

On a Generic Framework for Sustainable Product Design: an Application to a Food Product

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ABSTRACT

Addressing sustainability is a major task in several industries to meet customer requirements. Together with the rapidly increasing population, the consumption of natural resources has drastically increased resulting in a global issue of scarcity. The manufacturing industry has been at the forefront of such sustainability challenges and sustainable product design is regarded as a key to achieving manufacturing sustainability. Several studies have already been conducted in the pursuit of promoting sustainable product design by satisfying the requirements of the triple-bottom line. However, significant gaps in sustainable product design were not yet explored in current literature which includes the limited (1) inclusion of social dimension, (2) consideration of multiple stakeholders and (3) use of the four-phase quality function deployment. This work attempts to address these gaps by proposing a general framework based on fuzzy quality function deployment-multiple criteria decision making in a multi-stakeholder multi-phase approach. A case study was conducted in an oil production to test the viability of the methodology. Results show that the oil industry's top priorities on phases I, II, III, and IV are accreditation requirements; follow standard specifications, procedures and processes, criticize all aspects of the product and make improvements, and consultation oil experts regularly. It is shown in this work that the framework is viable in implementing sustainable product design.

KEYWORDS: *analytic hierarchy process, analytic network process, decision-making trial and evaluation laboratory, fuzzy set theory, quality function deployment, sustainable product design*

1 INTRODUCTION

Quality function deployment (QFD) is a customer-oriented visual (Devanathan *et al.*, 2010) and analytical tool that is widely used in product design and development (Chan and Wu, 2002). It provides a systematic approach in the translation of customer

requirements (CRs) or customer attributes (CAs) into design requirements (DRs), which is also termed by some scholars as technical characteristics (TCs) (Younesi and Roghanian, 2015) or engineering characteristics (ECs) (Lee *et al.*, 2010; Liu, 2011) to meet customers' expectation by bridging the perception disparity between the customers and the design team (Ko, 2015). Cheng and Ko (2009) described the QFD in four phases: (1) relating the voice of the customer to product design requirements, (2) translating these design requirements into parts characteristics, (3) manufacturing operations, and (4) production requirements. The first phase of the QFD is inspired by the house of quality (HoQ) (Younesi and Roghanian, 2015) and it is considered as the central construct of the QFD. In fact, most of published works on QFD-based product design focuses only on the HoQ, the first phase of the QFD.

For years, in the pursuit of integrating the environmental requirements with the traditional design requirements, several product designs have considered the environmental aspects of products based on the QFD in order to assess, improve, and develop criteria for an environmentally-benign product design. The first attempt can be traced back from the work of Hochman and O'Connell (1993) which considered some environmental requirements into the traditional QFD. Zhang *et al.* (1999) developed the green QFD-II which is based on life cycle assessment (LCA) and life cycle cost. Masui *et al.* (2001) developed the QFDEnvironment which prioritizes the functions and components of the product. Wong and Jupiter (2002) improved the approach of Zhang *et al.* (1999) by proposing a green QFD that relates product's environmental specifications, demanded (or required) quality, and technical specifications. Rahimi and Weidner (2002) participated the race by introducing the QFD-Design for Environment (QFD-DfE) which attempts to relate customer satisfaction, cost reduction and environmental impacts of products. Kato and Kimura (2003) proposed the Environmental QFD which provides a systematic association of environmental and technological requirements. Yim and Herman (2003) developed an extension by focusing on the CRs and then coming up with the voice of environmental customer (eco-voice). They coined the term Eco-VOC (Eco-Voice of Customers) to integrate

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the eco-voice. In the same year, Emzer *et al.* (2003) proposed the E12QFD which extends the eco-voice to voice of the environment through the eco-indicator 99. Sakao *et al.* (2003) extended the QFD to design environmentally conscious services. Ernzer and Birkhofer (2003) promoted an eco-QFD that translates CRs to product environmental requirements. Shih and Liu (2005) developed the 3D QFDE of Masui *et al.* (2001) which highlights product design decisions within the context of environmental requirements. Sakao *et al.* (2005) extended their previously developed QFDE by incorporating the LCA. Cagno and Trucco (2007) improved the QFD-II of Zhang *et al.* (1999) by excluding the life cycle costing. Sakao (2007) provided again an extension of their QFDE-LCA by integrating the concept of TRIZ problem-solving technique. Kuo *et al.* (2009) adopted the fuzzy logic to the widely used Eco-QFD model to address the uncertainty of environmental CRs which must be translated to DRs. Vinodh and Rathod (2010) integrated LCA and ECQFD in order to reflect the voice of the customers. Otani and Yamada (2011) pointed out that there are three parts for sustainable product design: customer needs, environmental performance, and economic in which QFD for environment (QFDE) or environmental QFD (E-QFD) includes these considerations. QFDE is one of the most significant tools and most cited methods in the subject of environmental QFD (Younesi and Roghanian, 2015) derived from the traditional QFD, which was developed by Masui *et al.* (2001). A major drawback of this integration is that it failed to address the social dimension of sustainability which is an equally important dimension. The social dimension, in the context of product design, ensures the development and processing of manufactured products that promote health and safety of the customers, the well-being of the employees and the community, welfare of the products' stakeholders (e.g., suppliers, shareholders, government) and social value in terms of poverty alleviation, job creation, and gender, culture and racial equity.

