# Analysis of the Sustainable Supply Chain Structure with Incomplete Preferences

G. Büyüközkan[1] and G. Çifçi

***Abstract*— Integration of sustainable development in the business and supply chain is potentially a source of competitive differentiation for firms. Sustainable supply chain (SSC) management is the management of material, information and capital flows as well as cooperation among companies along the supply chain while taking goals from all three dimensions of sustainable development, i.e., economic, environmental and social, into account which are derived from customer and stakeholder requirements. By using the quality function deployment (QFD) as a product/system development tool, an effective SSC structure can be obtained. The objective of this study is to apply an extended QFD methodology in SSC by introducing a new group decision making (GDM) approach that takes into account incomplete information of decision makers by means of fuzzy set theory. This methodology is compatible with the requirements of the various stakeholders, suppliers, manufacturers and clients, involved in the supply chain. Finally, to assess the validity of the proposed approach, a specific supply chain example is given.**

***Index Terms*—Fuzzy sets, incomplete preference relations, quality function deployment, sustainable supply chain management.**

## I. Introduction

Organizations worldwide are continuously trying to develop new and innovative ways to gain and maintain a competitive advantage in the global market. In response to heightened governmental regulations and rising public awareness of the effect of industrial production on the environment, many organizations are now undertaking major initiatives to transform their supply chain processes [1]. Consideration is given to the convergence of supply chains and sustainability [2]. The emergence of sustainable supply chain (SSC) is one of the most significant developments in the past decade, offering the opportunity for companies to align their supply chains in accordance with environmental and sustainability goals.

Great efforts have recently resulted in increasing the environmental performance of supply chains. However, to obtain more sustainable solutions, organization properties must meet SSC and customer requirements. Especially, quality function deployment (QFD) is one of the techniques for designing needs of customer and turning them into practical measures. This approach enables the firms to become proactive to quality problems rather than taking a reactive position by acting on customer complaints. The approach bases on total quality management, which offers a vast technique to ensure the improvement of quality and productivity. QFD is comprised of major group decision making (GDM) processes. In practice, determining the weights of customer requirements (CRs) is a GDM process. This mainly because of the ‘danger’ of relying on a single decision maker (DM) with his/her limitations of experiences, preferences or biases about the issues involved, and the fact that individuals are often unable to clearly identify their own states. Multiple DMs, thus GDM, are often preferred rather than a single DM to avoid the bias and minimize the partiality in the decision process [3]–[6].

Generally, different and/or even subjective opinions are quite often in a GDM process due to the limitations of experience and impreciseness. Obviously, the importance of each CR in QFD is determined by a group of people with ambiguity. In addition, due to constraints as time pressure, lack of expertise in related issue, etc.; decision makers (DMs) may develop incomplete preferences in which some of the elements cannot be provided. Under such circumstances, fuzzy set theory [7] and incomplete preference relations [8]–[14] can be applied to deal with group decisions when the information is imprecise and missing. This paper develops a new fuzzy logic based GDM approach in QFD with incomplete preference relations. Moreover, a specific supply chain example is provided to show the proposed GDM approach can be effectively used in QFD. As incomplete preferences in fuzzy environments are not widespread yet, there exists no study in literature that neither combines it with QFD or any other methods, nor applies it in SSC management (SSCM) field.

The paper is organized as follows. In section 2, SSCM concept and model description are given. Section 3 describes the proposed approach and computational procedure step by step. After the application of the SSC model in Section 4, Section 5 contains some concluding remarks.

