Developing Resilient Supply Chain in Disruption Condition Using QFD and LPP: A Case Study in A Pharmaceutical Company During Covid-19

Shahpar Sattar

Department of Industrial Engineering, K.N. Toosi University of Technology, Tehran, Iran

Shahpar.ind.96@gmail.com

Emad Roghanian*

Department of Industrial Engineering, K.N. Toosi University of Technology, Tehran, Iran

E_roghanian@kntu.ac.ir

Abstract

In this paper, we design a resilient supply chain by determining risks, prioritizing resilient strategies, and also determining the relationships between them using the Quality Function Deployment (QFD) method during Covid-19. Moreover, those strategies with required further attention to minimize supply chain risks are determined by applying the Linear Physical Programming (LPP) approach, which is a flexible and easy approach in order to determine the accurate weights in the objective space. This research contributes to the growing literature on the resilient supply chain to demonstrate how to develop a mathematical model for designing a resilient supply chain using QFD and LPP methods during Covid-19. Based on the obtained results, three strategies play a crucial role in reducing the supply chain risks of a pharmaceutical company and also increasing its supply chain resilience based on the results: implementing appropriate and relevant policies in terms of the number and selection of suppliers, employing up-to-date procedures in pricing and market analysis, upgrading supply chain agility to cope with natural disasters. Hence, this study can bring important insights to managers and professionals involving with the supply chain area to use them in applying appropriate strategies while facing supply chain risks.

Keywords Supply chain, Resilience, Risk, Quality Function Deployment, Linear Physical Programming

*Corresponding author

1. Introduction

The implementation of supply chain resilience has recently played a vital role, owing to its substantial factors which influence the business continuity. The influence of supply chain resilience is greatly varying, to embrace companies' efficiency during a crisis such as COVID-19. The business organizations need to understand the current COVID-19 situation, the supply chain risks, and their impact on the other factors. The present business situations strongly suggest, and the majority of experts agree that sustainability in terms of supply chain resilience is not only the key of success, but is also mandatory for business survival.

The main purpose of the traditional supply chain is to connect supply and demand in costs, profits or the level of optimal services in sustainable conditions [1]. However, supply chain programming in companies is now more complicated than the past since supply chains are often exposed to a wide range of risks and disruptions such as natural disasters, loss of an important supplier, cyber-attacks, recession, and supply, production, and distribution system disruptions. In such circumstances, businesses must prepare to face a continuous flow of the mentioned challenges; otherwise, the survival of their supply chain will face some problems and its consequences and costs will negatively affect the company's performance.

"Resilience" capability is one of the strategies to deal with such challenges and helps the supply chain to be prepared for such unexpected events and in the event of such disruptions not only respond to them appropriately, but also provide the conditions to return to the original state and the continuation of supply chain activities. To implement this type of supply chain, it is necessary to identify and implement appropriate strategies to face the risks and disruptions. However, the identification of these strategies is sometimes difficult, and none of these strategies are enough on their own for reducing all risks. Therefore, determining these strategies and the importance of each of them in reducing supply chain risks is substantially important. The *Quality Function Deployment* (QFD) approach is an effective method for reducing supply chain risks and consequently increasing supply chain resilience.

The QFD concept was introduced by Akao [2] in Japan. Following World War II, Japanese companies that used to copy products, changed their approach and resorted to manufacturing new products. QFD was introduced into such an environment as a concept for developing new products. In other words, QFD is a comprehensive and systematic method, which allows the translation of customer requirements into the technical characteristics of the product to develop the product and increase customer satisfaction. The QFD approach is also used as a suitable method for identifying the supply chain disruptions and risks and developing resilience strategies for disruption and its risks. However, the optimization of this method has always been among the concerns of researchers. Various optimization methods including linear programming, mixed integer programming and dynamic programming have been used to optimize the QFD approach [3]. Moreover, to the aforementioned methods, Lai [4] introduced the *Linear Physical Programming* (LPP) method for QFD optimization, which was an effective and efficient method for QFD optimization.

LPP is a new and effective multi-objective optimization method that develops a cumulative objective function of criteria with the fragmented Archimedean ideal programming method. Most multi-objective optimization problems require direct or indirect numerical weighting. Therefore, in the LPP procedure, the decision maker states the priorities for each criterion using four different classes. In fact, the decision maker classifies each criterion into one of the four classes. Each class is composed of two functions: a soft function and a hard function [5]. The soft function is generally used to describe the design objectives, while the hard function is used to describe the design constraints.

