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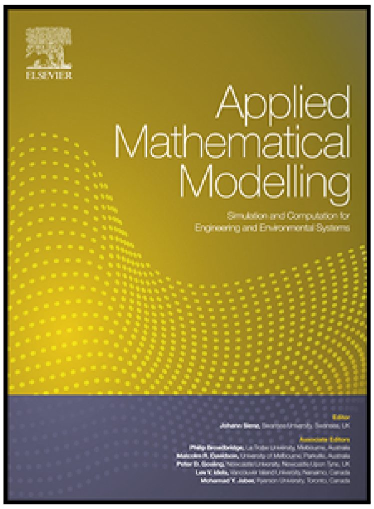


# An Evaluation of the Environmental Factors for Supply Chain Strategy Decisions Using Grey Systems and Composite Indicators

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**Highlights**

- Environmental factors condition supply chain strategy
- Environment factors must be prioritized to analyze their impact on the supply chain
- Composite Indicator with an uncertainty analysis have more strength than the GST

**Title**:

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## Abstract

The purpose of this work is to assess the importance of environmental factors in a supply chain with four partners as a preliminary step to select the competitive strategies and objectives. To achieve this purpose, a real case study was carried out in a footwear supply chain, in which two approaches were used: the grey system theory and uncertainty analysis tools for composite indicators. In order to validate both approaches, a seven-phase research methodology was developed and applied to our case study. In addition, the priorization of environmental factors was calculated individually for each partner. The results allow managers to establish the competitive strategy that best suits the prioritization of the most relevant factors and to define the most appropriate objectives where the supply chain should invest its efforts and resources.

## Key Words

grey system theory; composite indicator; supply chain; environmental factors; environmental uncertainty;

## 1. Introduction

Highly competitive products and services do not usually depend exclusively on the company that manufactures them, but on all the companies that collaborate in making the final product or service available to customers [1]. Nowadays, many factors make companies' decision-making highly dynamic and complex (the life cycle of products/services is getting shorter and shorter, which leads to new products/services constantly being launched; changing processes that require rapid adaptation; partners coming and going; various customer preferences; modification of distribution channels; acceleration of technological obsolescence; globalization; government regulations; etc.). For Stonebraker and Liao [2], the level of environmental turbulence and the strategic orientation of a firm have a direct positive impact on the degree, stages, and breadth of supply chain (SC) integration.

Accordingly, Lalmazloumian and Yew [3] reported how the intricate nature of SC networks, the changing and complex environment, and the dynamic relationships between the different sectors that comprise a SC mean that a certain degree of uncertainty in their management and planning is inevitable, which must be dealt with in the best possible way. This uncertainty is known as environmental uncertainty, which Miles and Snow [4] defined as "the predictability of conditions in the organization's environment." Later, Milliken [5] defined environmental uncertainty as "an individual's perceived inability to predict something accurately" and identified three types of perceived uncertainty about the environment: (a) state uncertainty – the inability to predict the future state of the environment; (b) effect uncertainty – the decision-makers' inability to predict how environmental changes will impact their organizations; and (c) response uncertainty – the managers' inability to identify potential organizational actions and their outcomes. Although much progress has been made to address the uncertainty problem in SCs, it is still one of the most important problems and a main challenge [6]. This major research task has become urgent in our current world [7].

In a supply chain, each partner has their own perception of the environmental factors that can affect it. However, when you want to manage the SC as a global entity, you have to think about those factors that have an influence on this global entity, even knowing that not all factors affect all SC partners with the same intensity. This situation creates a need to prioritize the factors from a SC point of view. Thus, in order to establish the strategy and objectives that will help the SC to compete, the weight of the factors prioritized by consensus will have to be taken into account. This shared vision enhances trust and equity among the partners of the SC. For all these reasons, having an all-round vision of the SC is vital to tackle all its problems globally. In this context, it is customary to redefine strategies and objectives that guide all SC partners toward common goals so that all efforts converge equitably in the search for the best overall performance. In the sector chosen to develop the case study of this work (the footwear industry), as in other sectors, competitiveness is very high, and uncertainty factors have a great influence.

The objective of this paper is to assess the importance of environmental factors in a SC context as a preliminary step to select its competitive strategies and objectives. A case study carried out in a footwear SC is outlined. As the assessment of factors uses the judgments of a group of managers who represent all the companies that make up the SC, two approaches were chosen that take into account the degree of uncertainty of value judgments. First, the Grey System Theory (GST) is proposed as a quantitative method to address subjectivity in managers' judgments. Second, the construction of a composite indicator (CI) is proposed to obtain a ranking of the importance of environmental factors by considering the degree of uncertainty of a group of managers' opinions.

These two approaches are part of a methodology that provides three main contributions: a) it is a universal methodology that can be used in any SC, regardless of the number of partners, the sector in which it operates and the environmental factors analyzed; b) it provides the managers with relevant information to set the competitive strategy of the SC in such a way that it is aligned with the most important factors; c) it helps to compare the convergence of the prioritized factors at the SC level in relation to the factors prioritized at the individual level by each partner.

This paper is organized as follows: Section 2 describes the background on the uncertainty of environmental factors, decision-making and the GST. Section 3 deals with the research methodology. Section 4 addresses the case study description. Finally, Section 5 presents the conclusions.

## 2. Background

### 2.1. Uncertainty of environmental factors

Given the changing and dynamic environment in which companies currently operate, and therefore the SC that they form part of, it is necessary to point out the uncertainty inherent in the many environmental factors that affect the decision-making process as far as possible. MacCarthy et al. [8] have identified six factors that affect SC evolution (technology and innovation; policy and regulation; markets and competition; economics; procurement and sourcing; and supply chain strategies and re-engineering). In this line, Simangunsong et al. [6] presented an empirical study to investigate the effective management of SC uncertainty in the Indonesian food industry. This study uses a previous conceptual model that identifies a set of sources of uncertainty and their associated uncertainty management strategies [9]. After the study, they proposed that “the management strategies that aim to reduce an uncertainty at its source lead to better overall supply chain performance than strategies that merely cope with uncertainty, which only have an impact on firm-level performance.”

Many decisions to be made both individually and collectively are done so in an uncertainty context given either the nature of the information used in the decision-making process (partial, incomplete, obsolete information, etc.) or the uncertain nature of the factors that affect or will be affected by the decisions made. These factors may come from the microenvironment, which is made up of competitors, customers, suppliers, potential incomers, substitute products and providers of complementary products [10], or from the macroenvironment, which is made up of the political, economic, ecological, societal and technological landscapes (PEEST) that surround the business microenvironment [11]. At this point, it is also interesting to differentiate between the factors that create uncertainty by affecting individuals (particularly SC partners) and those that affect them in such a way that they create collective uncertainty. A complete definition of collective uncertainty is provided by De Vasconcelos Gomes et al. [12]: "collective uncertainty refers to situations in which the actors encounter difficulties with predicting a relevant business aspect, such as the number of partners affected by a specific uncertainty, how a given uncertainty affects the performance of these partners and how the partners perceive and conceive (make sense) of an uncertainty." For these authors, one particular uncertainty can become a collective uncertainty due to uncertainty propagation. All this further increases the complexity of the decision-making process. Flynn et al. [13] differentiated between three key types of supply chain uncertainty (micro-, meso- and macro-level). Each of these types of uncertainty has specific characteristics, but they all coexist in a supply chain and may interact with each other. Micro-level and meso-level uncertainty are positively related to SC integration, nevertheless macro-level uncertainty is inversely related to it.

The uncertainty generated in the SC by micro- and macroenvironmental factors reflects the impossibility of reasonably predicting how performance will evolve at both the individual and SC levels. When managers cannot predict the business environment because sufficient information is lacking, it can be understood as perceived environmental uncertainty [14]. This environmental uncertainty creates high co-ordination costs and transaction risks [15], which obliges companies to make changes (organizational, structural, strategic, etc.) that allow them to quickly adapt to the circumstances imposed by this environment [16, 17]. When the degree of uncertainty is high, it generates more dynamism in companies, which is not easy to manage. On this aspect, Lee [18] highlighted the need for supply chains to develop strategies for coping with environmental turbulence. The flexibility strategies that supply chain participants adopt in response to various perceived environmental uncertainties is a very important factor [19]. Lonbani [17] talked about implementing a formal well-controlled and well-sustained environmental scanning system.

The purpose of attempting to point out and/or reduce environmental uncertainty in the SC is to acquire more and better information and to make it more solid to improve the decision-making process through more reliable, effective and efficient performance management systems. Some years ago, Boyle et al. [20] highlighted the tendency of supply chain researchers to neglect the state of the supply chain environment as a factor affecting supply chain efficacy. For Agami et al. [21], "today's supply chain performance measurement systems are still too inward looking as they ignore the external environmental factors that might affect overall future SC performance when setting new targets." The environment can influence management control since both are closely related [22]. For Otley [7], what is surprising today is that most of our planning and control devices seem to function as if uncertainty does not exist.