## II. Sustainable Supply Chain Management

### A. Requirements for a SSCM

Firstly to provide a sense of its concept, SSC contains the integration of environment, economic and social performances. The interaction between sustainability and supply chains is the critical next step from recent

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examinations of operations and the environment [15] and operations and sustainability [16]. Interest in green and now sustainable supply chains has been growing for over a decade and the topic is becoming mainstream [16]–[19]. Seuring and Müller [20] define SSC as “the management of material, information and capital flows as well as cooperation among companies along the supply chain while taking goals from all three dimensions of sustainable development, i.e., economic, environmental and social, into account which are derived from customer and stakeholder requirements”. Another definition comes from Pagell and Wu [18]: “SSC is one that performs well on both traditional measures of profit and loss as well as on an expanded conceptualization of performance that includes social and natural dimensions”. Discussions of sustainability are driven by the basic notion that a supply chain’s performance should be measured not just by profits, but also by the impact of the chain on ecological and social systems [18], [21]–[23].

Different authors and researchers have defined SSCM from similar and different perspectives, driving forces and purposes. However, all SSCM structures have commonly tree main aspects, namely economical, environmental and social. Fig. 1 depicts the requirements defined according to literature survey and expert views.

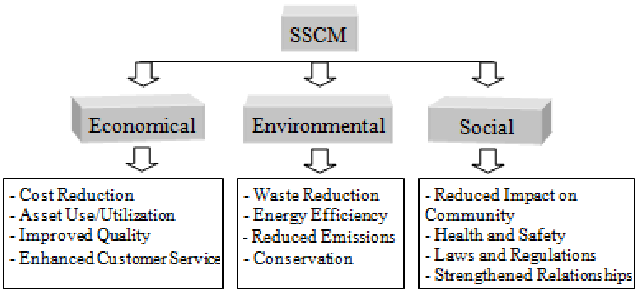


Fig. 1. Requirements from a SSC

*Economical requirements* ($CR_1$): There is no doubt that cost reduction and continuing financial benefit are fundamental goals of a supply chain. A number of studies have found that an increased emphasis on sustainability in the supply chain is related to lower costs and a neutral or positive effect on value [24]–[26]. Asset utilization is another important concern in SSC [27]–[30]. Reducing the materials used is needed for efficiency of the supply chain. Quality level should be maximized because quality is sine qua non for environmental protection and sustainable development. Quality is a widely accepted performance indicator for SSCs and it represents a common driving force for sustainable supply activities [24], [31], [32]. Finally, to enhance customer service is one the main focuses of SSCs. Several studies identified a trend that organizations are integrating environmental processes to their supply chains to reduce operating costs and improve their customer service [24]–[26].

*Environmental Requirements* ($CR_2$): The four major economical requirements dimensions are waste reduction, emission reduction, energy efficiency and conservation. The environmental based expectations of companies from a SSC are reduction of waste produced, material substitution through environmental sourcing of raw materials, waste minimization of hazardous materials, efficient use of energy, fuel and environment conservation [1], [28], [30], [32]. The environmental practices are dependent on wider aspects to be integrated in order to achieve firm’s goal of waste elimination and lower environmental impact. Hence, firms must integrate environmental aspects to ensure corporate survival and toward sustainable development. Rothenberg [33] noted that pollution prevention-environmental activities are often value-added for the firm since they reduce costs through material use reduction or through the avoidance of waste management costs.

*Social Requirements* ($CR_3$): Social requirements comprise four main dimensions such as reduced impact on community, health and safety, strengthened relationships, and laws and regulations. The aims to comply with legal requirements and to create a systematic management system have been reported as important driving forces for companies to implement sustainable/environmental activities [26], [32], [34]. Commitment to health and safety which meets minimum legal requirements is also needed as a social responsibility in a SSC. As final target, strengthened customer and business partner relationships is an important requirement for a SSC. By this means, firms can gain competitive advantage and improve firm performance.