Aside from the lack of integration with the social dimension, current literature also failed to address the explicit requirements of different stakeholders in sustainable product design since previous studies have treated customer requirements as the primary focus. Gmelin and Seuring (2014) stated that the main drivers for sustainable products are the customers but argued that there might be more triggers for a sustainable product design internally or externally. In addition to the claim, Ocampo and Clark (2014) have also the internal and external factors that would drive the implementation of sustainability. Internal factors are the self-driven interest such as top management pressure and organizational culture while external factors are stakeholders' interest such as international standards, government regulations, community pressures, competitors, and suppliers' interest (Ocampo and Clark, 2014). Since sustainable product design must be more encompassing, the design considerations must supposedly address the four phases of the QFD but current literature seemed to deliberately exclude other

phases of the QFD. Cohen (1995) argued that QFD is incomplete unless a series of interrelated matrices are constructed. The holistic consideration of the QFD that is portrayed in four phases is crucial in sustainable product design because it integrates the interconnected sustainability decisions in product planning, design deployment, manufacturing planning, and production planning.

The integration of multi-attribute decision-making (MADM) methods has addressed some issues of the traditional QFD. For instance, the traditional QFD uses a scale of 1-5 to rank the importance of CRs while the integrated QFD-MADM adopts a linguistic scale (e.g., Saaty (1980)) and performs a pairwise comparison between CRs with respect to a goal (e.g., sustainable product design) to generate weights which reflect the important priority of CRs. Another point of advances of QFD-MADM considers the interrelations of CRs which may reflect real-life conditions. The integration is viable since HoQ is a matrix approach in all conventional QFDs (Aghdam *et al.*, 2015; Cohen, 1995) and MADM tools deal with matrices. The integration of MADM tools or hybrid MADM tools in QFD for sustainable product design was explored by Chen and Ko (2009), Lee *et al.* (2010), Kim *et al.* (2010), and Modjedh and Younesi (2015).

Among various MADM methods, analytic hierarchy process (AHP) and analytic network process (ANP) are popularly used (Mehrerjedi, 2010). AHP and ANP were developed by Saaty (1980; 1996) who offers a framework of deriving priority weights of elements on the same level with respect to an element in a higher level or in another component in the same level (i.e., in the ANP). Thus, AHP and ANP are suitable for the prioritization of CRs and DRs of QFD and this has been reported in several works. Rajesh and Mallinga (2013) integrated AHP with QFD for supplier selection wherein AHP was used to determine the weights of CRs and for the computation of individual scores for each supplier. Chadawada *et al.* (2015) have similarly used AHP in QFD for the selection of a facility location. Pal *et al.* (2007) integrated ANP to incorporate the inner dependence issues into CRs and DRs in the HoQ to propose a rapid tooling route selection for metal casting. Other less prominent MADM methods in QFD-MADM integration include decision-making trial and evaluation laboratory (DEMATEL) (Yazdani *et al.*, 2017), a technique for order preference by similarity to an ideal solution (TOPSIS) (Li *et al.*, 2014; Haq and Boddu, 2015; Akbaşa and Bilgen, 2017; Cho *et al.*, 2017). Aside from using MADM methods in QFD, the use of fuzzy set theory (FST) with MADM becomes popular because in the traditional QFD, most of the variable inputs are assumed to be precise and are treated as crisp numerical data. This limitation contrasts real-life conditions of impreciseness and ambiguity; thus, the use of linguistic variables with corresponding fuzzy numbers is considered as a more appropriate approach (Zaim *et al.*, 2014). FST deals with uncertainty in decision-making, a widely-known characteristic in decision-making particularly in MADM. The difference between the conventional QFD

and fuzzy QFD is in the data representation found in Section D of the HoQ, the former uses symbols to represent the strength of its relationship with a corresponding quantitative value (Cohen, 1995) and the values were treated as precise while the latter uses a linguistic scale with corresponding fuzzy numbers to deal with the impreciseness of rating values (Zaim *et al.*, 2014). The use of fuzzy QFD has been reported in several recent works (e.g., Ayağ *et al.*, 2013; Lee *et al.*, 2015; Lima-Junior and Carpinetti, 2016; Çevik Onar *et al.*, 2016; Haq and Boddu, 2017).

This paper identifies the major gaps in the current literature of sustainable product design which include the following: (1) the social dimension of sustainability is not addressed, (2) stakeholder requirements are not explicitly considered, (3) interrelated matrices are not reflected in the design process, and (4) recent QFD-MADM frameworks have some limitations in addressing holistic interrelationships among stakeholder requirements and design requirements. Thus, this study aims to address these gaps by proposing a comprehensive sustainable product design by incorporating stakeholder requirements in the context of sustainability and by offering a hybrid MADM approach under a fuzzy environment. FST is integrated with AHP, ANP, and DEMATEL into a carefully structured QFD in four phases. To demonstrate the applicability of the approach, a case study involving food product design was carried out in this work. The contribution of this study is the holistic approach to sustainability in a multi-stakeholder fashion in developing a sustainable product design.