The approaches adopted in the literature to deal with environmental uncertainty in SCs assume a more or less solid and uniform structure. However, the set of companies that make up a SC have business models which, if viewed independently, often differ by having management structures, technologies, procedures and processes that have nothing to do with one another. This means that the uncertainty from the environment unequally affects each company in the SC, which can have very serious implications. The problem is that studies on uncertainty at the network level do not focus on managing the uncertainties that affect the network [23]. For Huang et al. [24] “environmental uncertainty is multidimensional in nature and supply chain integration facilitates the transfer of complex knowledge and sensitive information among partners, and thereby contributes to overcoming the impact of technological uncertainty.” Indeed excess, absence and/or lack of information for decision-making is usually the case, which makes the definition, measurement and management of the objectives and competitive strategies difficult. In order to define a competitive strategy, the uncertainty associated with information from the environment must be taken into account. With a conceptual map, Widyaningdyah et al. [25] have described the relationship that links the perceived uncertainty of the business environment, the use of performance measurement systems and the competitive advantage.

Uncertainty can be dealt with from several perspectives. One of the most traditional ones pertains to strategic management and distinguishes between planning and adaptation approaches [26, 27]. On the other hand, causation and effectuation are two fundamental strategic decision-making logics that firms use to form strategies to cope with uncertainty [28]. In the study conducted by Yu et al. [29] to explore the effects of causation and effectuation on firm performance in emerging economies, the authors found that firms should adopt causation as a priority in a less uncertainty environment and should combine causation and effectuation in a more uncertain environment. According to Vecchiato [11], no matter what kinds of uncertainty there are, the main contribution that foresight efforts bring to strategy formulation lies not in predicting the future (i.e., in the predictions themselves that represent the outputs of foresight) but in preparing the managers of the organization to handle the future.

### 2.2. Decision-making and the Grey System Theory

Facilitating decisions under uncertainty conditions requires making a choice about how this uncertainty should be modeled [30]. These authors identify different tools that can be used to represent uncertain evaluations. The decision-making process carried out in any type of organization often requires subjective and qualitative judgments based on incomplete or imprecise information that cannot be easily turned into probability values. Such judgments give rise to different uncertainty types, which include fuzziness, epistemic uncertainty, ignorance and imprecision. According to [31], the four most recognized research methods employed for the investigation of uncertain systems are: probability and statistics, fuzzy mathematics, grey systems theory and rough set theory. Table 1 shows a comparison between these models [31].

| | **Probability and statistics** | **Fuzzy math** | **Grey systems** | **Rough sets** |
|---|---|---|---|---|
| *Research objects* | Stochastics | Cognitive uncertainty | Poor information | Indiscernibility |
| *Basic sets* | Cantor sets | Fuzzy sets | Grey sets | Approximation sets |
| *Procedures* | Frequency distribution | Cut set | Sequence operator | Lower and upper approximation |
| *Data requirement* | Typical distribution | Membership known | Any distribution | Equivalent relations |
| *Objective* | Historical laws | Cognitive expression | Laws of reality | Concept approximation |
| *Characteristics* | Large sample | Experience | Small sample | Information systems (tables) |

Table 1: Comparison of the different uncertainty models. Simplified from [31]

In particular, fuzzy logic is a good technique when uncertainty can be described by discrete/continuous membership functions validated by experts. When problems are solved using probability and statistics, the relevant distribution function must be known, or a high volume of samples must be available in order to achieve the required validity [32]. However, these premises cannot always be fully met, which is when other techniques must be used, e.g. the GST, which is considered to be a multiple-attribute decision-making technique. Among the advantages that GST offers is to tackle flexibly with the fuzziness situation [33, 34]. Furthermore, grey systems do not need previous information because they work with objective data, while fuzzy mathematics holds certain prior information, usually based on experience [35].

Considering that the purpose of this work is to assess the importance of environmental factors in a supply chain, the intention is to prioritize these factors based on the opinion of managers belonging to the CS in uncertain conditions. Multi-criteria decision-making (MCDM) approaches have been widely used in this typology of problems. Some of the most used approaches are: FAHP (Fuzzy Analytic Hierarchy Process), FANP (Fuzzy Analytic Network Process), FTOPSIS (Fuzzy Technique for Order of Preference by Similarity to Ideal Solution) and GST (Grey System Theory). Although other hybrid methods [36] have also been developed in recent years (AHP+TOPSIS-Grey; FANP+TOPSIS; VIKOR+GRA; etc.), they have not yet been tested in a wide variety of problems. Table 2 shows a comparison between the different MCDM approaches [30, 37, 38], including the proposal of this work (GST-CI).

| | **Process needs** | **Information gathering** | **Validation of process consistency** |
|---|---|---|---|
| **FAHP** | Requires hierarchy between components<br>Requires paired comparisons of criteria and alternatives | Long and complex process | Compliance with the RI consistency ratio |
| **FANP** | Requires paired comparisons of criteria and alternatives | Long, complex and tedious process | Needs the calculation of interdependence of the criteria |
| **FTOPSIS** | It only requires the preferences of each alternative with respect to each sub-criterion and the preferences of each sub-criterion | Not a long process, slightly complex and not very tedious | Does not have a standardized consistency check measure |
| **GST** | Does not require paired comparisons of criteria and alternatives | Simple, short and slightly tedious process | Does not need consistency check |
| **GST-CI** | Does not require paired comparisons of criteria and alternatives<br>Define a probability distribution function to assign uncertainty to the criteria weights in the CI methodology | Simple, short and slightly tedious process<br>The CI part is a bit more tedious because of the simulations of different scenarios and the computation of the alternatives' rankings in each scenario. However, it contributes to having more robust results. | Does not need consistency check |

Table 2: Comparison of the different MCDM approaches.

Among the most important characteristics that drive the use of the GST-CI approach are the following: a) Information gathering is a simple, short and slightly tedious process, and only the CI part is a bit more tedious due to the simulations of different scenarios. However, this contributes to having more robust results; b) It does not need a consistency check; c) It does not require paired comparisons of criteria and alternatives. It is necessary to define a probability distribution function to assign uncertainty to the criteria weights in the CI methodology.

Although GST is relatively new and was developed by Deng [39], it has been widely used to solve very diverse problems, where the information obtained by decision-makers or researchers may be partially unknown, uncertain or incomplete [40]. This situation is common in most real systems (economic, social, biological, etc.). Some papers historically reviewed the application of this technique in recent decades [41, 42] and have demonstrated its practical usefulness in many areas (Engineering, Operations Research Management Science, Business Economics, Environmental Sciences Ecology, Mechanics, Mathematics, Materials Science, etc.). Current grey system applications can be classified as evaluation, modeling, prediction, decision-making and control [32]. Dong et al. [43] attempted to introduce a new approach to solve multicriteria decision-making problems under uncertain conditions based on the concept of grey possibility degree and linguistic variables. This technique helps conduct what-if analyses. Wei et al. [44] have used a method based on grey theory to improve the understanding of work-related accidents and to analyze the dynamic and future situation of work safety in mainland China. Rajesh et al. [45] used an approach combining grey theory and digraph-matrix methodologies for quantifying various supply chain risk mitigation strategies. Kaviani et al. [46] presented a method to measure SC resilience based on a GST approach. Jahantigh et al. [32] developed an integrated approach to prioritize strategic objectives under uncertainty using the balanced scorecard as a reference framework. They combined two methods: focus group interviews as the qualitative method and the GST as the quantitative method. Huang et al. [47] proposed a new method of using the grey system theory to account for uncertainties in a project’s start time, completion time, transportation time, as well as cost.

## 3. Research methodology

The followed process comprised these phases:

A. Selecting the SC
B. Creating a working group made up of representatives from each SC component
C. Determining the importance of factor typologies (criteria weights)
D. Selecting the environmental factors that affect the SC and their assessment for each criterion
E. Assessing environmental factors via the GST
F. Assessing environmental factors via a composite indicator with an uncertainty analysis
G. Determining the ranking of the main environmental factors for each SC partner

The methodologies involved in phases C, D, E, F and G are further described below.

### 3.1. Evaluating environmental factors by the GST

In this work, the approach of Jahantigh et al. [32] based on the GST was adapted to obtain a final classification of environmental factors according to their importance.

In the GST, the uncertainty of numerical parameters can be represented using grey numbers. A grey number can be viewed as an interval of values $[\underline{a}, \overline{a}]$, with $\underline{a} < \overline{a}$, meaning that the value of a given numerical parameter is considered to be bound between $\underline{a}$ and $\overline{a}$. In other words, a grey number is not an interval, but an indeterminate number represented by an interval [58].

Grey numbers are usually denoted by prefixing or suffixing the symbol ⊗ to them (or by just this symbol alone), to distinguish them from 'white' numbers (i.e., usual numbers that represent information with no uncertainty). Grey numbers can also be operated by following some stated arithmetical rules (for instance, [48]).