### B. *Design Requirements for a SSCM structure*

As a result of the literature survey in the previous section and expert views, determined design requirements (DRs) for a SSCM are:

- $DR_1$: Price strategy
- $DR_2$: SC optimization
- $DR_3$: Supplier management
- $DR_4$: Flexible technology
- $DR_5$: Delivery performance
- $DR_6$:Environmental management system (ISO quality standards)
- $DR_7$: Environmental product design
- $DR_8$:Environmental activity capability (reuse, recycle, back packaging, ...)
- $DR_9$: Eco-friendly transportation
- $DR_{10}$: Collaboration with partners
- $DR_{11}$: Employee Practices (labor education, …)
- $DR_{12}$: Protecting rights (suppliers, customers, property, etc.)

## III. Integrated QFD Methodology

### A. *HOQ of QFD*

QFD was originally developed by Yoji Akao in 1966 when the author combined his work in quality assurance and quality control points with function deployment used in Value Engineering. Mr. Akao described QFD as “method to transform user demands into design quality, to deploy the functions forming quality, and to deploy methods for achieving the design quality into subsystems and component parts, and ultimately to specific elements of the manufacturing process” [35]. Although there have been many QFD studies and applications in the literature, different authors use different terms and methods and they also focus on different parts of the QFD system. There have been no consistent or

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unified accounts of the QFD concepts and procedures, which is uncommon for such a popular methodology and may be quite confusing for non-specialists [36].

The technique is characterized by a matrix called the House of Quality (HOQ) which is represented in Fig. 2. This matrix contains information about what to do (e.g., what customers want), how to do it (e.g., how technically CRs can be achieved), and the relationships between each of these aspects; prioritization of CRs and DRs; and what are the company's target levels. Quality functions are deployed by carrying "how to do" into the successive HOQ as "what to do" [37]. The detailed steps of HOQ applied in this paper can be seen in Sec. III-C.

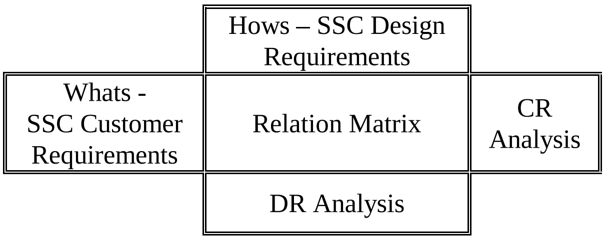


Figure 2. HOQ for SSC development

*B. Incomplete Preference Relations*

Recently, linguistic preference relations used by decision makers to express their linguistic preferences when comparing decision alternatives have been investigated in many documents [38]–[41]. Each of these preference relations necessitates the completion of all n(n-1)/2 judgments in its entire top triangular portion. Sometimes, however, it is difficult to obtain such a preference relation. This may be due to an expert not possessing a precise or sufficient level of knowledge of part of the problem, or because that expert is unable to discriminate the degree to which some options are better than others [10]. Since QFD approach contains multiple DMs and group decision process, with the use of incomplete preference relations, the evaluation would be more strong and healthier. As incomplete fuzzy preferences are not widespread as of today, incomplete preference studies are limited in the literature [10]–[14], [42], [43]. In addition there exists no study in the literature that neither combines those with QFD, nor any applications in the SSCM field.

*C. The Computational Procedure of Proposed Approach*

Step by step description of the proposed approach is as follows.

*Step 1: "Whats"*: This first step can also be called as *identifying the CRs*. In this step customer requirements must be identified and placed on the left side of the house. These requirements can be identified by making questionnaires to customers, by expert views, by literature survey, etc.

*Step 2: "Priority Analysis"*: In this step, a comparison of the CRs is wanted to determine the importance degrees. However, the information gained from DMs may not be adequate to accurately assign the importance degrees. We will overcome this obstacle through fuzzy GDM.

*Step 2.1: "CR Evaluation"*. Firstly, for the purpose of measuring the importance degrees among CRs, it is required to design a comparison scale. The scale shown in Table I is used to indicate the relative strength of each pair of elements $\tilde{p}_{ij} = (p^l_{ij}, p^m_{ij}, p^u_{ij})$ which indicates the importance among the compared criteria (importance of $i$ over $j$) where $i = j = 1,2,\ldots,n$.