Since the use of QFD calls for determining the relationships between the customer demands and technical requirements as well as the correlation between technical requirements, commenting on these relationships and correlations takes place through verbal data such as “weak relationship”, “strong relationship”, or “highly strong relationship “, which are more comprehensible to humans than numbers.

In this paper, it is attempted to develop a resilient supply chain using LPP in QFD optimization. For this purpose, by considering all the factors affecting the increase in supply chain resilience and determining the optimal level of each resilience strategy, it is possible to identify those strategies that have to be considered more to minimize supply chain risks. In this regard, after collecting general information by studying the research literature and considering the opinions of the QFD team members, a list of supply chain risks is prepared. Then, using the Delphi method, some risks can be selected and placed in the customer requirements section of the house of quality. Likewise, a list of resilient strategies is selected and placed in the technical characteristics section of the house of quality. Finally, by using LPP method, the weight of importance for each supply chain risk is calculated and a model is designed to determine effective resilient supply chain strategies.

In second section of the paper, the literature of the resilient supply chain, quality function deployment, supply chain risks and linear physical programming are studied. In the third section, the proposed methodology is described in detail. In the fourth section, the proposed framework for controlling and reducing the supply chain risks of a pharmaceutical company is used as a practical case and in the fifth section, the research results and future suggestions are presented.

2. Concepts and literature review

2.1. Supply chain

The supply chain includes all activities related to the flow and conversion of goods from the raw material stage to delivery to the final consumer, as well as related information flows. Therefore, supply chain management includes the integration of supply chain activities and related information flows by improving chain relationships to achieve a reliable competitive advantage in different industries.

In food industry, Hamidi-asl et al. [6] designed an efficient network for date products to increase product flow efficiency in a forward direction and reduce the total associated costs of the supply chain by optimizing the costs and emissions. In digital good industry, Taleizadeh et. al [7] formulated a supply chain model with a manufacturer and two retailers. Digital goods, which were produced by manufacturer, were sold through a traditional and a digital retail channel. The aim of their study was maximizing profit for the supply chain so that the best contract is offered to the retailers by manufacturer. Recently, a closed loop Supply Chain with multi-stage products is designed with respect to the green production principles and Quality Control (QC) policy under back-logged and lost sale types of the shortage [8]. Finally, Taleizadeh et al. [9] investigated the retailer’s optimal ordering strategy in the SCs.

Considering constraints of supply chain is vitally important to design of a real supply chain. For instance, Askari et al. [10] designed a mixed-integer nonlinear programming model that consider warehouse space and budget constraints in supply chain. They tried to maximize the revenue by the calculation of the optimal level of production of every item in different scenarios. Also, Taleizadeh et al. [11] evaluated a manufacturing-inventory system with a single machine and multiple products which constraints of machine capacity, service level, warehouse space, and budget were considered in their supply chain. They tried to minimize total cost of system and calculate the optimal value of backorder and the length of cycle.

2.2. Supply chain resilience

In the last two decades, various definitions of supply chain resilience have been introduced as new paradigms to the field of supply chain. The first step in explaining resilience in the supply chain context was taken by Rice and Caniato [12]: “The ability to respond to an unexpected disruption such as the impact of a terrorist attack or a natural disaster and restoration to the original state”.

A notion that is directly or indirectly mentioned in most definitions of sustainable supply chain is the existence of uncertainty or risk, which are used interchangeable [13]. According to Tang 's study, not all risks identified in the supply chain certainly occur, and time determines the impact of each risk on the supply chain. Risks could either be positive or negative. Although risk is considered to be a word with a negative connotation by some people, not all risks are solely negative or harmful. Positive risks are opportunities that can positively affect the project through useful means, and negative risks may negatively affect the project dimensions. Table 1 lists the supply chain risks identified in various studies.

Insert Table 1

In today’s competitive world, in which globalization plays an important role in organizations, resilience strategies have to be used to overcome any disruption and risk [31]. Hence, researchers have resorted to the design and implementation of a resilient supply chain.