In this study, grey numbers were used to model the uncertainty regarding the qualitative assessments of both the relative importance of the criteria being considered (phase C of the above procedure) and the environmental factors with regards to these criteria (phase D of the above procedure) made by decision-makers. To be precise, this notation was followed:

- $\{V_1, \ldots, V_m\}$ denotes the set of $m$ environmental factors being assessed.
- $\{Q_1, \ldots, Q_n\}$ denotes the set of $n$ typologies or criteria being considered to evaluate environmental factors.
- $\{D_1, \ldots, D_p\}$ denotes the set of $p$ decision-makers or experts that evaluate the criteria and environmental factors.
- $\otimes w_j^k = \left[\underline{w_j^k}, \overline{w_j^k}\right]$ is the grey number that represents the weight given to criterion $Q_j$ by decision-maker $D_k$, for $j = 1, \ldots, n$, $k = 1, \ldots, p$.
- $\otimes G_{ij}^k = \left[\underline{G_{ij}^k}, \overline{G_{ij}^k}\right]$ is the grey number that represents the evaluation of the importance of environmental factor $V_i$ regarding criterion $Q_j$ made by decision-maker $D_k$, for $i = 1, \ldots, m$, $j = 1, \ldots, n$, $k = 1, \ldots, p$.

Grey numbers $\otimes w_j^k$ and $\otimes G_{ij}^k$ were obtained by transforming qualitative (i.e., linguistic) evaluations into (grey) numerical information. These grey numbers represent the input data for the evaluation methodology proposed herein.

According to Jahantigh et al. [32], the procedure to be carried out is the following:

Step 1. Determining $\otimes w_1, \ldots, \otimes w_n$, the weight of the $n$ typologies being considered, as:

$$\otimes w_j = \left[\underline{w_j}, \overline{w_j}\right] = \frac{1}{p}\sum_{k=1}^{p} \otimes w_j^k = \left[\frac{1}{p}\sum_{k=1}^{p} \underline{w_j^k}, \frac{1}{p}\sum_{k=1}^{p} \overline{w_j^k}\right], \tag{1}$$

for all $j = 1, \ldots, n$.

Step 2. Calculating the evaluation or rating of each environmental factor with regards to each factor:

$$\otimes G_{ij} = \left[\underline{G_{ij}}, \overline{G_{ij}}\right] = \frac{1}{p}\sum_{k=1}^{p} \otimes G_{ij}^{k} = \left[\frac{1}{p}\sum_{k=1}^{p} \underline{G_{ij}^{k}}, \frac{1}{p}\sum_{k=1}^{p} \overline{G_{ij}^{k}}\right], \quad (2)$$

for all $i = 1, \dots, m$ , $j = 1, \dots, n$.

Step 3. Normalizing the values $\otimes G_{ij}$:

$$\otimes G_{ij}^{*} = \left[\underline{G_{ij}^{*}}, \overline{G_{ij}^{*}}\right] = \left[\frac{\underline{G_{ij}}}{G_j^{\max}}, \frac{\overline{G_{ij}}}{G_j^{\max}}\right], \quad (3)$$

where $G_j^{\max} = \max_i\{\overline{G_{ij}}\}$, for all $i = 1, \dots, m$ , $j = 1, \dots, n$.

(4)

The normalized grey numbers $\otimes G_{ij}^{*}$ are defined so that they are all included within the interval [0,1].

Step 4. Calculating the weighted normalized grey decision matrix $\left[\otimes N_{ij}\right]_{i=1,\dots,m; j=1,\dots,n}$ as follows:

$$\otimes N_{ij} = \left[\underline{N_{ij}}, \overline{N_{ij}}\right] = \otimes G_{ij}^{*} \cdot \otimes w_j = \left[\underline{G_{ij}^{*}} \cdot \underline{w_j}, \overline{G_{ij}^{*}} \cdot \overline{w_j}\right], \quad (5)$$

for all $i = 1, \dots, m$, $j = 1, \dots, n$.

Step 5. Calculating the ideal referential alternative vector $\{\otimes V_1^{\max}, \dots, \otimes V_n^{\max}\}$ as:

$$\otimes V_j^{\max} = \left[\underline{V_j^{\max}}, \overline{V_j^{\max}}\right] = \left[\max_i\left\{\underline{N_{ij}}\right\}, \max_i\{\overline{N_{ij}}\}\right], \quad (6)$$

for each $j = 1, \dots, n$.

Step 6. Calculating the grey possibility degree matrix $\left[p_{ij}\right]_{i=1,\dots,m; j=1,\dots,n}$ as:

$$p_{ij} = \Pr\left(\otimes N_{ij} \le \otimes V_j^{\max}\right) = \frac{\max\left\{0, \overline{V_j^{\max}} - \underline{N_{ij}}\right\} - \max\left\{0, \underline{V_j^{\max}} - \overline{N_{ij}}\right\}}{\left(\overline{N_{ij}} - \underline{N_{ij}}\right) - \left(\overline{V_j^{\max}} - \underline{V_j^{\max}}\right)}, \quad (7)$$

for all $i = 1, \dots, m$, $j = 1, \dots, n$. Note that $p_{ij}$ is not a grey number, but it is a white number that expresses the probability of the grey number $\otimes N_{ij}$ being less than the ideal value $\otimes V_j^{\max}$.

Step 7. Finally, calculating the grey possibility degree for each environmental factor $V_i$ as:

$$p_i = \frac{1}{n}\sum_{j=1}^{n} p_{ij}, \quad (8)$$

for each $i = 1, \ldots, m$. The value $p_i$ measures how the environmental factor $V_i$ compares against an ideal alternative. The smaller the value $p_i$ is, the closer $V_i$ is to being ideal.

Step 8. As a result, the $m$ environmental factors can be ranked according to $p_i$; more precisely, the smaller the value $p_i$, the higher the rank of the environmental factor $V_i$.

### 3.2 Evaluating environmental factors via a composite indicator with an uncertainty analysis

As a way to complement the results offered by the GST, we propose also processing the information produced by the working group using uncertainty analysis tools for composite indicators. Let's introduce what a composite indicator is and the process to apply an uncertainty analysis to it.

A composite indicator (CI) is a mathematical model aggregation of a selected set of suitably weighted indicators [49]. The model takes the following general expression:

$$Y = f(X_1, X_2, \ldots, X_n) = f(\boldsymbol{X}) \tag{9}$$

where $Y$ is the output factor or CI value, and $X_i$ are the input factors or indicators that are aggregated using a weighting scheme.

In this study, the goal of the CI construction is to obtain a ranking of the environmental factors by regarding the uncertainty of decision-makers' opinions. The model expression considered in the case study is as follows:

$$Y_i = w_1 X_{i1} + w_2 X_{i2} + w_3 X_{i3} + w_4 X_{i4} + \cdots w_n X_{in} \tag{10}$$

where

$Y_i$ is the CI value for each environmental factor $i$ ($i = 1, \ldots, m$);

$w_j$ is the weight given to criterion $j$ ($j = 1, \ldots, n$); and

$X_{ij}$ is the evaluation of the importance of environmental factor $i$ regarding criterion $j$ made by all the decision-makers $k$ ($k = 1, \ldots, p$). The importance $X_{ij}$ is defined as:

$$X_{ij} = \sum_{k=1}^{p} \frac{\underline{G}_{ij}^{k} + \overline{G}_{ij}^{k}}{2} \tag{11}$$

where $\underline{G}_{ij}^k$ and $\overline{G}_{ij}^k$ are defined in Section 3.1.

The CI is constructed using linear aggregation by assuming that the values of the indicators $X_{ij}$ can be compensated among themselves to obtain the CI value for each environmental factor.

The most debated problem in constructing composite indicators is the difficulty in properly evaluating the plurality of perspectives and opinions about the relative importance of the indicators. For this reason, the construction of composite indicators should be accompanied by an uncertainty analysis, used as a tool for the quality assessment and robustness of composite indicators to ensure good practices. An uncertainty analysis focuses on how the uncertainty in the factors that affect CI construction propagates through the CI structure and affects the CI value. In this study, evaluating the weight given to each criterion, $w_j$, is considered a factor of uncertainty. $w_j$ is defined by the group of decision-makers as a grey number, $\otimes w_j$, which is common for all the environmental factors.

Various methods are available to evaluate CI uncertainty. Here, the Monte Carlo approach was presented and was adapted to our study context, based on performing multiple evaluations of the model by considering uncertainty in the weighting scheme $\boldsymbol{w}$. The procedure involved four steps [50]:

1. Assigning a probability density function (pdf) to each weight $w_j$. As the grey number represents an interval of values $[\underline{a}, \overline{a}]$, with $\underline{a} < \overline{a}$, which correspond to the least and greatest importance of each criteria considering the decision-makers' opinions, then the best fitting pdf is the uniform distribution.
2. Randomly generating $r$ combinations of weights $\boldsymbol{w^l}$, with $l = 1, \dots, r$ (a set of weights $\boldsymbol{w^l} \coloneqq (w_1^l, \dots, w_j^l), j = 1, \dots, n,$ is called a weight sample).

