calculated from the SF-AHP model. Based on the process of G-COPRAS, the normalized grey decision matrix and the weighted normalized grey decision matrix of G-COPRAS are presented in Tables A2 and A3 (Appendix A). Following that, the evaluation of the utility degree of G-COPRAS is shown in Table 12 and visualized in Figure 4. From the result, THACO Parts (Supplier 02) achieves the highest qualitative performance with a utility degree of 100%. MARUEI Viet Nam Precision Company Limited (Supplier 01), with a utility degree of 98.28%, ranks second, and GDC Viet Nam Joint Stock Company (Supplier 03) ranks third with a utility degree of 94.49%. Meanwhile, Dac Yen Company Limited (Supplier 05) has the lowest qualitative performance with a utility degree of 75.77%.

Table 12. The evaluation of the utility degree of G-COPRAS.

Suppliers	P_h	R_h	Q_h	N_h (%)	Ranking
Supplier 01	0.192	0.028	0.220	98.28	2
Supplier 02	0.190	0.023	0.224	100	1
Supplier 03	0.186	0.031	0.212	94.49	3
Supplier 04	0.145	0.028	0.174	77.45	4
Supplier 05	0.145	0.032	0.170	75.77	5

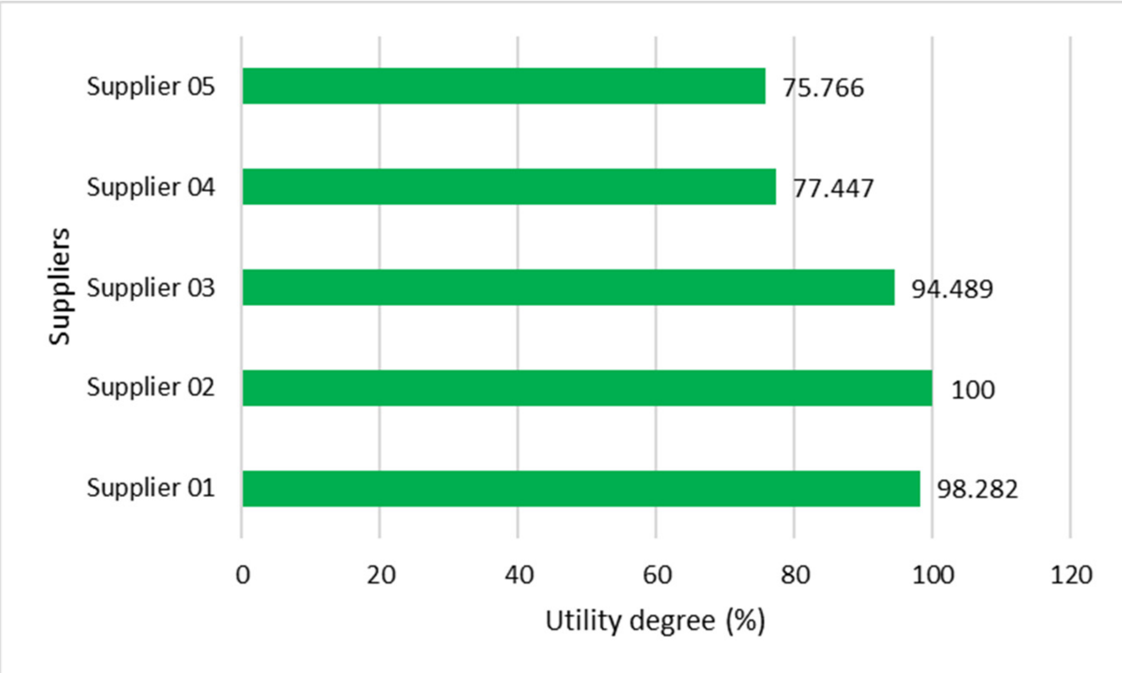

Figure 4. Final ranking of suppliers.