2 PROPOSED FRAMEWORK

To address the gaps in the current literature, Figure 1 shows the proposed fuzzy QFD-MADM structure. Each section is presented with corresponding letters. Fuzzy AHP is adopted to obtain the values of section A with respect to the goal – sustainable product design. Fuzzy DEMATEL is adapted to generate the causal relationships of stakeholder requirements (SRs) in section B and the causal relationships of DRs in section D. Once the most significant causal relationships are identified in sections B and D, fuzzy AHP is used to calculate the values of section C with respect to SR and to section E with respect to DR. To determine the values in section F, fuzzy AHP is used by performing a pairwise comparison of DRs with respect to SRs.

Figure 2 shows the proposed sustainable product design in four phases (i.e., product planning, design deployment, process planning, and production planning) in a sequential and interconnected manner. The processes in the succeeding phases (i.e., design deployment, process planning, and production planning) are patterned similarly to the processes in product planning phase (phase 1) with variables consistent to the requirements of each phase.

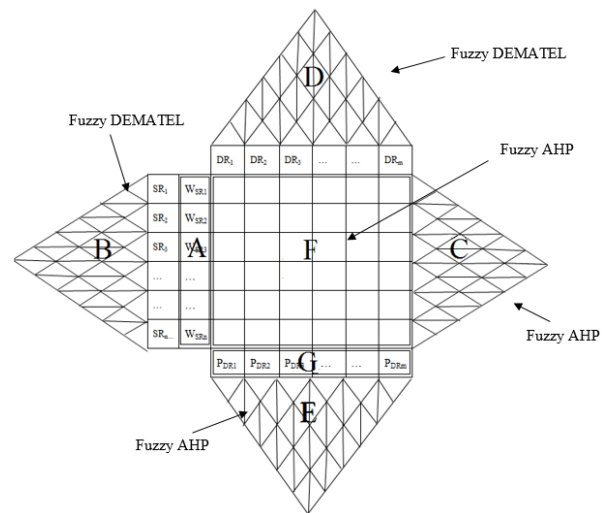


Figure 1. Proposed fuzzy QFD-MADM structure

3 METHODOLOGY

This work aims to propose an integrated framework for sustainable product design by explicitly incorporating stakeholder requirements and implementing an interconnected computational approach based on FST, AHP, DEMATEL, and ANP for the four phases of the QFD. The detailed computations were based on Figure 1 and Figure 2 are presented as follows:

Phase I – Product Planning

A. Calculation of weights located at Section A in Figure 2.

Step 1. Identify the SRs of the product and deploy relevant DRs.

Step 2. Generate a pairwise comparison matrix (PCM) among SRs with respect to the goal.

Step 3. Integrate FST with AHP, where the linguistic variables with corresponding fuzzy numbers (e.g., Tseng *et al.*, 2012) are used in comparing SRs with respect to the goal – which is to achieve a sustainable product design – in the PCM. Proposed by Tseng *et al.* (2008), Table 1 shows an example of linguistic variables with corresponding fuzzy numbers and their reciprocals. Triangular fuzzy numbers (TFNs) are widely used among other forms of fuzzy numbers (Ocampo *et al.*, 2015).

Step 4. Gather the elicited individual judgments from the *K* decision-makers.

Step 5. Set up the fuzzy PCM \tilde{A}^k elicited by the *k*th decision-maker represented as:

$$\tilde{A}^k = \begin{bmatrix} \langle 1,1,1 \rangle & \tilde{a}_{12}^k & \dots & \tilde{a}_{1n}^k \\ \tilde{a}_{21}^k & \langle 1,1,1 \rangle & \dots & \tilde{a}_{2n}^k \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{a}_{n1}^k & \tilde{a}_{n2}^k & \dots & \langle 1,1,1 \rangle \end{bmatrix}, k = 1,2,3, \dots K \quad (1)$$

where $\tilde{a}_{ij}^k = (l_{ij}^k, m_{ij}^k, u_{ij}^k)$, $i, j \in n$ and $l_{ij}^k \leq m_{ij}^k \leq u_{ij}^k$ where \tilde{a}_{ij}^k represents the fuzzy judgment assessed by the k th decision-maker on the relative importance of SR i over SR j with respect to the development of a sustainable product design using the scale shown in Table 1.

Step 6. Check for the consistency index of each \tilde{A}^k by solving the non-linear programming problem proposed by Mikhailov and Tsvetinov(2004) as shown in (2).

$$\begin{aligned} &\max \lambda \\ &\text{subject to:} \\ &(m_{ij} - l_{ij}) \lambda w_j - w_i + l_{ij} w_j \leq 0; \\ &(u_{ij} - m_{ij}) \lambda w_j + w_i - u_{ij} w_j \leq 0; \\ &\sum_{k=1}^n w_k = 1; w_k > 0. \end{aligned} \tag{2}$$

$$l_{ij} = \left(\prod_{k=1}^K (l_{ijk})^{v_k}\right); m_{ij} = \left(\prod_{k=1}^K (m_{ijk})^{v_k}\right); u_{ij} = \left(\prod_{k=1}^K (u_{ijk})^{v_k}\right) \tag{3}$$

Where v_k is the weight associated with the importance of the decisions carried out by the k th decision-maker. This process results to an aggregate fuzzy PCM $\tilde{A} = (\tilde{a}_{ij})_{n \times n} = ((l_{ij}, m_{ij}, u_{ij}))_{n \times n}$ as shown in (4).

$$\tilde{A} = \begin{bmatrix} \langle 1,1,1 \rangle & \tilde{a}_{12} & \dots & \tilde{a}_{1n} \\ \tilde{a}_{21} & \langle 1,1,1 \rangle & \dots & \tilde{a}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{a}_{n1} & \tilde{a}_{n2} & \dots & \langle 1,1,1 \rangle \end{bmatrix} \tag{4}$$

The consistency of the initial set of fuzzy judgments made by the decision-makers can be measured using this formula. If the optimal value λ is positive and within the range from 0 to 1, all solution ratios completely satisfy the fuzzy judgments which means that the initial set of fuzzy judgments is consistent. On the other hand, if the optimal value λ is negative, the solution ratios of the fuzzy judgments are strongly inconsistent. If $\lambda < 0$, then the decision-makers must reconsider their judgments.