Table I. Corresponding linguistic terms

| Linguistic variables | Fuzzy Scales |
|---|---|
| No influence (No) | (0. 0. 0.1) |
| Very low influence (VL) | (0. 0.1, 0.3) |
| Low influence (L) | (0.1, 0.3, 0.5) |
| Medium influence (M) | (0.3, 0.5, 0.7) |
| High influence (H) | (0.5, 0.7, 0.9) |
| Very high influence (VH) | (0.7, 0.9, 1) |
| Extreme influence (E) | (0.9, 1, 1) |

*Step 2.2: "Completion of the missing values"*. Once the DMs construct and evaluate the fuzzy pairwise comparison matrices of components, defuzzify those using Eq. (1).

$$F\left(\tilde{p}_{ij}\right) = 1/2 \int_0^1 \left(\inf_{x\in\Re} \tilde{p}^{\alpha}_{ij} + \sup_{x\in\Re} \tilde{p}^{\alpha}_{ij}\right) d\alpha \tag{1}$$

Then, missing values in a DM's incomplete preference relation can be computed. Based on Tanino's [44] "additive transitivity" property, by using an intermediate alternative $a_y$, the preference value of $p_{ij}$ $(i \neq j)$ can be calculated in three ways [10]:

1. From $p_{ij} = p_{iy} + p_{yj} - 0.5$, we obtain the estimate
$$cp^{y1}_{ij} = p_{iy} + p_{yj} - 0.5 \tag{2}$$
2. From $p_{yj} = p_{yi} + p_{ij} - 0.5$, we obtain the estimate
$$cp^{y2}_{ij} = p_{yj} - p_{yi} + 0.5 \tag{3}$$
3. From $p_{iy} = p_{ij} + p_{jy} - 0.5$, we obtain the estimate
$$cp^{y3}_{ij} = p_{iy} - p_{jy} + 0.5 \tag{4}$$

The preference value of one alternative over itself is always assumed to be equal to 0.5.

*Step 2.3: "Checking the consistency level"*. When working with the incomplete preference relation, the following sets can be used to estimate its consistency level:

$$H^1_{ij} = \{y \neq i, j \mid (i, y), (y, j) \in \text{EV}\} \tag{5}$$

$$H^2_{ij} = \{y \neq i, j \mid (y, i), (y, j) \in \text{EV}\} \tag{6}$$

$$H^3_{ij} = \{y \neq i, j \mid (i, y), (j, y) \in \text{EV}\}. \tag{7}$$

where EV is the set of pairs of alternatives for which the expert provides preference values, and $H^1_{ij}$, $H^2_{ij}$, $H^3_{ij}$ are the sets of intermediate alternative $a_y$ $(y \neq i,j)$ that can be used to estimate the preference value $p_{ij}$ $(i \neq j)$ using (5)–(7), respectively.

The consistency level $CL_{ij}$, associated with a preference value $p_{ij}$ $(i \neq j) \in$ EV,

$$CL_{ij} = \left(1-\alpha_{ij}\right)\cdot\left(1-\varepsilon p_{ij}\right) + \alpha_{ij}\cdot\frac{CP_i + CP_j}{2}, \ \alpha_{ij} \in [0,1] \tag{8}$$

is defined as a linear combination of the average of the completeness values associated to the two alternatives involved in that preference degree $CP_i$ and $CP_j$,

$$CP_i = \frac{\# EV}{2(n-1)} \tag{9}$$

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where $\# EV$ is the number of preference values known. And its associated error $\varepsilon p_{ij}$,

$$\varepsilon p_{ij} = \frac{2}{3} \cdot \frac{\varepsilon p_{ij}^1 + \varepsilon p_{ij}^2 + \varepsilon p_{ij}^3}{\kappa} \tag{10}$$