5. Sensitivity Analysis

A sensitivity analysis of criteria in the decision-making process is conducted to observe the consequences of the weights of criteria. In this section, the top five most influential criteria are selected to fluctuate their weights from ±10%, ±30%, and ±50% [83–85], which are (a) C32. Quality, (b) C43. Use of personal protective equipment, (c) C33. Cost/Price, (d) C13. Safety and health practices and wellbeing of suppliers, and (e) C42. Economic recovery programs. In this situation, there will be 30 sensitivity analysis possibilities in all. Figure 5 shows that the suppliers' final ranking results are relatively stable. THACO Parts (Supplier 02) and MARUEI Viet Nam Precision Company Limited (Supplier 01) are ranked first and second on 10%, 30%, and 50% more weight and 10%, 30%, and 50% less weight than the base case, respectively. In general, the curve was rather smooth, indicating that the proposed MCDM (SF-AHP and G-COPRAS) ranking result was stable and appropriate. This study effectively presented an integrated fuzzy multi-criteria decision-making model by integrating SF-AHP and G-COPRAS to aid the decision-making process, and to assess and select sustainable supplier selection, especially in the current pandemic, using a case study in the automotive sector.

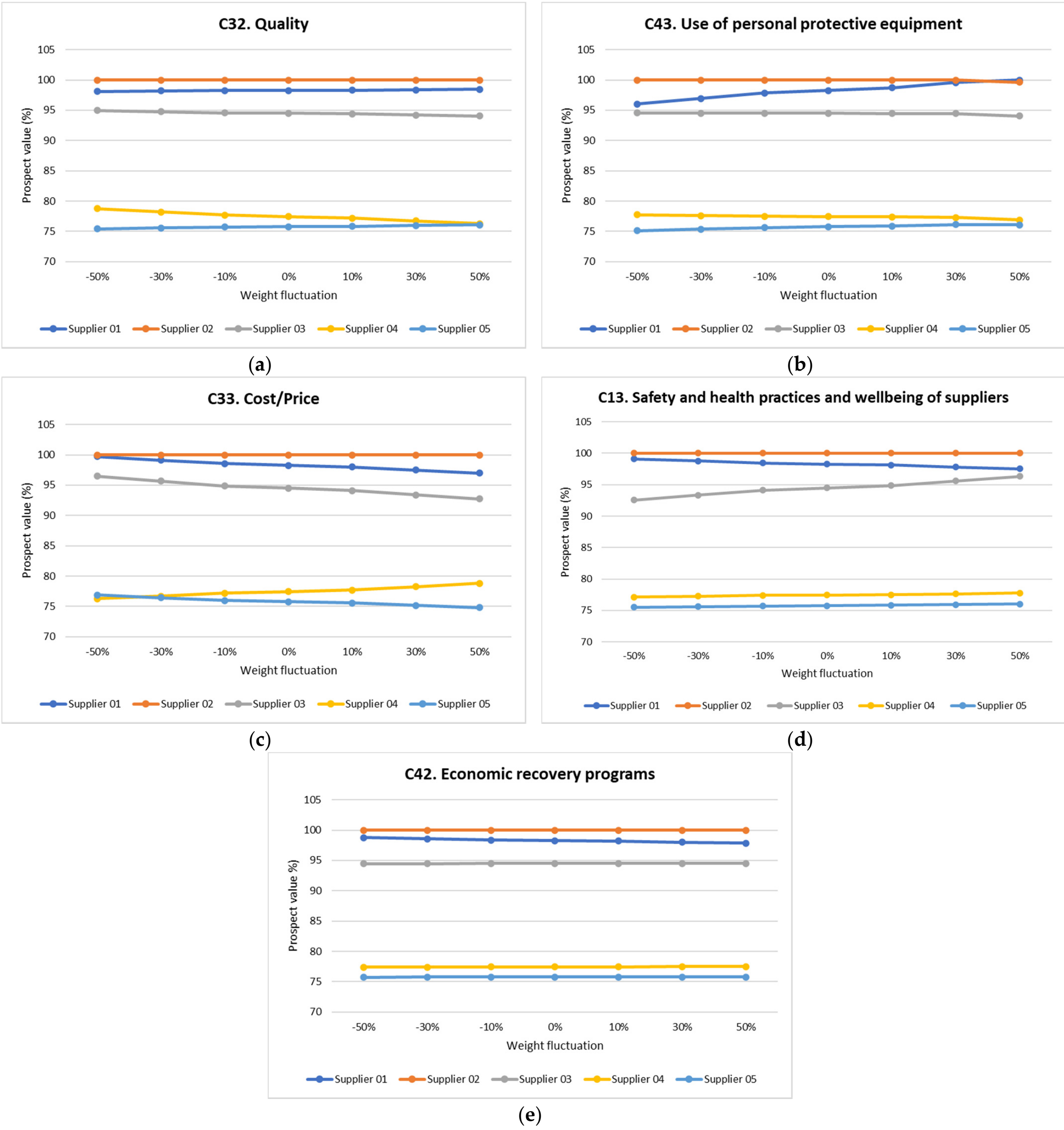

Figure 5. Sensitivity analysis of criteria (**a**) C32. Quality, (**b**) C43. Use of personal protective equipment, (**c**) C33. Cost/Price, (**d**) C13. Safety and health practices and wellbeing of suppliers, (**e**) C42. Economic recovery programs.

6. Managerial Implications

A methodology for SSS with a focus on sustainable development and the COVID-19 pandemic response measures has been developed in the proposed case study. Business owners and managers can use the recommended framework to evaluate their suppliers in any sort of supply chain. The findings of this study supported prior studies on the pandemic's influence on supply chains by emphasizing the relevance of COVID-19 pandemic response methods in SSS in the industrial sector. Finally, the findings reveal that, in order to achieve long-term development and improved competitiveness, manufacturing businesses must prioritize the integration of reaction mechanisms during SSS implementation in the COVID-19 pandemic age. This will result in considerable cost and resource savings, as well as decreased environmental consequences and a long-term supply chain, independent of the crisis.

In this study, all considered factors will assist businesses in the automotive industry, especially in the context of Vietnam, in dealing with various challenges and improving their efforts to develop environmentally friendly products. Developing SSS evaluation criteria based on industry experts' responses and literature is also a significant benefit of this proposed work. Managers and practitioners will be able to test the observation stability using the applied sensitivity analysis.

7. Conclusions