Step 7. Aggregate the judgments of K decision-makers using the weighted geometric mean method proposed by Promentilla *et al.* (2014) shown in equation (3)

Step 8. Compute for the weights of the elements in the aggregate fuzzy PCM and its corresponding consistency using (2). The strength of the model in (2) compared to other approaches in solving fuzzy AHP is that it can compute for sparse PCM, i.e. incomplete PCM because of the hesitance of the decision-makers in eliciting judgments for a particular element or a number of elements in the PCM.

Step 9. Place the weights in the corresponding positions in Section A.

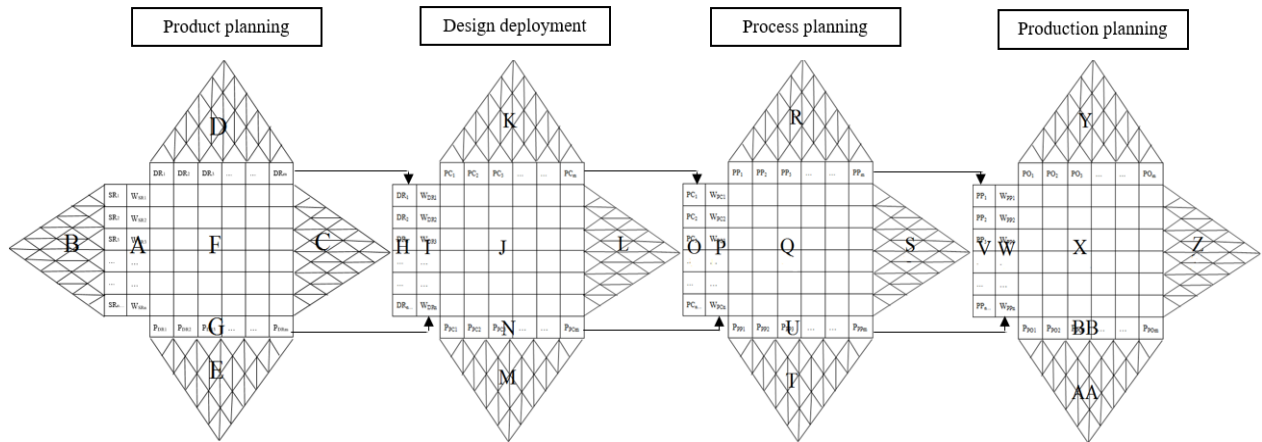


Figure 2. Proposed sustainable product design framework

B. Calculation of SRs causal relationships

Step 1. Gather the elicited individual judgments from the K decision-makers regarding the causal relationships among SRs.

Step 2. Construct the fuzzy direct-relation matrix (\tilde{Z}^k) where $k=1,2,\dots,K$ using the linguistic variables shown in Table 2 as adopted from Tseng (2012). Note that the corresponding triangular fuzzy numbers of the linguistic variables are not only limited to the description presented in Table 2. The causal relationship between two attributes denoted as \tilde{z}_{ij}^k is based on the causal impact of the i th attribute on the j th attribute as perceived by the k th decision-maker. The fuzzy direct-relation matrix is represented as:

$$\tilde{Z}^k = \begin{bmatrix} 0 & \tilde{z}_{12}^k & \dots & \tilde{z}_{1n}^k \\ \tilde{z}_{21}^k & 0 & \dots & \tilde{z}_{2n}^k \\ \vdots & \vdots & 0 & \vdots \\ \tilde{z}_{n1}^k & \tilde{z}_{n2}^k & \dots & 0 \end{bmatrix}, k = 1,2, \dots, K \tag{5}$$

Table 2 shows the linguistic variables with the corresponding influence score and triangular fuzzy scale.

Step 3. Aggregate the judgment of the decision-makers by using (6).

$$l_{ij} = \frac{\sum_{k=1}^K l_{ijk}}{K}; m_{ij} = \frac{\sum_{k=1}^K m_{ijk}}{K}; u_{ij} = \frac{\sum_{k=1}^K u_{ijk}}{K} \quad (6)$$

Construct the fuzzy aggregate initial direct relation matrix $\tilde{Z} = (\tilde{z}_{ij})_{n \times n} = (l_{ij}, m_{ij}, u_{ij})_{n \times n}$ represented as:

Step 4. Obtain the fuzzy normalized direct relation matrix \tilde{X} using Eq. (8).