Moreover, Ghavamifar et al. [32] designed a resilient competitive supply chain considering the uncertainties and risks of disruption using a two-tier multi-objective programming approach in which the producer and buyers attempted to attain their goals. They also used a combination of two programming methods including compromise programming and Benders’ decomposition method to provide a hybrid solution to solve their model.

Table 2 presents the identified supply chain resilience strategies in various studies.

Insert Table 2

2-3- Quality function deployment

QFD is establishment of a transparent link between the demands and expectations of the stakeholders (including customers) from the product, processes and production (service) activities. One of the most important activities in the use of QFD is identifying the needs and expectations of customers to answer this question: what product characteristics are linked to the customer requirements?

The *House of Quality* (HOQ) is the most important QFD tool, which involves the matrix of customer requirements (*CRs*) and technical requirements (*TRs*) as well as the weights of importance of customer requirements (R_{ij}) and the correlation matrix of technical characteristics (Y_{jk}). In Figure 1, R_{ij} represents the relationship between $CR_i$and TR_j, and r_{jk}shows the relationship between $TR_k$and TR_j.

Insert Figure 1

QFD was originally introduced by Akao in Japan as an appropriate tool for translating customer requirements into technical requirements to meet customer requirements. A review of the QFD literature reveals that due to the high flexibility of this method, it has been used in various other areas such as designing ergonomic products [42], changing the rules of soccer [43], assessing the quality of nursing education services [44], and determining the best marketing strategies in housing projects [45].

The scope of applications of QFD has also been extended to SCM. Today, many products are manufactured through different levels of the supply chain and are provided to the end user. Hence, the systematic reliability control method is of significant importance at different stages of the supply chain. In this regard, Wang et al. [46] proposed a new framework for the top-quality design of the supply chain of complex and large products through the integration of fuzzy QFD and Grey Decision-Making approach. Recently, Ocampo et al. [47] have presented a comprehensive QFD-MADM multi-step framework for sustainable product design considering all stakeholder requirements and the triple-bottom-line (TBL) of sustainable development.

2.4. Linear Physical Programming

Multi-objective optimization methods require the determination of the objective weights; so, the main challenge in solving these problems is weighting the objectives correctly during the optimization process. Therefore, the design team needs to both locally and globally determine the accurate weights in the objective space with a flexible and easy approach. LPP offers a systematic yet different approach to the achievement of the objective weights both locally and globally. It also integrates the weight calculation method with the optimization process to obtain optimal results.

LPP does not determine the weight of each objective separately; it allows the decision maker to express their preference for each criterion using four different class functions. The level of utility of each criterion in each class function is expressed as ideal, desirable, tolerable, undesirable, highly undesirable, and unacceptable. It is easier for decision makers or experts in the decision-making process to express these values. The value of the class function for each design criterion controls the optimization path in the objective space [48].

The four prominent characteristics of the class function are as follows:

-Non-negative

-Continuous

-Linear and segmented

-Convex

The four LPP classes are defined as follows:

Class S1: The lower the value of the criterion is, the more desirable it is (minimization).

Class S2: The higher the criterion value is, the more desirable it is (maximization).

Class S3: Utility is a point.

Class S4: Utility has a range.

Figure 2 shows the four LPP classes.

Insert Figure 2

After determining the class functions and utility limits of each criterion and applying the Eqs. (1) to (7), the importance weights of each of the utility intervals of the criteria are calculated according to the LPP method.

z^s is a constant number for all "i"s, which is calculated through Eq. (1). The OVO rule (one versus one) is used to calculate the preference functions. This rule ensures the following inter-criterion priority for each criterion, g_i. If the following two options are considered:

Choice 1: "Complete improvement in g_i across a given domain (e.g. domain-3)"

Choice 2: “Complete reduction in all other criteria across the next better domain (i.e. domain-2)”

Choice 1 is preferred to choose 2. In other words, the worst criterion is always improved first. Basically, this philosophy has an implicit sequential nature whereby the minimization of the worse criterion is automatically prioritized [49].