where

$$\varepsilon p_{ij}^1 = \begin{cases} \sum_{j \in H_{ij}^l} \left| cp_{ij}^{kl} - p_{ij} \right| \Big/ \# H_{ij}^l & , if \left( \# H_{ij}^l \neq 0 \right); l \in \{1,2,3\} \\ 0 & , otherwise \end{cases} \tag{11}$$

and

$$\kappa = \begin{cases} 3, & if \left( \# H_{ij}^1 \neq 0 \right) \wedge \left( \# H_{ij}^2 \neq 0 \right) \wedge \left( \# H_{ij}^3 \neq 0 \right) \\ 2, & if \left( \# H_{ij}^a = 0 \right) \wedge \left( \left( \# H_{ij}^b \neq 0 \right) \wedge \left( \# H_{ij}^c \neq 0 \right) \right); a,b,c \in \{1,2,3\} \\ 1, & otherwise \end{cases} \tag{12}$$

with $\alpha_{ij} = f\left( \# EV_i + \# EV_j - \# \left( EV_i \cap EV_j \right) \right)$, being $f$ a decreasing function with $f(0) = 1$ and $f(4(n-1)-2) = 0$,

$$\alpha_{ij} = 1 - \frac{\# EV_i + \# EV_j - \# \left( EV_i \cap EV_j \right)}{4(n-1) - 2}. \tag{13}$$

Detailed information about incomplete fuzzy preference relations and their mathematical formulation are given in [10].

*Step 2.4: "Aggregation of the evaluations"*. This process will reflect the opinions of the majority of the DMs. On this line, let $\{p_{ij}^1, \ldots, p_{ij}^l\}$ be the set of values to be aggregated for any $i, j \in R$ where the number DMs is denoted as $l = 1, \ldots, L_k$. Then the ordered weighted geometric (OWG) operator which is defined as:

$$\Phi^G \left\{ \left( p_{ij}^1, p_{ij}^2, \ldots, p_{ij}^{L_k} \right) \right\} = \prod_{l=1}^{L_k} \left( \overline{p}_{ij}^l \right)^{w_l}. \tag{14}$$

where, $W = (w_1, \ldots, w_{L_k})$ is an exponential weighting vector, such that $w_l \in [0,1]$ and $\sum w_l = 1$, and each $\overline{p}_{ij}^l$ is the $l$th largest valued element in the set $\left\{ p_{ij}^{k1}, p_{ij}^{k2}, \ldots, p_{ij}^{kL_k} \right\}$ [4], [45]. The OWG operator reflects the fuzzy majority if we calculate its weighting vector $W$ by means of a fuzzy linguistic quantifier [46]. In this study, we make use of the fuzzy majority which is a soft majority concept expressed by a fuzzy linguistic quantifier. Proportional quantifiers, such as *most*, *at least half*, may be represented by fuzzy subsets of the unit interval, [0,1]. Then, for any $r \in [0,1]$, $Q(r)$ indicates the degree to which the proportion $r$ is compatible with the meaning of the quantifier it represents. For a non decreasing relative quantifier, $Q$, the weights are obtained as $w_l = Q(l/L_k) - (Q(l-1)/L_k)$, $l = 1, \ldots, L_k$ where $Q(y)$ is defined as: 0, if $y <$ a; $(y - a)/(b - a)$, if $a \leq y \leq b$; and 1, if $y \geq b$. Note that $a$, $b$, $y \in [0,1]$ and $Q(y)$ indicates the degree to which the proportion $y$ is compatible with the meaning of the quantifier it represents. Some examples for the relative quantifiers are "most" (0.3, 0.8), "at least half" (0, 0.5) and "as many as possible" (0.5, 1). When the fuzzy quantifier $Q$ is used for calculating the weights of the OWG operator $\Phi_W^G$, it is represented by $\Phi_Q^G$. Therefore, the collective multiplicative relative importance relation is obtained as follows;

$$p_{ij}^k = \Phi_Q^G \left( p_{ij}^{k1}, p_{ij}^{k2}, \ldots, p_{ij}^{kL_k} \right), 1 \leq i \neq j \leq n. \tag{15}$$