$$\tilde{Z} = \begin{bmatrix} 0 & \tilde{z}_{12} & \dots & \tilde{z}_{1n} \\ \tilde{z}_{21} & 0 & \dots & \tilde{z}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{z}_{n1} & \tilde{z}_{n2} & \dots & 0 \end{bmatrix} \quad (7)$$

$$\tilde{X} = \begin{bmatrix} 0 & \tilde{x}_{12} & \dots & \tilde{x}_{1n} \\ \tilde{x}_{21} & 0 & \dots & \tilde{x}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{x}_{n1} & \tilde{x}_{n2} & \dots & 0 \end{bmatrix},$$

where $\tilde{x}_{ij} = \frac{\tilde{z}_{ij}}{r} = \left(\frac{x_{lij}}{r}, \frac{x_{mij}}{r}, \frac{x_{uij}}{r} \right);$
 $r = \max_{1 \leq i \leq n} (\sum_{j=1}^n u_{ij}) \quad (8)$

Step 5. Let $\tilde{x}_{ij} = (l'_{ij}, m'_{ij}, u'_{ij})$ and define X_l, X_m and X_u as

$$X_l = \begin{bmatrix} 0 & l'_{12} & \dots & l'_{1n} \\ l'_{21} & 0 & \dots & l'_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ l'_{n1} & l'_{n2} & \dots & 0 \end{bmatrix};$$

$$X_m = \begin{bmatrix} 0 & m'_{12} & \dots & m'_{1n} \\ m'_{21} & 0 & \dots & m'_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ m'_{n1} & m'_{n2} & \dots & 0 \end{bmatrix};$$

$$X_u = \begin{bmatrix} 0 & u'_{12} & \dots & u'_{1n} \\ u'_{21} & 0 & \dots & u'_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ u'_{n1} & u'_{n2} & \dots & 0 \end{bmatrix} \quad (9)$$

Step 6. Compute for the fuzzy total relation matrix T using Eq. (10).

$$\tilde{T} = \lim_{k \rightarrow \infty} (\tilde{X}^1 + \tilde{X}^2 + \dots + \tilde{X}^k)$$

where matrix $\tilde{T} = \begin{bmatrix} \tilde{t}_{11} & \tilde{t}_{12} & \dots & \tilde{t}_{1n} \\ \tilde{t}_{21} & \tilde{t}_{22} & \dots & \tilde{t}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{t}_{n1} & \tilde{t}_{n2} & \dots & \tilde{t}_{nn} \end{bmatrix} \quad (11)$

$$\tilde{t}_{ij} (l''_{ij}, m''_{ij}, u''_{ij}) \text{ and } [l''_{ij}] = X_l \times (I - X_l^{-1}) \quad (12)$$

$$[m''_{ij}] = X_m \times (I - X_m^{-1}), [u''_{ij}] = X_u \times (I - X_u^{-1}) \quad (13)$$

Step 7. Construct a crisp (non-fuzzy) total relation matrix $T = (t_{ij})_{n \times n}$ where

$$t_{ij} = \frac{l''_{ij} + 4m''_{ij} + u''_{ij}}{6} \quad (14)$$

Step 8. Obtain the sum of rows denoted as D using (15) and the sum of columns denoted as R using (16) to compute the values of influence and relation by using D-R and D+R

$$D = [\sum_{j=1}^n t_{ij}]_{n \times 1} = [t_i]_{n \times 1} \quad (15)$$

$$R = [\sum_{i=1}^n t_{ij}]_{1 \times n} = [t_j]_{1 \times n} \quad (16)$$

Step 9. It is necessary for the DMs to set up a threshold value α to filter out some negligible effects. If $t_{ij} \geq \alpha$, then the impact of SR i on SR j is significant.

Step 10. Construct a matrix $\tilde{T} = (\tilde{t})$ where $\tilde{t} = 1$ if $t_{ij} \geq \alpha$ and $\tilde{t} = 0$ if $t_{ij} < \alpha$.

Step 11. Reflect the results in section B.

C. Calculation of weights of SRs

Step 1. Construct fuzzy PCMs of SRs with respect to SRs with results from **Step 10** of part B.

Step 2. Perform steps 6 to 8 in part A to obtain the corresponding weights of the SRs.

Step 3. Place the results to the corresponding designated area of section C.

Step 4. Repeat steps 1 to 3 until all of the weights of appropriate SRs were placed to the corresponding area of section C.

D. Calculation of DRs causal relationships

Step 1. Gather the elicited individual judgments of K decision-makers regarding the causal relationships among DRs.

Step 2. Perform steps 2 to 11 of part B in order to get the corresponding causal impacts between DRs.

Step 3. Place the results in section D.

E. Calculation of weights of DRs

Step 1. Construct fuzzy PCMs of DRs with respect to DRs with results from **Step 10** of part B.

Step 2. Perform steps 6 to 8 in part A to obtain the corresponding weights of the DRs.

Step 3. Place the results to the corresponding designated area of section E.

Step 4. Repeat steps 1 to 3 until all of the weights of appropriate DRs were placed to the corresponding area of section E.

F. Calculation of weights of DRs with respect to SRs

Step 1. Construct fuzzy PCMs of DRs with respect to SRs.

Step 2. Perform steps 6 to 8 in part A to obtain the corresponding weights of the DRs for each SR.

Step 3. Place the results to the designated area of section F located in the row of the corresponding SR.