It is highly unpredictable what would happen next in the immediate aftermath of the global disaster created by the COVID-19 outbreak. Businesses, on the other hand, can limit potential consequences by implementing robust supply chain operations and recovery-ready plans. A thorough knowledge of COVID-19's effects on global supply networks is critical to disaster mitigation and management efficiency. The pandemic forces businesses to rethink their supply networks in order to be more efficient and agile in the case of a crisis. A set of contingency-based continuity plans is provided to help companies better mitigate risk by emphasizing responsiveness to disruptions in complex supply chains. This paper establishes an effective SSS method with prominence on the COVID-19 pandemic impacts for an emerging country. After examining the literature and engaging industry experts, the assessment criteria system was created. The suggested method allows SF-AHP to determine the weights of the assessment criteria and subsequently G-COPRAS to rank the alternatives. To test the applicability of the proposed model, a case study in the Vietnamese automotive market was undertaken. "Quality," "usage of personal protective equipment," "cost/price," "safety and health practices and supplier well-being," and "economic recovery programs" are the evaluation factors with the highest weight priority in the study. THACO Parts (Supplier 02) was the best supplier among the alternatives, according to the final rating. To evaluate the model's resilience, a sensitivity analysis was performed, with the findings demonstrating that the applied approaches achieve common SSS ranks. This demonstrates that the proposed method is practical in nature.

The following are the key accomplishments and contributions of this study. First, using a case study in the automobile sector that has never been documented in the current literature, this study is the first attempt to identify possible sustainable suppliers for businesses in the situation of Vietnam. A thorough set of criteria, including economic, social, and environmental sustainability features, as well as COVID-19 pandemic response tactics, is developed for evaluating the alternatives by literature analysis and expert perspectives, which is a key benefit of this work. Methodologically, for the first time, the combination of SF-AHP and G-COPRAS is presented to address the SSS problem, which has been identified as a relevant and effective techniques for the SSS problem. All of the evaluation metrics and expert measurements provided for management implications in this study can serve as a foundation for managers and decision-makers in any sort of organization to make educated judgments. Managers of enterprises may use our technique and the generated data to identify the suitable supplier for their firm once a case study in Vietnam has been completed. This will save substantial resources and expenses while allowing the present epidemic or any future crises to be dealt with properly. The model suggested can potentially be used in other countries and businesses.