*Step 2.5: "Obtaining priorities from the judgment matrix"*. After the group opinion collected in the matrix $P$, it must be exploited to determine the importance weights of the criteria. Note that in $P$, the $ij$ element reflects the relative importance of criterion $i$ compared to criterion $j$. Next, calculate the quantifier guided importance degree of each criterion, which quantifies the importance of one criterion compared to others in a fuzzy majority sense. By using the OWG operator, we have

$$QGID_i = \frac{1}{2}\left( 1 + \log_9 \Phi_Q^G \left( p_{ij} : j = 1, \ldots, n \right) \right). \tag{16}$$

for all $i = 1, \ldots, n$. Finally, the obtained $QGID_i$ values should be normalized, i.e., $QGID_i = QGID_i / \sum_i QGID_i$, to have the importance degrees in percentage. These steps need to be pursued in all nodes of the evaluation model.

*Step 3: "Hows":* This step can also be called as *developing/defining DRs*. The first step of the DR part is transforming CRs to technical attributes. DRs are specified on the basis of the company's operational or managerial resource allocation plans in order to satisfy the customers. In defining the DRs, the most important point is, finding direct solutions to defined CRs.

*Step 4: "Relation Matrix":* Here relationship matrix is constructed between CRs and DRs. Each of the DRs is correlated individually to each of the CRs by considering to what extent a requirement contributes to meeting customer needs for the attribute. Depending upon the impact of the DRs on meeting CRs for the attribute, "Empty=no relationship", "1=possible relationship", "3=moderate relationship", and "9=strong relationship" is assigned.

*Step 5: "Prioritizing DRs":* The importance of each DR is computed using the relationship matrix and the relative importance of each CR. The accuracy of the results in this step relies heavily on the quality of the relationship matrix. This computation process intertwines CRs with DRs. That is, the resulting value determines the relative weight of each DRs as compared to CRs. The importance of each DR is calculated as the sum of each CR importance value multiplied by the quantified relationship between the same CR and the current DR.

## IV. APPLICATION OF THE SSC MODEL

Here, the SSC model determined in Sec. II is illustrated with the proposed approach. In our example there are three DMs, namely project manager, R&D engineer and top manager.

*Step 1: "Whats"*: The SSC model determined in Sec. II comprises the whats-CRs.

*Step 2: "Priority Analysis"*:

*Step 2.1:* Table II gives the evaluation of the DMs for the purpose of measuring the importance degrees among primary level factors namely economic (CR1), environmental (CR2) and social (CR3) requirements.

Table II. Incomplete linguistic evaluation of DMs

| | DM1 | | | DM2 | | | DM3 | | |
|---|---|---|---|---|---|---|---|---|---|
| | $CR_1$ | $CR_2$ | $CR_3$ | $CR_1$ | $CR_2$ | $CR_3$ | $CR_1$ | $CR_2$ | $CR_3$ |
| $CR_1$ | - | M | M | - | x | x | - | x | x |
| $CR_2$ | x | - | x | M | - | VH | x | - | x |

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| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| $CR_3$ | x | x | - | x | x | - | VH | H | - |

*Step 2.2:* To complete the missing values, firstly by using Eq. (1), Table III which shows the defuzzified incomplete preferences of the group is obtained. Eqs. (2-4) are used to estimate the missing values shown in Table IV.