Step 4. Perform steps from 1 and 3 until all of the weights of DRs with respect SR were placed into the designated area in section F.

G. Construction of the Supermatrix

Step 1. Construct the initial supermatrix based on the corresponding decision model generated from the QFD.

Step 2. Populate the initial supermatrix with the corresponding local priority vectors with values obtained from sections A, C, E, and F.

Step 3. Transform the initial supermatrix into a normalized supermatrix by dividing each element with its column sum.

Step 4. Raise the normalized matrix to large powers until column values are identical which implies that the normalized supermatrix reaches a limiting supermatrix. Each column of the limiting supermatrix represents the global priority weights of the elements in the supermatrix.

Step 5. Locate the global priority weights of DRs in the limiting supermatrix and place these values in section G.

Phase II – Design Deployment

H. Elements of section H

The DRs from phase 1 are reflected to phase 2 section H.

I. Values of Section I

The values presented in section G of phase 1 are reflected to phase 2 section I.

J. Values of Section L

The values from phase 1 section E are now reflected in phase 2 section L.

K. Calculation of DCs causal relationships of section K

The steps in phase 1 part D are adopted.

L. Calculation of weights of DCs of section M

The steps in phase 1 part E are adopted.

M. Calculation of DC weights with respect to DRs in section J

The steps in part F of phase 1 are adopted.

N. Construction of the supermatrix for phase 2

The steps in phase 1 part G are adopted.

Phase III – Process Planning

O. Elements of section O

The DCs from phase 2 are reflected to phase 3 section O.

P. Values of Section P

The values presented in section N of phase 2 are reflected to phase 3 section P.

Q. Values of Section S

The values presented in phase 2 section M are reflected in phase 3 section S.

R. Calculation of PPs causal relationships of section R

The steps in phase 1 part D are adopted.

S. Calculation of weights of PPs of section T

The steps in phase 1 part E are adopted.

T. Calculation of PP weights with respect to DCs in section Q

The steps in part F of phase 1 are adopted.

U. Construction of the supermatrix for phase 3

The steps in phase 1 part G are adopted.

Phase IV – Production Planning

V. Elements of section V

The PPs from phase 3 are reflected to phase 4 section V.

W. Values of Section W

The values presented in section U of phase 3 are reflected to phase 4 section W.

X. Values of Section Z

The values from phase 3 section T are reflected in phase 4 section Z.

Y. Calculation of POs causal relationships of section Y

Steps in phase 1 part D are adopted.

Z. Calculation of weights of POs of section AA

The steps in phase 1 part E are adopted.

AA. Calculation of PO weights with respect to PPs in section X

The steps in part F of phase 1 are adopted.

BB. Construction of the supermatrix for phase 4

The steps in phase 1 part G are adopted

4 CASE STUDY

A case study in the design of an edible oil product, an agricultural product, in a medium-sized food manufacturing company in Cebu, Philippines was carried out to elucidate the proposed framework. The company is aiming to design its edible oil product as well as its manufacturing processes to conform to sustainability. Thus, the proposed approach was adopted to help promote a sustainable product design for edible oil which encompasses the design and manufacturing processes. The design parameters are shown in Table 3.

In carrying out the proposed approach, 10 experts from the food manufacturing industry were asked to participate in the decision-making processes suggested in the proposed approach. This choice of the number of experts is consistent with MADM methods as explained by Ocampo and Promentilla (2016). The composition of the 10 experts is as follows: seven experts from the industry with a minimum of 10 years working experience in food product design and three experts from the academe who have at least a Master's degree in operations management, industrial engineering, general management, business administration, and related fields and at the same time, they have published papers in sustainability. Since these industry experts are currently or were previously affiliated with manufacturing firms which are members of various supply chains, these experts represent customers, suppliers, competitors, and final consumers. These satisfy the multi-stakeholder approach of the proposed methodology. For brevity, only supermatrices for the corresponding four phases are shown here for as an illustration. Table 4, Table 5, Table 6, and Table 7 show the supermatrices generated from the product planning, design deployment, process planning, and production planning, respectively. These matrices were obtained using parts A-G for Table 4, parts H-N for Table 5,

parts O-U for Table 6, and parts V-BB for Table 7 as discussed in Section 3 (Methodology).

The top five priority stakeholder requirements are FDA compliance, safe for consumption, proper wastewater and solid disposal, product quality, and competitive pricing. The product design team must give more attention to these requirements. The top five design requirements are GMP and HACCP accreditation, accept only safe raw materials, treat wastewater and segregate solid waste, produce at consistent specifications, and calibrate instruments. The

top three parts characteristics are: follow standard specifications, procedures and processes, do not accept defective raw materials, and study and compare your product and competitors'. The top three process parameters are: criticize all aspects of the product and make improvements, careful inspection of raw materials, and provide work instructions. Finally, the top three production operations are: consult experts regularly, update work instructions regularly, and conduct an inspection of raw materials upon delivery.