Samples can be generated by various procedures, such as simple random sampling, stratified sampling, and quasi-random sampling, among others [51]. The use of the quasi-random sampling technique with low-discrepancy sequences is recommended because it has the property of covering a space of dimension $n$ more uniformly than a sequence of random points does. The formula to compute the sample is defined in [52]. Note that the number of samples is a power of base 2 according to the formula. In addition, the greater the number of simulated samples, the smaller the discrepancy between points. The matrix of weights obtained with the $r$ weight samples is:

$$\boldsymbol{W} := \begin{bmatrix} w_1^1 & \dots & w_j^1 & \dots & w_n^1 \\ \vdots & & \vdots & & \vdots \\ w_1^l & \dots & w_j^l & \dots & w_n^l \\ \vdots & & \vdots & & \vdots \\ w_1^r & \dots & w_j^r & \dots & w_n^r \end{bmatrix} \in R^{r \times n} \quad (12)$$

where $w_j^l$ is the *l-th* simulated weight for criterion $j$, with $l = 1, \dots, r$ and $j = 1, \dots, n$.

3. Evaluating model $Y$ for each environmental factor $i$ regarding each weight sample $\boldsymbol{w}^{\boldsymbol{l}}$, which results in the following matrix:

$$\boldsymbol{M} := \begin{bmatrix} Y_{1,\boldsymbol{w}^1} & \dots & Y_{1,\boldsymbol{w}^l} & \dots & Y_{1,\boldsymbol{w}^r} \\ \vdots & & \vdots & & \vdots \\ Y_{i,\boldsymbol{w}^1} & \dots & Y_{i,\boldsymbol{w}^l} & \dots & Y_{i,\boldsymbol{w}^r} \\ \vdots & & \vdots & & \vdots \\ Y_{m,\boldsymbol{w}^1} & \dots & Y_{m,\boldsymbol{w}^l} & \dots & Y_{m,\boldsymbol{w}^r} \end{bmatrix} \in R^{m \times r} \quad (13)$$

where $Y_{i,w^l}$ is the value of the CI for environmental factor $i$ ($i = 1, \dots, m$) using weight sample $\boldsymbol{w}^{\boldsymbol{l}} := (w_1^l, \dots, w_j^l)$ for $j = 1, \dots, n$

4. Analyzing the resulting output vector $\boldsymbol{Y}^{\boldsymbol{l}} := \{Y_{1,\mathbf{w}^l}, \dots, Y_{\mathrm{m},\mathbf{w}^l}\}$ with $l = 1, \dots, r$ (the columns of the matrix $\boldsymbol{M}$). The sequence of $\boldsymbol{Y}^{\boldsymbol{l}}$ allows the empirical pdf of output $Y$ to be constructed. The characteristics of the pdf, such as mean, variance and higher order moments, can be estimated at an arbitrary level of precision, which is related to the size

of the simulation $r$ and could be used to make comparisons between environmental factors.

**4. Case study**

Phase A: Selecting the SC.

For the case study, the SC of a footwear manufacturer located in Alicante (Spain) was selected. This SC can represent a typical case of the Spanish footwear industry.

This sector features fashion and product variety, so product cycles are usually fast, and the intensive pressure for on-time delivery is a critical issue that often causes low quality levels [53]. In order to reduce the SC's complexity and facilitate the meetings of the working group, a four-echelon supply chain was chosen: one supplier of raw materials (liquid silicone and polyurethane foam), the manufacturer, its main distributor and, finally, the customer with the highest sales share, which is a multi-brand footwear store chain. These four partners have been working together for more than 7 years and regularly collaborate in different processes. Specifically, it was the manufacturer who chose the rest of the supply chain partners to participate in the case study.

Phase B: Creating a working group consisting of representatives from each SC partner.

After a round of meetings held with the four companies in the SC, a decision was made to form a working group with only two individuals to represent each partner — eight people in all. All these individuals hold tactical/strategic positions (sales manager and process manager, or their equivalent) and have ample experience in the footwear sector.

Phase C: Determining the importance of factor typologies (criteria weights).

After defining the working group, three face-to-face meetings were held. The first meeting focused on the purpose of the study to be conducted and the methodology to be pursued. At the second meeting, the working group discussed and selected the environmental factors that, in the group's opinion, could bring more uncertainty to the SC. To facilitate the definition and selection of these factors, a list with a set of factors was shown to the working group. This list had been previously prepared after reviewing different sources trying to obtain a vision that encompasses both the general view (global footwear industry) and the local view (region and country). Some of the factors compiled with the global vision were [54, 55]: E-commerce; social media; sustainability and corporate social responsibility; eco footwear; trade agreements; technological developments; ageing factors in the design of products for seniors; personalization; consumer awareness; trend spotting; three-dimensional printing; and market regulation. These factors were checked by reviewing the sources focused on the local vision [56, 57, 58]: new technologies; online sales channel; strong competition in price; flexibility, sustainable innovation; renewable materials; globalization; and productivity increase. After showing this set of factors to the working group, fifteen environmental factors were initially defined that were later grouped into four large typologies to cover the aspects of the micro- and macroenvironment: marketplace (globalization, fashion trends, raw materials price, changing taste of consumers, and recycling); government (tax increase, new hiring policies, and environmental regulation); social changes (environmental awareness, fair trade, and influence of social networks) and technological changes (3D-printing, smart footwear, productivity increase with new processes, and new materials or substitutes). Since some of these environmental factors may have a different interpretation depending on the context, the following factors are described in more detail:

- Tax increase: This was defined by the working group as an environmental factor because local or national governments can increase them at any time and companies do not have the capacity to influence these decisions. Examples include the taxes paid for the generation of waste from processes, materials, packaging, etc. and taxes for the use of non-renewable energy sources.

- Changing taste of consumer: This was pointed out by the working group as an environmental factor relative to the marketplace that directly influences the materials or raw material used, the manufacturing process, the design, etc. For example, new colors, models and intelligent materials force companies to modify their manufacturing processes to adapt them to these consumer trends. This factor implies a high degree of uncertainty in the footwear sector that affects decisions related to investments in process improvement, design of new collections and replacement of old ones, etc.

- Productivity increase: This factor was included because Spanish manufacturing companies consider that it has a direct influence on competitiveness in the sector, especially in pricing, design of manufacturing processes, machinery, etc. However, after the analysis carried out in the work, it has been possible to confirm (see Table 10) that it occupies the last place in the ranking of factors once they have been prioritized.

Finally, at the third meeting, the importance of the four types of environmental factors (criteria weights) was determined. To this end, the individual judgment of each working group member was collected. To take into account the uncertainty of these trials, a questionnaire was employed using grey numbers. Table 3 shows the scale used to establish the weight of the factor typologies (criteria weights). Table 4 shows the opinions of all the working group members for each criterion, along with the obtained results (Section 3.1, Step 1).

| Scale | | ⊗W |
|---|---|---|
| (VL) | Very low | [0.0, 0.1] |
| (L) | Low | [0.1, 0.3] |
| (ML) | Medium low | [0.3, 0.4] |
| (M) | Medium | [0.4, 0.6] |
| (MH) | Medium high | [0.6, 0.7] |
| (H) | High | [0.7, 0.9] |
| (VH) | Very high | [0.9, 1.0] |

Table 3: The scale for establishing criteria weights

| | | Supplier | | Manufacturer | | Distributor | | Customer | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Criteria | $K_1$ | $K_2$ | $K_3$ | $K_4$ | $K_5$ | $K_6$ | $K_7$ | $K_8$ | Grey number |
| MK | Marketplace | VH | H | VH | VH | H | H | VH | VH | [0.825, 0.962] |
| GV | Government | VH | H | VH | VH | H | H | M | M | [0.700, 0.862] |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| SC | Social Changes | L | VL | VH | M | L | VL | H | M | [0.325, 0.487] |
| TC | Technological Changes | VH | VH | VH | H | ML | M | L | L | [0.537, 0.687] |

Table 4: Criteria weights

Phase D: Selecting the environmental factors that affect the SC and their evaluation for each criterion

Fifteen environmental factors were initially defined. However, in the second round, some of these factors were questioned by various members of the working group. After analyzing each factor one-by-one, the working group concluded that working with fifteen factors could be excessive, taking into account that some factors were only defended by one or two members of the working group. Therefore, after several rounds of discussion, only those factors with the highest consensus were considered for the case study, which gave 10 factors in all (Table 5). The numbering of the factors in Table 5 indicates neither order nor priority.

| Nº | Factor |
|---|---|
| (1) | 3D-Printing |
| (2) | Recycling |
| (3) | Environmental regulation |
| (4) | Changing taste of consumers |
| (5) | Tax Increase |
| (6) | Productivity increase |
| (7) | New materials or substitutes |
| (8) | Environmental awareness |
| (9) | Raw materials price |
| (10) | Globalization |

Table 5: The factors selected by the working group

Then, each factor was ranked according to all four factor typologies (criteria). To this end, each member answered an individual questionnaire using the scale in Table 6 based on linguistic variables and turned into grey numbers, according to that explained in Section 3.1 (Step 2). All the collected information is outlined in Table 7, along with the aggregated assessment of each factor per criterion.

| Scale | | ⊗W |
|---|---|---|
| (VP) | Very poor | [0, 1] |
| (P) | Poor | [1, 3] |
| (MP) | Medium poor | [3, 4] |
| (F) | Fair | [4, 6] |
| (MG) | Medium good | [6, 7] |
| (G) | Good | [7, 9] |
| (VG) | Very good | [9, 10] |