For future research, by including unique and brand-new criteria, particularly those related to the present crisis (COVID-19), the suggested method in this study can also handle the dynamic and unpredictable environment. Besides, the present study could be applied to different areas to see if the findings are generalizable. Other MCDM methods (VIKOR, MABAC, WASPAS, MULTIMOORA, etc.) could be applied to the SSS problem in future research.

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Appendix A

Table A1. The integrated spherical fuzzy comparison matrix of SF-AHP.

Criteria	C11			C12			C13			C21			C22		
	α	β	γ	α	β	γ	α	β	γ	α	β	γ	α	β	γ
C11	0.500	0.400	0.400	0.485	0.498	0.314	0.517	0.464	0.315	0.507	0.471	0.321	0.493	0.482	0.336
C12	0.450	0.525	0.318	0.500	0.400	0.400	0.455	0.531	0.314	0.449	0.549	0.285	0.519	0.467	0.310
C13	0.414	0.565	0.307	0.493	0.484	0.413	0.500	0.400	0.400	0.608	0.373	0.297	0.470	0.532	0.279
C21	0.433	0.541	0.321	0.484	0.508	0.146	0.338	0.649	0.269	0.500	0.400	0.400	0.493	0.482	0.336
C22	0.458	0.511	0.338	0.425	0.557	0.170	0.395	0.593	0.286	0.458	0.511	0.338	0.500	0.400	0.400
C23	0.512	0.464	0.321	0.517	0.467	0.358	0.410	0.571	0.310	0.493	0.475	0.332	0.508	0.473	0.310
C31	0.517	0.452	0.327	0.367	0.620	0.142	0.488	0.479	0.336	0.512	0.470	0.308	0.493	0.475	0.332
C32	0.512	0.470	0.308	0.517	0.452	0.327	0.475	0.494	0.336	0.556	0.417	0.315	0.583	0.409	0.287
C33	0.406	0.580	0.293	0.508	0.481	0.480	0.578	0.405	0.297	0.527	0.462	0.297	0.475	0.514	0.303
C34	0.425	0.550	0.314	0.454	0.522	0.197	0.354	0.631	0.282	0.354	0.626	0.289	0.354	0.626	0.289
C35	0.323	0.676	0.248	0.450	0.547	0.154	0.347	0.650	0.255	0.320	0.659	0.281	0.302	0.688	0.243
C41	0.425	0.557	0.306	0.421	0.572	0.212	0.458	0.534	0.291	0.458	0.511	0.338	0.476	0.505	0.314
C42	0.552	0.432	0.304	0.458	0.511	0.342	0.373	0.613	0.283	0.531	0.446	0.319	0.437	0.563	0.272
C43	0.551	0.420	0.317	0.532	0.453	0.449	0.542	0.445	0.302	0.541	0.447	0.305	0.556	0.427	0.306
C44	0.296	0.706	0.215	0.433	0.534	0.301	0.316	0.684	0.235	0.338	0.647	0.276	0.308	0.676	0.262