Table 1. Linguistic variables with corresponding fuzzy numbers for fuzzy AHP (adopted from Tseng *et al.*, 2008)

Linguistic Scale	Code	Triangular fuzzy scale	Triangular fuzzy reciprocal scale
Just equal		(1,1,1)	(1,1,1)
Equal importance	EQ	(1/2,1,3/2)	(2/3,1,2)
Moderate importance	MO	(5/2,3,7/2)	(2/7,1/3,2/5)
Strong importance	ST	(9/2,5,11/2)	(2/11,1/5,2/9)
Demonstrated importance	DE	(13/2,7,15/2)	(2/15,1/7,2/13)
Extreme importance	EX	(17/2,9,9)	(1/9,1/9,2/17)

Table 2. Linguistic variables with corresponding fuzzy numbers for fuzzy DEMATEL (adopted from Tseng, 2012)

Linguistic terms	Influence score	Triangular fuzzy scale
No influence	0	(0.0,0.1,0.3)
Very low influence (VL)	1	(0.1,0.3,0.5)
Low influence (L)	2	(0.3,0.5,0.7)
High influence (H)	3	(0.5,0.7,0.9)
Very high influence (VH)	4	(0.7,0.9,1.0)

Table 3. Design parameters of the food product

Codes	Stakeholder requirements	Codes	Parts characteristics
SR1	Product quality	DR10	Innovate
SR2	Affordability	DR11	Establish pricing strategy at par with competitors
SR3	Safe for consumption	DR12	Use efficient and eco-friendly machines
SR4	Proper wastewater and solid disposal	Codes	Parts characteristics
SR5	Fortify product with Vitamin A	PC1	Follow standard specifications, procedures, and processes
SR6	FDA compliance	PC2	Do not accept defective raw materials
SR7	Consistent demand of company to supplier	PC3	Use alternative ingredients subject to research
SR8	Financial viability of product development	PC4	Study and compare your product and competitors'
SR9	Differentiator	PC5	Proper selection of machine and equipment to be used
SR10	Competitive pricing	PC6	Be aware of competitors' prices
SR11	Less energy and raw material	Codes	Process parameters
Codes	Design requirements	PP1	Careful inspection of raw materials
DR1	Produce at consistent specifications	PP2	Research and development of alternative ingredients
DR2	Accept only safe raw materials	PP3	Criticize all aspects of the product and make improvements
DR3	Calibrate instruments	PP4	Identify significant machine specifications
DR4	Choose affordable raw materials	PP5	Observe and understand competitor's pricing strategy
DR5	Conduct water analysis	PP6	Provide work instructions
DR6	Treat wastewater and segregate solid waste	Codes	Production operations
DR7	Add Vitamin A to the product's formula	PO1	Conduct inspection of raw materials upon delivery
DR8	GMP and HACCP accreditation	PO2	Consult experts regularly
DR9	Establish good supplier coordination	PO3	Train workers regularly
		PO4	Update work instructions regularly

Table 4. Supermatrix for the Product Planning Phase

T	G	SR1	SR2	SR3	SR4	SR5	SR6	SR7	SR8	SR9	SR10	SR11	DR1	DR2	DR3	DR4	DR5	DR6	DR7	DR8	DR9	DR10	DR11	DR12
G		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
SR1	0.11		0.12	0.33		0.30	0.12																	
SR2	0.09	0.15				0.09																		
SR3	0.13	0.75	0.10				0.23																	
SR4	0.11						0.32																	
SR5	0.04						0.32																	
SR6	0.19			0.67	1.00	0.60																		
SR7	0.03																							
SR8	0.07		0.22																					
SR9	0.03		0.09																					
SR10	0.11	0.10	0.46																					
SR11	0.10																							
DR1		0.21		0.14		0.12					0.27			0.13					0.37	0.20				
DR2		0.11		0.19		0.10	0.13												0.31	0.42				
DR3		0.13		0.16			0.12						0.50								0.19			
DR4			0.49			0.05					0.37												0.54	
DR5		0.09		0.22			0.22							0.16				0.33	0.16					
DR6					0.75		0.14										0.29		0.08	0.19				
DR7		0.11				0.73								0.06										
DR8		0.25		0.29	0.25		0.38						0.50	0.65	1.00		0.71	0.67				0.22	1.00	
DR9		0.05	0.18					1.00			0.22													
DR10									0.62	1.00												0.24		
DR11			0.33						0.38		0.41													
DR12		0.06										0.73							0.08					

Table 5. Supermatrix for the Design Deployment Phase

	G	DR1	DR2	DR3	DR4	DR5	DR6	DR7	DR8	DR9	DR10	DR11	DR12	PC1	PC2	PC3	PC4	PC5	PC6
G		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
DR1	0.08		0.13					0.37	0.20										
DR2	0.10							0.31	0.42										
DR3	0.08	0.50							0.19										
DR4	0.06											0.54							
DR5	0.07		0.16				0.33	0.16											
DR6	0.10					0.29		0.08	0.19										
DR7	0.03		0.06																
DR8	0.27	0.50	0.65	1.00		0.71	0.67					0.22	1.00						
DR9	0.04																		
DR10	0.05											0.24							
DR11	0.06																		
DR12	0.05							0.08											
PC1		0.51	0.25	1.00		1.00	1.00	0.79	0.54	1.00	0.32	0.22			0.69	0.25			
PC2		0.22	0.75					0.21	0.30					0.71					
PC3					1.00										0.16		0.47		0.20
PC4		0.09									0.68					0.75		1.00	0.80
PC5		0.19						0.16					1.00	0.29					
PC6										0.34	0.78				0.15		0.53		