Table 6: Scale to assess the importance of each factor according to the different criteria

| Factors | | Supplier | | Manufacturer | | Distributor | | Customer | | |
|---|---|---|---|---|---|---|---|---|---|---|
| $V_i$ | Criteria | $K_1$ | $K_2$ | $K_3$ | $K_4$ | $K_5$ | $K_6$ | $K_7$ | $K_8$ | $\otimes G_{ij}$ |
| $V_1$ | MK | MG | F | G | VG | F | MP | MP | MP | [4.875, 6.250] |
| | GV | P | P | MP | P | MP | P | P | F | [1.875, 3.625] |
| | SC | P | P | P | MP | P | P | MP | P | [1.500, 3.250] |
| | TC | VG | G | VG | VG | VG | VG | G | G | [8.250, 9.625] |
| $V_2$ | MK | G | G | G | VG | G | VG | G | G | [7.500, 9.250] |
| | GV | G | VG | VG | G | G | MG | MG | MG | [7.125, 8.500] |
| | SC | MG | G | VG | G | VG | VG | F | G | [7.250, 8.750] |
| | TC | MG | MG | G | G | VG | G | G | MG | [6.875, 8.375] |
| $V_3$ | MK | F | F | F | G | MG | F | F | F | [4.625, 6.500] |
| | GV | VG | VG | VG | VG | G | G | MG | F | [7.500, 8.875] |
| | SC | G | MG | F | F | F | MG | F | F | [4.875, 6.625] |
| | TC | F | F | G | G | F | F | MG | F | [5.000, 6.875] |
| $V_4$ | MK | G | G | G | MG | G | G | G | G | [6.875, 8.750] |
| | GV | P | VP | P | P | VP | VP | P | VP | [0.500, 2.000] |
| | SC | F | MG | G | G | MG | MG | F | MG | [5.750, 7.250] |
| | TC | F | F | MP | F | MG | F | MG | MG | [4.625, 6.125] |
| $V_5$ | MK | P | P | P | MP | P | P | P | MP | [1.500, 3.250] |
| | GV | VG | VG | VG | VG | VG | G | VG | VG | [8.750, 9.875] |
| | SC | VP | VP | P | P | VP | P | P | P | [0.625, 2.250] |
| | TC | P | VP | VP | VP | VP | VP | VP | VP | [0.125, 1.125] |
| $V_6$ | MK | P | P | P | P | P | P | P | P | [1.000, 3.000] |
| | GV | VP | VP | VP | P | VP | VP | P | VP | [0.250, 1.500] |
| | SC | VP | VP | P | VP | VP | VP | VP | P | [0.250, 1.500] |
| | TC | G | G | VG | VG | VG | VG | G | VG | [8.250, 9.625] |
| $V_7$ | MK | G | G | VG | VG | G | G | G | G | [7.500, 9.250] |
| | GV | F | F | F | MP | F | MP | MP | F | [3.625, 5.250] |
| | SC | MG | G | G | G | G | G | VG | G | [7.125, 8.875] |
| | TC | VG | VG | VG | VG | G | G | VG | VG | [8.500, 9.750] |
| $V_8$ | MK | F | MP | MP | F | F | F | MG | F | [4.000, 5.625] |
| | GV | G | G | G | G | G | VG | VG | G | [7.500, 9.250] |
| | SC | G | VG | G | VG | VG | VG | VG | G | [8.250, 9.625] |
| | TC | G | MG | MG | MG | G | F | G | MG | [6.125, 7.625] |
| $V_9$ | MK | G | G | G | G | G | G | MG | G | [6.875, 8.750] |
| | GV | G | G | VG | G | G | MG | G | G | [7.125, 8.875] |
| | SC | P | MG | MP | P | P | P | P | MP | [2.125, 3.750] |
| | TC | P | P | P | P | P | P | P | P | [1.000, 3.000] |
| $V_{10}$ | MK | G | G | VG | VG | G | VG | MG | G | [7.625, 9.125] |
| | GV | F | MG | G | F | F | F | F | MP | [4.500, 6.250] |
| | SC | MG | G | G | G | MG | MG | MG | MG | [6.375, 7.750] |
| | TC | F | F | MG | MG | F | G | F | MP | [4.750, 6.375] |

Table 7: Aggregated assessment of each factor per criterion



Phase E: Assessing environmental factors by the GST

In order to assess the importance of each environmental factor, it is compulsory to construct the normalized grey weighted matrix (Section 3.1, Steps 3, 4 and 5) and to obtain positive optimal alternatives first (Table 8).

| $\otimes N_{ij}$ | MK | GV | SC | TC |
|---|---|---|---|---|
| $V_1$ | [0.4347, 0.6503] | [0.1329, 0.3166] | [0.0506, 0.1646] | [0.4548, 0.6786] |
| $V_2$ | [0.6689, 0.9625] | [0.5050, 0.7424] | [0.2448, 0.4431] | [0.3780, 0.5905] |
| $V_3$ | [0.4125, 0.6763] | [0.5316, 0.7751] | [0.1646, 0.3355] | [0.2756, 0.4847] |
| $V_4$ | [0.6131, 0.9104] | [0.0354, 0.1746] | [0.1941, 0.3672] | [0.2549, 0.4318] |
| $V_5$ | [0.1337, 0.3381] | [0.6202, 0.8625] | [0.0211, 0.1139] | [0.0068, 0.0881] |
| $V_6$ | [0.0891, 0.3121] | [0.0177, 0.1310] | [0.0084, 0.0759] | [0.4548, 0.6786] |
| $V_7$ | [0.6689, 0.9625] | [0.2569, 0.4585] | [0.2405, 0.4495] | [0.4685, 0.6875] |
| $V_8$ | [0.3567, 0.5853] | [0.5316, 0.8079] | [0.2785, 0.4875] | [0.3376, 0.5376] |
| $V_9$ | [0.6131, 0.9104] | [0.5050, 0.7751] | [0.0717, 0.1899] | [0.0551, 0.2115] |
| $V_{10}$ | [0.6800, 0.9494] | [0.3189, 0.5458] | [0.2152, 0.3925] | [0.2618, 0.4495] |
| $\otimes V_j^{max}$ | *[0.6800, 0.9625]* | *[0.6202, 0.8625]* | *[0.2785, 0.4875]* | *[0.4685, 0.6875]* |

Table 8: The normalized grey weighted matrix

Next, the grey possibility degree $[p_{ij}]_{i=1,\dots,m;j=1,\dots,n}$ for each factor (Table 9) should be calculated (Section 3.1, Step 6).

| | MK | GV | SC | TC |
|---|---|---|---|---|
| $V_1$ | 1 | 1 | 1 | 0.52551574 |
| $V_2$ | 0.50967742 | 0.74529858 | 0.59585492 | 0.71667908 |
| $V_3$ | 1 | 0.68110749 | 0.85 | 0.96218645 |
| $V_4$ | 0.6025641 | 1 | 0.7679558 | 1 |
| $V_5$ | 1 | 0.5 | 1 | 1 |
| $V_6$ | 1 | 1 | 1 | 0.52551574 |
| $V_7$ | 0.50967742 | 1 | 0.59090909 | 0.5 |
| $V_8$ | 1 | 0.63808361 | 0.5 | 0.83511859 |
| $V_9$ | 0.6025641 | 0.69765287 | 1 | 1 |
| $V_{10}$ | 0.51178451 | 1 | 0.70491803 | 1 |

Table 9: The grey possibility degree per factor

Finally, the overall importance of each environmental factor is determined (Section 3.1, Step 7). Table 10 shows the score obtained by each one. Those factors with a possibility degree lower than their optimal value were more important.

| | | $p_i$ | Rank |
|---|---|---|---|
| $V_1$ | 3D-Printing | 0.8813789 | 9 |
| $V_2$ | Recycling | 0.6418775 | 1 |
| $V_3$ | Environmental regulation | 0.8733234 | 7 |
| $V_4$ | Changing taste of consumers | 0.8426299 | 6 |
| $V_5$ | Tax Increase | 0.875 | 8 |
| $V_6$ | Productivity increase | 0.8813789 | 10 |
| $V_7$ | New materials or substitutes | 0.6501466 | 2 |
| $V_8$ | Environmental awareness | 0.7433005 | 3 |
| $V_9$ | Raw materials price | 0.8250542 | 5 |
| $V_{10}$ | Globalization | 0.8041756 | 4 |

Table 10: Score obtained by each environmental factor

In the case study, the three most important environmental factors were: recycling, new materials or substitutes, and environmental awareness.

Phase F. Assessing environmental factors by a composite indicator with an uncertainty analysis

First, according to that explained in Section 3.2, a uniform distribution was assigned to each criterion weight (Table 11) representing the grey number $\otimes w_j$ as an interval of uncertainty.

| **Criterion** | **pdf** |
|---|---|
| Marketplace | $w_1 \in U(0.825, 0.962)$ |
| Government | $w_2 \in U\ (0.700, 0.862)$ |
| Social Changes | $w_3 \in U\ (0.325, 0.487)$ |
| Technological Changes | $w_4 \in U\ (0.537, 0.687)$ |

Table 11: Uniform distribution assigned to each criterion weight

Second, we generated $r = 2^{13} = 8{,}192$ samples from each probability distribution function using quasi-random sampling with low-discrepancy sequences. A large enough sample size was considered so that the results would not be limited by the sample.