Table III. Defuzzified incomplete evaluation of DMs

| | DM1 | | | DM2 | | | DM3 | | |
|---|---|---|---|---|---|---|---|---|---|
| | $CR_1$ | $CR_2$ | $CR_3$ | $CR_1$ | $CR_2$ | $CR_3$ | $CR_1$ | $CR_2$ | $CR_3$ |
| $CR_1$ | - | 0.50 | 0.50 | - | x | x | - | x | x |
| $CR_2$ | x | - | x | 0.50 | - | 0.88 | x | - | x |
| $CR_3$ | x | x | - | x | x | - | 0.88 | 0.70 | - |

Table IV. Estimated complete evaluation of DMs

| | DM1 | | | DM2 | | | DM3 | | |
|---|---|---|---|---|---|---|---|---|---|
| | $CR_1$ | $CR_2$ | $CR_3$ | $CR_1$ | $CR_2$ | $CR_3$ | $CR_1$ | $CR_2$ | $CR_3$ |
| $CR_1$ | - | 0.50 | 0.50 | - | 0.50 | 0.88 | - | 0.32 | 0.12 |
| $CR_2$ | 0.50 | - | 0.50 | 0.50 | - | 0.88 | 0.68 | - | 0.30 |
| $CR_3$ | 0.50 | 0.50 | - | 0.12 | 0.12 | - | 0.88 | 0.70 | - |

As an example, to estimate $p_{23}$ in the evaluation of DM1, the procedure is as follows:

$H_{23}^{1} = \{1\}$ as $cp_{23}^{11} = p_{21} + p_{13} - 0.5 =$ unknown

$H_{23}^{2} = \emptyset$ as $cp_{23}^{12} = p_{13} - p_{12} + 0.5 = 0.50$

$H_{23}^{3} = \emptyset$ as $cp_{23}^{13} = p_{21} - p_{31} + 0.5 =$ unknown

thereby, $cp_{23} = 0.50$.

*Step 2.3:* After missing values are completed, finally consistency is checked. The corresponding consistency level matrix is shown in Table V.

Table V. Consistency levels of DMs' evaluations

| | DM1 | | | DM2 | | | DM3 | | |
|---|---|---|---|---|---|---|---|---|---|
| | $CR_1$ | $CR_2$ | $CR_3$ | $CR_1$ | $CR_2$ | $CR_3$ | $CR_1$ | $CR_2$ | $CR_3$ |
| $CR_1$ | - | 0.58 | 0.58 | - | 0.58 | 0.50 | - | 0.50 | 0.58 |
| $CR_2$ | 0.58 | - | 0.50 | 0.58 | - | 0.58 | 0.50 | - | 0.58 |
| $CR_3$ | 0.58 | 0.50 | - | 0.50 | 0.58 | - | 0.58 | 0.58 | - |

Continuing on the same example, the consistency level is calculated using Eqs. (8-13) as follows:

$EV_1 = \{(1,2),(1,3)\}$; $EV_2 = \{(1,2)\}$; $EV_3 = \{(1,3)\}$.

$CP_1 = 2/4$, $CP_2 = 1/4$, $CP_3 = 1/4$.

$\alpha_{23} = 1 - \left[(2 + 1 - 1)/4(3 - 1) - 2\right] = 0.67$ .

As there is no intermediate alternative to calculate an estimated value except $a_1$, consequently $\varepsilon p_{23} = 0$ and,

$$CL_{23} = (1 - 0{,}67)\cdot(1 - 0) + 0{,}67 \cdot \frac{1/4 + 1/4}{2} = 0.50.$$

*Step 2.4:* Taking into account all matrices obtained from project managers group, using of Eqs. (14-15), the OWG operator with fuzzy linguistic quantifier 'at least half' is used to compute the group importance relation matrix as shown in Table VI with weighting vector (0.666, 0.334, 0.000).

Table VI. Importance relation matrix of DMs

| | $CR_1$ | $CR_2$ | $CR_3$ |
|---|---|---|---|
| $CR_1$ | 0.50 | 0.50 | 0.73 |
| $CR_2$ | 0.61 | 0.50 | 0.61 |
| $CR_3$ | 0.60 | 0.56 | 0.50 |

*Step 2.5:* Eq. (16) is used to compute group aggregated importance values with weighting vector (0.066, 0.667, 0.267) corresponding to the fuzzy linguistic quantifier 'most'. The collaborative importance values are calculated as (0.3994, 0.3766, 0.3621). Then by normalizing these values, priority of the primary level requirements is determined as (0.35, 0.33, 0.32). Same computational procedure is carried out for all secondary level comparisons to obtain the priorities. Finally, global importance values are calculated by multiplying primary level priorities with related secondary level priorities.