Criteria	C23			C31			C32			C33			C34		
C11	0.435	0.553	0.307	0.418	0.567	0.306	0.419	0.573	0.289	0.529	0.459	0.304	0.513	0.467	0.317
C12	0.408	0.586	0.282	0.569	0.418	0.296	0.418	0.567	0.306	0.436	0.559	0.290	0.472	0.515	0.306
C13	0.544	0.438	0.318	0.458	0.521	0.327	0.471	0.508	0.328	0.373	0.621	0.273	0.596	0.383	0.304
C21	0.450	0.531	0.321	0.419	0.573	0.289	0.354	0.639	0.271	0.416	0.579	0.283	0.589	0.383	0.312
C22	0.431	0.559	0.296	0.450	0.531	0.321	0.340	0.661	0.246	0.470	0.524	0.300	0.589	0.383	0.312
C23	0.500	0.400	0.400	0.479	0.518	0.288	0.396	0.595	0.286	0.469	0.517	0.318	0.589	0.383	0.312
C31	0.458	0.534	0.291	0.500	0.400	0.400	0.407	0.582	0.293	0.503	0.479	0.310	0.619	0.356	0.298
C32	0.542	0.436	0.311	0.537	0.439	0.313	0.500	0.400	0.400	0.632	0.360	0.279	0.643	0.360	0.257
C33	0.479	0.499	0.321	0.429	0.547	0.310	0.308	0.687	0.242	0.500	0.400	0.400	0.580	0.403	0.304
C34	0.354	0.626	0.289	0.338	0.647	0.276	0.325	0.675	0.235	0.363	0.622	0.283	0.500	0.400	0.400
C35	0.347	0.645	0.262	0.512	0.446	0.337	0.294	0.701	0.230	0.288	0.712	0.216	0.410	0.571	0.310
C41	0.458	0.534	0.291	0.458	0.511	0.338	0.425	0.550	0.314	0.381	0.594	0.309	0.414	0.568	0.306
C42	0.507	0.483	0.304	0.446	0.532	0.307	0.373	0.611	0.289	0.458	0.511	0.338	0.532	0.444	0.317
C43	0.578	0.411	0.288	0.532	0.444	0.317	0.551	0.440	0.300	0.493	0.475	0.332	0.517	0.452	0.327
C44	0.357	0.640	0.262	0.338	0.647	0.276	0.328	0.670	0.238	0.302	0.700	0.222	0.360	0.632	0.265

Criteria	C35			C41			C42			C43			C44		
C11	0.628	0.371	0.278	0.519	0.467	0.310	0.401	0.592	0.287	0.364	0.628	0.278	0.661	0.347	0.246
C12	0.470	0.532	0.279	0.511	0.487	0.289	0.493	0.482	0.336	0.420	0.573	0.293	0.501	0.471	0.328
C13	0.606	0.393	0.280	0.479	0.518	0.288	0.565	0.421	0.305	0.401	0.595	0.280	0.623	0.381	0.271
C21	0.608	0.355	0.317	0.493	0.482	0.336	0.412	0.578	0.300	0.398	0.599	0.280	0.619	0.356	0.298
C22	0.631	0.353	0.283	0.464	0.526	0.304	0.476	0.528	0.280	0.358	0.639	0.265	0.628	0.342	0.299
C23	0.599	0.393	0.289	0.479	0.518	0.288	0.433	0.564	0.290	0.356	0.642	0.253	0.601	0.397	0.283
C31	0.424	0.553	0.319	0.493	0.482	0.336	0.480	0.505	0.303	0.415	0.573	0.300	0.619	0.356	0.298
C32	0.644	0.349	0.270	0.513	0.467	0.317	0.575	0.406	0.307	0.373	0.628	0.265	0.587	0.416	0.273
C33	0.679	0.323	0.244	0.573	0.397	0.321	0.493	0.482	0.336	0.450	0.531	0.321	0.654	0.353	0.253
C34	0.544	0.438	0.318	0.533	0.451	0.310	0.415	0.573	0.300	0.418	0.567	0.306	0.582	0.413	0.283
C35	0.500	0.400	0.400	0.410	0.573	0.306	0.476	0.504	0.324	0.419	0.570	0.296	0.593	0.397	0.291
C41	0.532	0.434	0.325	0.500	0.400	0.400	0.431	0.558	0.307	0.407	0.582	0.293	0.602	0.377	0.299
C42	0.466	0.505	0.329	0.511	0.466	0.323	0.500	0.400	0.400	0.571	0.393	0.326	0.659	0.342	0.254
C43	0.521	0.457	0.310	0.537	0.439	0.313	0.370	0.601	0.309	0.500	0.400	0.400	0.623	0.371	0.276
C44	0.357	0.635	0.269	0.347	0.638	0.276	0.288	0.710	0.216	0.340	0.655	0.255	0.500	0.400	0.400

Table A2. The normalized grey decision matrix of G-COPRAS.