Then, we evaluated the model $Y$ for each environmental factor regarding the uncertainty in the criterion weights, $w_j$, and applied the Monte Carlo methodology described in Section 3.2. Finally, the box-and-whisker representation of the pdf that resulted for each environmental factor is shown in Figure 1.

Overlapping of plots means that there are weight scenarios in which the positions of the environmental factors might vary. Let's explain the case of $V_7$ and $V_8$. Regarding the median (red line) of the possible positions for both factors, $V_7$ is slightly more important than $V_8$. However, both plots are very close and overlap, which means that there are scenarios of weights, $w_j$, that consider $V_8$ better than $V_7$. Therefore, the inclusion of uncertainty in the criterion weights takes into account the possible overlaps between the positions of the environmental factors and enables the distances between them to be determined as being similar or clearly differentiated. This information is most interesting in the decision-making of companies.

The results obtained with larger sample sizes were the same, which indicates that the results obtained with the generated sample are robust enough.

Table 12 shows the environmental factors ranking after considering the distribution median for each environmental factor pdf, and the GST results.

| | | Rank (GS) | Rank (CI) |
|---|---|---|---|
| $V_1$ | 3D-Printing | 9 | 8 |
| $V_2$ | Recycling | 1 | 1 |
| $V_3$ | Environmental regulation | 7 | 5 |
| $V_4$ | Changing taste of consumers | 6 | 7 |
| $V_5$ | Tax Increase | 8 | 9 |
| $V_6$ | Productivity increase | 10 | 10 |
| $V_7$ | New materials or substitutes | 2 | 2 |
| $V_8$ | Environmental awareness | 3 | 3 |
| $V_9$ | Raw materials price | 5 | 6 |
| $V_{10}$ | Globalization | 4 | 4 |

Table 12: GS vs. CI ranking

Both methodologies agree as to the position of factors 1, 2, 3, 4 and 10. However, the positions of factors 5, 6, 7, 8 and 9 differ.

The CI methodology under uncertainty analysis considers 8,192 fixed weight scenarios for each criterion (uniformly defined within the grey number range of the criteria), and thereby it obtains a ranking of environmental factors bearing in mind each scenario. The objective of complementing the GST method with the CI method under uncertainty is to provide greater robustness for the results obtained by GST by proposing a greater uncertainty of possible weight scenarios based on the grey number of each criterion defined by eight experts. In the CI methodology, instead of working with 8 opinions and a grey number whose upper and lower ends are taken into account for the definition of the ranking, there are 8,192 simulated sets of fixed weights from the grey number of each criterion that simulate the opinion of 8,192 different experts. Therefore, the CI method contemplates lots of uncertainty in the environmental factors ranking model.

The advantage of the methodology proposed using CI with uncertainty analysis tools lies in considering the uncertainty analysis, which includes the full range of numbers of the grey number. However, the GST considers only the interval's extremes of the grey number.

After assessing the uncertainty factors by the GST and CI methodologies, we can see that the most important factors for the SC are (and in this order): recycling, new materials or substitutes, environmental awareness, and globalization. These four factors maintain the position or degree of importance regardless of the methodology used, which confers on them excellent robustness. We can see that all the other environmental factors do not maintain the same position in the applied methodologies. In our view, and as the use of CI with an uncertainty analysis includes the full range of numbers of the grey numbers, CI methodology may have more strength than the GST methodology. For this reason, it is convenient to follow the CI classification.

Phase G. Determining the ranking of the main environmental factors for each supply chain partner

In the previous phase, the most important factors for the supply chain as a whole were determined. This allows SC decision-makers to establish the SC's strategy and its objectives to be pursued by taking into account the key environmental factors. In this way, all partner efforts and resources focus on addressing these factors, especially in the mid-term. Since the assessment of environmental factors was carried out jointly by the representatives of the SC partners, and the opinions and judgments of each partner form part of the assessment process, it is easier for all the partners to feel included in devising the SC strategy and objectives by acting not only as a set of cooperating and collaborative companies but instead as a global organization. Moreover, the aspects associated with trust among partners, as well as the coherence of the decisions to be made, facilitate balance and equity among them.

However, it would be of utmost importance to know if any partner has a distant vision of the results obtained. This means that a partner can have a different prioritization of the environmental factors with respect to other partners, which can lead to tensions when the strategy and the consequent objectives are defined. For this reason, in this phase of the methodology, the ranking of the main environmental factors for each SC partner will be determined. Following the case study, a prioritized evaluation of only the four most important environmental factors according to both applied methodologies has been carried out for each partner ($V_2$: recycling; $V_7$: new materials or substitutes; $V_8$: environmental awareness; and $V_{10}$: globalization). To perform this evaluation, the procedure described in Section 3.1 has been followed. On this occasion, it is necessary to focus on each partner individually and calculate the prioritization of the four factors mentioned above according to the decision-makers' opinion. For this purpose, the information collected in Table 7 (Aggregated assessment of each factor per criterion) is taken into account. The results are shown in Figure 2.

It is observed that the prioritization for the distributor coincides exactly with the global prioritization. The prioritizations for the supplier and the manufacturer are very similar, shifting only the order of factors $V_{10}$ and $V_8$ (third and fourth position). However, the prioritization of the factors for the customer differs in the first three factors from the global prioritization of the SC.

This situation, as mentioned above, creates major tensions that are sometimes not easy to address. If you define a competitive strategy and global objectives that are not aligned with the preferences or opinion of a partner, (in our case study, it happens with the customer), such a partner will not feel integrated or represented. In this situation, the partner may not share resources, information and efforts for the benefit of the entire SC. It is noted that for the customer, the most relevant environmental factor is $V_7$ (New materials or substitutes), followed by $V_8$ (Environmental awareness). Contrarily, for the rest of the partners, the most relevant environmental factor is $V_2$ (Recycling), being also relevant for the customer but less so than $V_7$ and $V_8$. Given that the customer in our case study is a multi-brand footwear store chain, which has direct contact with the final customers (buyers), it has a very valuable knowledge to consider.

All the information obtained in the last two phases of the methodology is vital to establish the SC competitive strategy, trying to align it perfectly under all partners' vision. Thus, once the SC common objectives are also defined, all partners will have a positive disposition when it comes to using their resources in order to achieve mutual benefit.

With these results, and after several discussion sessions with the SC participants, the competitive strategy and its associated objectives for the coming years were defined (Figure 3):

Finally, we cannot highlight all objectives and actions plans defined for this SC because this information is confidential for managers.

To sum up, the managerial implications of applying this research methodology are:

- To identify the main environmental factors in both the individual company and the SC, which should serve to improve their medium-long term strategic decisions.
- To align their SC strategic decisions with their individual company's ones regarding key environmental factors. This will imply, among others, cost savings and brand image improvement.
- To improve the SC and by extension, individual companies' operations. The definition of more focused environmental SC objectives will bring a higher degree of cohesion

and collaboration between SC partners, which should end in a higher degree of SC flexibility, adaptability and operational improvement.

- To take the opportunity that this additional information offers, either by developing new strategic lines or increasing existing ones such as product innovation based on these identified environmental factors.
- To establish new business relationships at the SC level if, derived from the new products/services to be developed, other SC partners, such as new raw material suppliers, need to be sought.
- To improve SC business collaboration factors such as trust, equity or coherence, which would turn into higher business profits.



## 5. Conclusions

Nowadays, many factors make the decision-making process in organizations very complex, both individually in companies and collectively in supply chains. The origin of these factors may be internal or external to the organization. This work specifically focused on external factors (environmental factors) in the supply chain. The main objective was to assess the importance of environmental factors in an SC context as a preliminary step to choose its competitive strategies. Defining an adequate strategy that helps the SC to compete in a highly dynamic and competitive environment requires, among other things, knowing the degree of influence that environmental factors can have. Knowing these factors and evaluating and prioritizing them are essential steps to select the strategy and consequent objectives that will determine which efforts are to be made, and, consequently, the distribution of the resources to be used within the SC. To a greater or lesser extent, these factors inherently entail a dose of uncertainty, which is transferred to the decision-making process at both the intra- and interorganizational levels.

In order to address the aforementioned problems, two approaches were used in this work: the GST on the one hand, and uncertainty analysis tools for composite indicators on the other hand. First, the GST is proposed as a quantitative method to tackle the subjectivity in managers' judgments and to allow a final classification of factors to be obtained according to their importance. Next, constructing a composite indicator was proposed to provide more robustness for the results of GST by considering a high degree of uncertainty in the group of managers' opinions based on the grey number defined in GST. The results of both approaches can be compared to one another, which thus facilitates decision-making.