*Step 3: "Hows":* The SSC model determined in Sec. II again comprises the hows-DRs.

*Step 4: "Relation Matrix":* Relation degrees between CRs and DRs can be seen from the final HOQ matrix in Fig. 3. For instance, first economical factor "cost reduction" is in direct relationship with almost all the DRs because firms essentially aim to provide reduction in costs.

| Relationship Strength: S: Strong M: Moderate P: Possible | | $DR_1$ | $DR_2$ | $DR_3$ | $DR_4$ | $DR_5$ | $DR_6$ | $DR_7$ | $DR_8$ | $DR_9$ | $DR_{10}$ | $DR_{11}$ | $DR_{12}$ | Importance |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $CR_1$ $CR_2$ | $CR_{11}$ | | S | M | M | M | S | M | M | S | P | P | | 0.098 |
| | $CR_{12}$ | | S | | | P | | M | M | M | | | | 0.084 |
| | $CR_{13}$ | | S | S | M | M | M | M | M | M | M | M | P | 0.088 |
| | $CR_{21}$ | S | S | M | | M | S | M | | | M | S | M | 0.081 |
| $CR_3$ | $CR_{22}$ | | P | | | S | S | M | S | | | | | 0.026 |
| | $CR_{23}$ | | S | | S | | S | | | | | | | 0.086 |
| | $CR_{24}$ | | S | M | M | | S | | | M | | S | | 0.102 |
| | $CR_{31}$ | | S | M | S | M | S | | M | S | | S | | 0.116 |
| $CR_1$ | $CR_{32}$ | | P | | | | M | M | P | M | | | | 0.054 |
| | $CR_{33}$ | | | P | P | | S | M | P | | M | S | | 0.096 |
| | $CR_{34}$ | | | | M | | M | P | M | | P | S | S | 0.109 |
| | $CR_{11}$ | M | | S | | | | | | | S | M | S | 0.061 |
| Importance of DRs | | 0.907 | 5.963 | 2.620 | 3.098 | 1.466 | 6.193 | 1.689 | 1.869 | 2.906 | 1.546 | 5.071 | 1.855 | |
| Importance % | | 0.026 | 0.169 | 0.074 | 0.088 | 0.042 | 0.176 | 0.048 | 0.053 | 0.083 | 0.044 | 0.144 | 0.053 | |
| Ranking | | 12 | 2 | 6 | 4 | 11 | 1 | 9 | 7 | 5 | 10 | 3 | 8 | |

Figure 3. The final HOQ

*Step 5: "Prioritizing DRs":* Priorities of the DRs can be seen from the final HOQ matrix in Fig. 3. For example, importance weight of DR1 is calculated such that (9*<0.0805) + (3*0.0608) = 0.907. After it is normalized, its priority is equal to 0.0258 and its rank 12.

Looking at the DRs for a SSC, the most important factor is found as environmental management system. The reason is that factor has positive relations with almost all CRs. Following key factors are determined as SC optimization and employee practices. While SC optimization provides benefit to firms economically, it has direct positive relations with conditions such as reduction of emissions, energy efficiency, etc. Employee practices factor is also important for a SSCM design and it is in relationship with vital factors such as laws and regulation, health and safety, and improved quality.

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## V. Conclusion

In this study, requirements of a SSCM structure are investigated by the aid of HOQ which underlies the QFD technique. The most important issue to be considered is that firms avoid of SSC activities due to the cost of investments. Firms should be aware of the great advantages of these investments in terms of sustainability.

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