Table 6. Supermatrix for the Process Planning Phase

	G	PC1	PC2	PC3	PC4	PC5	PC6	PP1	PP2	PP3	PP4	PP5	PP6
G	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
PC1	0.37		0.69	0.25									
PC2	0.23	0.71											
PC3	0.09		0.16		0.47		0.20						
PC4	0.14			0.75		1.00	0.80						
PC5	0.10	0.29											
PC6	0.08		0.15		0.53								
PP1		0.28	1.00							0.13			
PP2				1.00						0.41		0.50	0.16
PP3					1.00			0.20	1.00		0.53	0.50	0.24
PP4		0.21				1.00				0.34			0.42
PP5							1.00			0.13	0.20		0.17
PP6		0.51						0.80			0.28		

Table 7. Supermatrix for the Production Planning Phase

	G	PP1	PP2	PP3	PP4	PP5	PP6	PO1	PO2	PO3	PO4
G	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
PP1	0.17			0.13							
PP2	0.14			0.41		0.50	0.16				
PP3	0.26	0.20	1.00		0.53	0.50	0.24				
PP4	0.16			0.34			0.42				
PP5	0.09			0.13	0.20		0.17				
PP6	0.17	0.80			0.28						
PO1		0.73								0.20	0.42
PO2			1.00	1.00	1.00	1.00				0.40	0.29
PO3		0.27						0.50			0.29
PO4							1.00	0.50		0.40	

The resulting priority ranks obtained from the supermatrices in Table 4, Table 5, Table 6, and Table 7 are presented in Table 8, Table 9, Table 10, and Table 11, respectively.

Table 8. Priority weights of stakeholder requirements

Stakeholder requirements	Priority weights	Rank
Product quality	0.1091	3
Affordability	0.0873	7
Safe for consumption	0.1273	2
Proper wastewater and solid disposal	0.1091	3
Fortify product with Vitamin A	0.0436	9
FDA compliance	0.1910	1
Consistent demand of company to supplier	0.0273	10
Financial viability of product developments	0.0727	8
Differentiator	0.0252	11
Competitive pricing	0.1091	3
Less energy and raw material consumption	0.0982	6

Table 9. Priority weights of design requirements

Design requirements	Priority weights	Rank
Produce at consistent specifications	0.0810	4
Accept only safe raw materials	0.1003	2
Calibrate instruments	0.0795	5
Choose affordable raw materials	0.0643	7
Conduct water analysis	0.0728	6
Treat waste water and segregate solid waste	0.0944	3
Add Vitamin A to the product's formula	0.0296	12
GMP and HACCP accreditation	0.2734	1
Establish good supplier coordination	0.0437	11
Innovate	0.0538	9
Establish pricing strategy at par with competitors	0.0604	8

Table 10. Priority weights of parts characteristics

Parts Characteristics	Priority weights	Rank
Follow standard specifications, procedures, and processes	0.37	1
Do not accept defective raw materials	0.23	2
Use alternative ingredients subject to research	0.09	5
Study and compare your product and competitors'	0.14	3
Proper selection of machine and equipment to be used	0.10	4
Be aware of competitors' prices	0.08	6

Table 11. Priority weights of process parameters

Process parameters	Priority weights	Rank
Careful inspection of raw materials	0.1718	2
Researching and Developing alternative ingredients	0.1448	5
Criticize all aspects of the product and make improvements	0.2628	1
Identify significant machine specifications	0.1592	4
Observe and understand competitor's pricing strategy	0.0932	6
Provide work instructions	0.1682	3

Table 12. Priority weights of production operations

Production operations	Priority weights	Rank
Conduct inspection of raw materials upon delivery	0.1203	3
Consult experts regularly	0.6189	1
Train workers regularly	0.0838	4
Update work instructions regularly	0.1771	2

5 CONCLUSION AND FUTURE WORK

Sustainability has become a major concern nowadays, so this study proposed a holistic and a comprehensive four-phased QFD-MCDM framework for sustainable product design with the integration of TBL and by incorporating all stakeholder requirements. This framework was conceptualized based on the gaps identified from the previous studies related to sustainable food product designs. Previous studies failed to consider the gaps found, hence the researchers decided to address all the gaps identified. This study aims to incorporate relevant sustainability interests of stakeholders in sustainable product design,

to carry out the four phases of the QFD in designing sustainable food products, and to implement an integrated hybrid multi-criteria decision-making framework along with four-phased QFD.

By conducting a case study on edible oil production, all the stakeholder requirements were identified and the proposed framework was used to test if it is applicable in two different firms and if it could generate relevant results with respect to the goal. Thus, the results of the case studies show that the framework is effective to provide the best priorities to focus. Moreover, the TBL was addressed simultaneously, and all the stakeholders are considered.

Stakeholder requirements are very important to address for a firm to stand and to compete in the market. Thus, the application of this methodology can generate highly relevant results to focus out of all those stakeholder requirements. The methodology provides a ranking on each phase which highly seeks to achieve sustainable product design. Therefore, the proposed methodology is an effective framework for achieving sustainable food product design. For future work, the framework can be helpful in generating relevant results to achieve sustainability so it is recommended to apply the framework in different industries. For future researchers who are interested in the study this serves as an opportunity to extend and discover more on the four-phased QFD since it is not usually used in current studies, different MCDM tools may be applicable to integrate with the four-phased QFD.

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