In order to validate both approaches, a seven-phase research methodology was followed and applied to a real case study. An SC was selected from the footwear sector, which consisted of four partners: supplier, manufacturer, distributor and customer. The working group, made up of two members from each partner, chose what they considered were the 10 most important environmental factors. After applying both the GST and CI approaches, the same result was obtained for the first four environmental factors, but the ranking for the other factors did not match. The results allowed managers to establish the competitive strategy that best suited the prioritization of the most relevant factors and to define the most appropriate objectives where the SC should invest its efforts and resources.

It should be pointed out that the robustness of both approaches was validated by the similarity of the obtained results. However, the advantage of the proposed methodology using CI with uncertainty analysis tools is that, when considering uncertainty, the full range of numbers of the grey numbers was included, which allowed many possible scenarios to be studied according to weights. However, the GST considers only the interval's extremes of grey numbers. In general, the developed methodology follows a simple, short and slightly tedious process compared to other approaches. Only the CI part is a bit more tedious because of the simulations of different scenarios and the computation of the alternatives' rankings in each scenario. However, it contributes to having more robust results.

Another interesting contribution of this work has been to calculate the prioritization of the environmental factors for each partner. The result allows us to determine the affinity degree of the SC global prioritization of the environmental factors, in relation to the individual prioritization. This helps us to select the best strategy for the supply chain, highlighting the perception of each partner and aligning it with the overall vision and mutual benefit.

In summary, the described methodology facilitates the decision process related to defining the strategy in the CS in several ways: it highlights the environmental factors that most of the partners believe may affect the CS; it helps align the prioritization of environmental factors between the individual and CS levels; it helps to think about the influence that environmental factors can have on the CS and facilitates the interaction among the partners in order to understand the global vision of the CS.

One of the limitations of the methodology proposed in this study is that the weights assigned to the criteria and the evaluation of each of the alternatives are based on expert judgments, so it is not a purely mathematical and objective assignment. In this sense, it should be ensured that the group of experts is as representative as possible and with common sense in order to make the study as transparent and reliable as possible.

In order to validate these findings, our future research will experiment with more factors and working group members. It would also be most interesting to ascertain the influence that these factors have on each SC member, especially after a sufficient time period for the defined strategy and objectives to be implemented. In addition, in the current work we have only focused on the external environmental factors, but it would be advisable to also have a prioritization of factors that included some internal factors (collaboration and maturity degree, organizational structure, etc.), since these factors are also subject to a certain level of uncertainty and therefore affect the decision-making process within the supply chain as well as the process of defining the strategy and objectives.

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**References**

[1] D.M. Lambert, M.C. Cooper, Issues in Supply Chain Management, Industrial Marketing Management. 29 (1) (2000) 65-83.

[2] P.W. Stonebraker, J. Liao, Environmental turbulence, strategic orientation: Modeling supply chain integration, International Journal of Operations & Production Management. 24 (10) (2004) 1037-1054.

[3] M. Lalmazloumian, K. Yew, A Review of Modelling Approaches for Supply Chain Planning Under Uncertainty, 9th Int. Conf. on Service Systems and Service Management (ICSSSM). (2012) 197-203.

[4] R.E. Miles, C.E. Snow, Organizational strategy, structure, and process, McGraw-Hill, 1978.

[5] F.J. Milliken, Three types of perceived uncertainty about the environment: State, effect, and response uncertainty, Academy of Management Review. 30 (1987) 91-109.

[6] E. Simangunsong, L.C. Hendry, M. Stevenson, Managing supply chain uncertainty with emerging ethical issues. International Journal of Operations & Production Management. 36 (10) (2016) 1272-1307.

[7] D. Otley, Performance management under conditions of uncertainty: some valedictory reflections, Pacific Accounting Review. 24 (3) (2012) 247–261.

[8] B.L. MacCarthy, C. Blome, J. Olhager, J.S. Srai, X. Zhao, Supply chain evolution – theory, concepts and science, International Journal of Operations & Production Management. 36 (12) (2016) 1696-1718.

[9] E. Simangunsong, L.C. Hendry, M. Stevenson, Supply-chain uncertainty: a review and theoretical foundation for future research, International Journal of Production Research. 50 (16) (2012) 4493-4523.

[10] M.E. Porter, Competitive Strategy, The Free Press, 1980.

[11] R. Vecchiato, Environmental uncertainty, foresight and strategic decision making: An integrated study, Technological Forecasting & Social Change. 79 (2012) 436–447.

[12] L.A. De Vasconcelos Gomes, M.S. Salerno, R. Phaal, D.R. Probert, , How entrepreneurs manage collective uncertainties in innovation ecosystems, Technological Forecasting & Social Change. 128 (2018) 164-185.

[13] B. Flynn, X. Kofteros, G. Lu, On theory in supply chain uncertainty and its implications for supply chain integration, Journal of Supply Chain Management. 52 (3) (2016) 3-25.

[14] L. Gordon, V.K. Narayanan, Management Accounting Systems, Perceived Environmental Uncertainty and Organizational Structure: An Empirical Investigation, Accounting, Organizations and Society. 9 (1) (1984) 33-47.

[15] B. Huo, Y. Ye, X. Zhao, J. Wei, Z. Hua, Environmental uncertainty, specific assets, and opportunism in 3PL relationships: A transaction cost economics perspective, International Journal of Production Economics. 203 (2018) 154–163

[16] Z. Hoque, A contingency model of the association between strategy, environmental uncertainty and performance measurement: impact on organizational performance, International Business Review. 13 (2004) 485–502.

[17] M. Lonbani, S. Sofian, M.B. Baroto, Balanced Scorecard implementation on SMEs: Addressing the moderating rol of environmental uncertainty, Global Business and Organizational Excellence. 3-4 (2016) 58-66.

[18] H.L. Lee, The Triple A supply chain, Harvard Business Review. October, (2004) 102–121.

[19] Y. Candace, E.W.T. Yi, Ngai, K.L. Moon, Supply chain flexibility in an uncertain environment: exploratory findings from five case studies, Supply Chain Management: An International Journal. 16 (4) (2011) 271-283.

[20] E. Boyle, P. Humphreys, R. McIvor, Reducing supply chain environmental uncertainty through e-intermediation: An organisation theory perspective, International Journal of Production Economics. 114 (2008) 347–362.

[21] N. Agami, M. Saleh, M. Rasmy, An Innovative Fuzzy Logic Based Approach for Supply Chain Performance Management, IEEE Systems Journal. 8 (2) (2014) 336-342.

[22] J.T. Arrive, M. Feng, The complexity of the environment, management control and firm performance, Business Strategy and the Environment. 27 (2018) 1347–1354.

[23] J. Sydow, G. Müller-Seitz, K.G. Provan, Managing uncertainty in alliances and networks - from governance to practice, In: Das, T.K. (Ed.), Managing Knowledge in Strategic Alliances. 1–43 2013.

[24] M.C. Huang, G.F. Yen, T.C. Liu, Reexamining supply chain integration and the supplier's performance relationships under uncertainty, Supply Chain Management: An International Journal. 19 (1) (2014) 64-78.

[25] A.U. Widyaningdyah, W. Mandala, A. Aryani, Perceived Environmental Uncertainty, Performance Measurement Systems, and Competitive Advantage, Review of Integrative Business and Economic Research. 5 (3) (2016) 117-134.

[26] H.I. Ansoff, Critique of Henry Mintzberg's The Design School: reconsidering the basic premises of strategic management, Strategic Management Journal. 12 (6) (1991) 449–461.

[27] H. Mintzberg, The Rise and Fall of Strategic Planning: Reconceiving Roles for Planning, Free Press, 1994.

[28] N. Nummela, S. Saarenketo, P. Jokela, S. Loane, Strategic decision-making of a born global: a comparative study from three small open economies, Management International Review. 54 (4) (2014) 527–550.

[29] X. Yu, Y. Tao, X Tao, F. Xia, Y. Li, Managing uncertainty in emerging economies: The interaction effects between causation and effectuation on firm performance, Technological Forecasting & Social Change. 135 (2017) 121-131.

[30] I.N. Durbach, T.J. Stewart, Modeling uncertainty in multi-criteria decision analysis, European Journal of Operational Research. 223 (2012) 1–14.

[31] S. Liu, J. Forrest, Y. Yang, A summary of the progress in grey system research, Proceedings of 2013 IEEE International Conference on Grey systems and Intelligent Services (GSIS) (2013), Conference Paper | Publisher: IEEE

[32] F. Jahantigh, B. Malmir, B.A. Avilaq, An integrated approach for prioritizing the strategic objectives of balanced scorecard under uncertainty, Neural Computing applications. 29 (6) (2018) 227–236.

[33] M.F. Chen, G.H. Tzeng, Combining grey relation and TOPSIS concepts for selecting an expatriate host country, Mathematical and Computer Modeling. 40 (2004) 1473–1490.

[34] M.L. Tseng, A causal and effect decision-making model of service quality expectation using grey-fuzzy DEMATEL approach, Expert System with Applications. 36 (4) (2008) 7738–7748.

[35] S.X. Wu, M.Q. Li, L.P. Cail, S.F. Liu, A comparative study of some uncertain information theories, In Proceedings of the Int. Conference on Control and Automation. (2005)1114–1119.