Criteria	**C11**		**C12**		**C13**		**C21**		**C22**	
Suppliers	$\underline{x}$	$\overline{x}$	$\underline{x}$	$\overline{x}$	$\underline{x}$	$\overline{x}$	$\underline{x}$	$\overline{x}$	$\underline{x}$	$\overline{x}$
Supplier 01	0.160	0.217	0.122	0.184	0.111	0.187	0.181	0.263	0.241	0.305
Supplier 02	0.169	0.230	0.181	0.233	0.160	0.240	0.111	0.198	0.229	0.299
Supplier 03	0.208	0.268	0.220	0.289	0.263	0.351	0.222	0.288	0.192	0.268
Supplier 04	0.208	0.272	0.207	0.256	0.134	0.218	0.169	0.251	0.076	0.134
Supplier 05	0.102	0.166	0.125	0.184	0.134	0.202	0.119	0.198	0.101	0.155
Suppliers	**C23**		**C31**		**C32**		**C33**		**C34**	
Supplier 01	0.150	0.204	0.212	0.274	0.218	0.272	0.185	0.244	0.189	0.247
Supplier 02	0.159	0.213	0.259	0.322	0.210	0.269	0.118	0.168	0.196	0.254
Supplier 03	0.142	0.193	0.167	0.224	0.174	0.228	0.238	0.297	0.199	0.252
Supplier 04	0.255	0.326	0.113	0.167	0.091	0.137	0.081	0.134	0.083	0.128
Supplier 05	0.153	0.204	0.104	0.158	0.174	0.228	0.238	0.297	0.199	0.252
Suppliers	**C35**		**C41**		**C42**		**C43**		**C44**	
Supplier 01	0.200	0.259	0.225	0.293	0.168	0.225	0.284	0.354	0.171	0.224
Supplier 02	0.203	0.263	0.216	0.283	0.196	0.262	0.166	0.216	0.158	0.221
Supplier 03	0.131	0.181	0.155	0.209	0.182	0.253	0.151	0.203	0.133	0.179
Supplier 04	0.209	0.278	0.126	0.187	0.156	0.208	0.102	0.160	0.156	0.211
Supplier 05	0.113	0.163	0.122	0.184	0.151	0.199	0.154	0.210	0.244	0.302

Table A3. The weighted normalized grey decision matrix of G-COPRAS.

Criteria	**C11**		**C12**		**C13**		**C21**		**C22**	
Suppliers	$\underline{x}$	$\overline{x}$	$\underline{x}$	$\overline{x}$	$\underline{x}$	$\overline{x}$	$\underline{x}$	$\overline{x}$	$\underline{x}$	$\overline{x}$
Supplier 01	0.011	0.015	0.008	0.012	0.008	0.013	0.012	0.017	0.016	0.020
Supplier 02	0.012	0.016	0.012	0.015	0.011	0.017	0.007	0.013	0.015	0.020
Supplier 03	0.014	0.019	0.014	0.019	0.019	0.025	0.015	0.019	0.013	0.018
Supplier 04	0.014	0.019	0.014	0.017	0.010	0.016	0.011	0.017	0.005	0.009
Supplier 05	0.007	0.012	0.008	0.012	0.010	0.014	0.008	0.013	0.007	0.010
Suppliers	**C23**		**C31**		**C32**		**C33**		**C34**	
Supplier 01	0.010	0.014	0.014	0.019	0.017	0.021	0.013	0.018	0.011	0.015
Supplier 02	0.011	0.015	0.018	0.022	0.016	0.021	0.009	0.012	0.012	0.015
Supplier 03	0.010	0.013	0.011	0.015	0.013	0.018	0.017	0.022	0.012	0.015
Supplier 04	0.018	0.022	0.008	0.011	0.007	0.011	0.006	0.010	0.005	0.008
Supplier 05	0.011	0.014	0.007	0.011	0.013	0.018	0.017	0.022	0.012	0.015
Suppliers	**C35**		**C41**		**C42**		**C43**		**C44**	
Supplier 01	0.011	0.015	0.014	0.019	0.012	0.016	0.021	0.026	0.008	0.011
Supplier 02	0.012	0.015	0.014	0.018	0.014	0.018	0.012	0.016	0.008	0.011
Supplier 03	0.007	0.010	0.010	0.013	0.013	0.018	0.011	0.015	0.006	0.009
Supplier 04	0.012	0.016	0.008	0.012	0.011	0.015	0.008	0.012	0.008	0.010
Supplier 05	0.006	0.009	0.008	0.012	0.011	0.014	0.011	0.016	0.012	0.015

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