[36] S. Vinodh, M. Prasanna, N. Hari Prakash, Integrated Fuzzy AHP–TOPSIS for selecting the best plastic recycling method: A case study, Applied Mathematical Modelling. 38 (2014) 4662-4672

[37] F. R. Lima, L. Osiro, L. C. R. Carpinetti, A comparison between Fuzzy AHP and Fuzzy TOPSIS methods to supplier selection, Applied Soft Computing. 21 (2014) 194–209.

[38] M. S. García, Métodos para la comparación de alternativas mediante un Sistema de Ayuda a la Decisión (S.A.D.) y Soft Computing. (2009). Doctoral Thesis

[39] J.L. Deng, Control problems of grey systems, Systems & Control Letters. 1 (5) (1982) 288–294.

[40] J.L. Deng, An introduction to grey system theory, Journal of Grey System. 1 (1989) 1–24.

[41] S.F. Liu, J. Forrest, The current development status on grey system theory, Journal of Grey System. 19 (2007) 111–123.

[42] M.S. Yin, Fifteen years of grey system theory research: A historical review and bibliometric analysis, Expert Systems with Applications. 40 (2013) 2767–2775.

[43] G. Dong, D. Yamaguchi, M. Nagai, A grey-based decision-making approach to the supplier selection problem, Mathematical and Computer Modelling. 46 (2006) 573–581.

[44] J. Wey, L. Zhou, F. Wang, D. Wu, Work safety evaluation in Mainland China using grey theory, Applied Mathematical Modelling. 39 (2015) 924-933.

[45] R. Rajesh, V. Ravi, R. Ventaka-Rao, Selection of risk mitigation strategy in electronic supply chains using grey theory and digraph-matrix approaches, International Journal of Production Research. 53 (1) (2015) 238-257.

[46] M.A. Kaviani, M. Mobin, E. Bottani, Supply Chain Resilience Assessment: A Grey Systems Theory Approach, Proceedings of the Int. Conf. on Industrial Engineering and Operations Management, USA, September. (2016) 23-25.

[47] B. Huang, L. Bai, A. Roy, N. Ma, A multi-criterion partner selection problem for virtual manufacturing enterprises under uncertainty, International Journal of Production Economics. 196 (2018) 68–81.

[48] S. Liu, Z. Fang, Y. Yang, J. Forrest, General grey numbers and their operations, Grey Systems: Theory and Application, 2 (3) (2012) 314-349.

[49] M. Nardo, M. Saisana, A. Saltelli, S. Tarantola, A. Hoffman, E. Giovannini, Handbook on constructing composite indicators: methodology and user guide, OECD Statistics Working Paper. 2008.

[50] M. Saisana, A. Saltelli, S. Tarantola, Uncertainty and sensitivity analysis techniques as tools for the quality assessment of composite indicators, Journal of the Royal Statistical Society. 168 (2) (2005) 1-17.

[51] A. Saltelli, M. Ratto, T. Andres, F. Campolongo, J. Cariboni, D. Gatelli, M. Saisana, S. Tarantola, Global Sensitivity Analysis. The premier. Chichester: John Wiley & Sons, Ltd. 2008.

[52] A. Saltelli, K.P.S. Chan, M. Scott, Sensitivity analysis. Chichester: John Wiley & Sons, Ltd. 2000.

[53] M.A. Sellitto, G.M. Pereira, M. Borchardt, R.I. Da Silva, C.V. Viegas, A SCOR-based model for supply chain performance measurement: application in the footwear industry, International Journal of Production Research. 53 (16) (2015) 4917-4926.

[54] Marketwatch. Footwear Market: Global Industry Size, Share, Trends, Growth, Demand and Forecast 2018-2026. https://www.marketwatch.com/press-release/footwear-market-global-industry-size-share-trends-growth-demand-and-forecast-2018-2026 (2018)

[55] CBI. Which trends present opportunities on the European footwear market? Ministry of Foreign Affairs, Netherlands Enterprise Agency (2016). https://www.cbi.eu/market-information/footwear/trends

[56] CESCE. Informe Sectorial de la economía española (2018). https://www.cesce.com.

[57] R. Rocamora. The challenges of footwear by 2020: flexibility, sustainable innovation and renewable materials. (2017). https://valenciaplaza.com/Losdesafosdelcalzadohacia2020

[58] AVECAL. Valencian Association of Footwear Entrepreneurs. (2019) https://www.avecal.es/

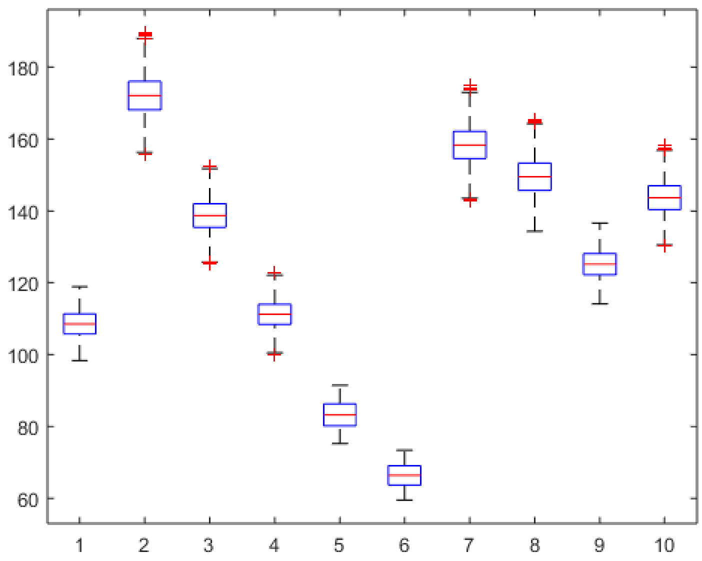
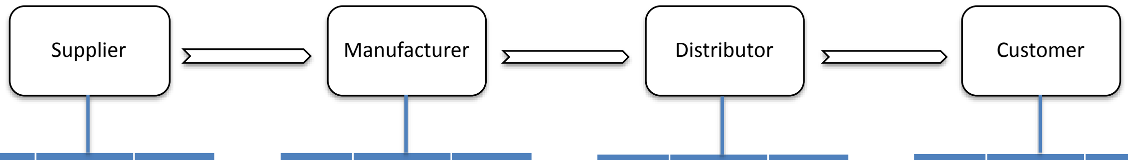



Figure 1: Uncertainty analysis results for each CI environmental factor




Supplier:

| Rank | P | Factor |
|---|---|---|
| 1-2 | 0.641891 | $V_2$ |
| 1-2 | 0.641891 | $V_7$ |
| 3 | 0.766891 | $V_{10}$ |
| 4 | 0.778587 | $V_8$ |

Manufacturer:

| Rank | P | Factor |
|---|---|---|
| 1 | 0.602380 | $V_2$ |
| 2 | 0.650990 | $V_7$ |
| 3 | 0.760526 | $V_{10}$ |
| 4 | 0.785 | $V_8$ |

Distributor:

| Rank | P | Factor |
|---|---|---|
| 1 | 0.553571 | $V_2$ |
| 2 | 0.679623 | $V_7$ |
| 3 | 0.687086 | $V_8$ |
| 4 | 0.722463 | $V_{10}$ |

Customer:

| Rank | P | Factor |
|---|---|---|
| 1 | 0.625 | $V_7$ |
| 2 | 0.641959 | $V_8$ |
| 3 | 0.661946 | $V_2$ |
| 4 | 0.820762 | $V_{10}$ |

Figure 2: Prioritization of environmental factors for each partner

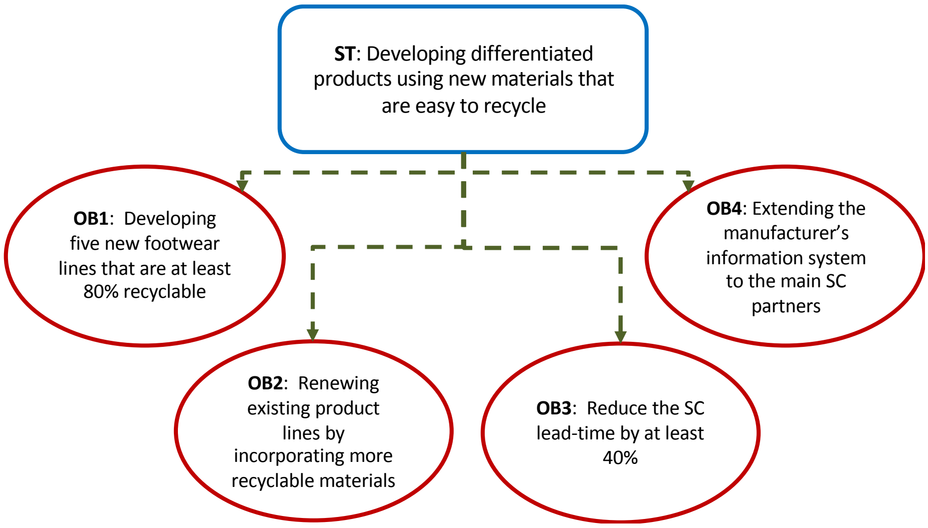



Figure 3: Strategy and objectives