Therefore, the difference between the preference functions between $t_{i(s-1)}$and t_{is} is denoted by $\tilde{z}^s$inEq. (3).

$$\tilde{z}^s = z^s - z^{s-1} \qquad (2 \le s \le 5) \tag{1}$$

$$\tilde{z}^1 = 0 \tag{2}$$

$$\tilde{z}^s < (p-1)\tilde{z}^{s-1} \qquad (3 \le s \le 5) \tag{3}$$

Using the convexity parameter (β), Eq. (3) changes to Eq. (4):

$$\tilde{z}^s = \beta(p-1)\tilde{z}^{s-1} \qquad (3 \le s \le 5) \tag{4}$$

According to the LPP method, positive small numerical values (e.g. 0.1) are z^2 =0.1 and β =1.1, where p is the number of customer requirements.

$$\tilde{t}_{is} = t_{i(s-1)} - t_{is} \qquad (2 \le s \le 5) \tag{5}$$

$$w_{is} = \tilde{z}^s / \tilde{t}_{is} \qquad (2 \le s \le 5) \tag{6}$$

Moreover, w_{is} denotes the weight of the *i-th* criterion at point s and t_{is} represents the utility of the *i-th* criterion at point s.

$$w_{i1} = 0 \tag{7}$$

The importance weight of each criterion range is calculated through the following relation.

$$\tilde{w}_{is} = w_{is} - w_{i(s-1)} \qquad (2 \le s \le 5) \tag{8}$$

In Eqs. (1) to (8), the parameters are defined as follows.

p: Number of criteria

i: The *i-th* criterion

s: Number of utility ranges

z^s: The value of the class function at the intersections of the ranges

t_{is}:The utility of the *i-th* criterion at point s

w_{is}: The weight of the *i-th* criterion at point s

Based on the above-mentioned characteristics and relations, after determining the weights ($\tilde{w}_{is}^{-}.\tilde{w}_{is}^{+}$) using physical programming, which shows the slopes of the penalty functions, the cumulative objective function (that has to be minimized) is formed as a weighted set from the deviations across all domains ($s = 2,3,\ldots,5$) and criteria ($i = 1,2,\ldots,n_{sc}$). The general LPP model is expressed as follows:

$$minJ = \sum_{i=1}^{n_{sc}} \sum_{n=2}^{5} (\tilde{w}_{is}^{-} d_{is}^{-} + \tilde{w}_{is}^{+} + d_{is}^{+}) \tag{9}$$

s.t

$$g_i = \sum_{j=1}^{n} r_{ij} * x_j \qquad for\ all\ i \tag{10}$$

$$g_i - d_{is}^{+} \le t_{i.s-1}^{+};\ d_{is}^{+} \ge 0;\ g_i \le t_{i5}^{+} \qquad \begin{matrix} for\ all\ i\ in\ classes\ 1S, 3S, 4S \\ i = 1.2. \ldots .10;\ s = 2. \ldots .5 \end{matrix} \tag{11}$$

$$g_i + d_{is}^{-} \ge t_{i.s-1}^{-};\ d_{is}^{-} \ge 0;\ g_i \ge t_{is}^{-} \qquad \begin{matrix} for\ all\ i\ in\ classes\ 2S, 3S, 4S \\ i = 1.2. \ldots ,10;\ s = 2. \ldots .5 \end{matrix} \tag{12}$$

This model has three types of variables: (i) the variable for the estimation level of each technical characteristic (x_j), which is a binary variable,(ii) the objective variable (g_i), which is defined as a variable dependent on the estimation level variable, and (iii) the deviation variables (d_{is}^{-} , d_{is}^{+}), which show the deviation of $g_i$from the objective levels of $t_{i.s-1}^{+}$ and $t_{i.s-1}^{-}$defined in the model. Moreover, the model has two types of constraints: (i) constraint (10) which is a criterion and showsg_i is a linear function ofx_j.In this constraint, the normalized relationships between the customer requirements and technical requirements are indicated by r_{ij}.(ii) Constraint (11) and (12) which are goal constraints and are defined for each domain. It is R_{ij} represents the relationship between CR_iandTR_j.

2.5. Literature review of integrated use of concepts

Various approaches have been adopted to QFD optimization. Chen and Ko [50] used fuzzy linear programming for QFD optimization. Zhou [51] used mixed integer programming and Joos [52] used the optimization of min-max parameters in the QFD optimization. Chowdhury and Quaddus [53] also used a binary multi-stage optimization model for QFD optimization. Another popular QFD optimization method is ideal programming. Research examples include the studies by Karsak et al. [54], Han et al. [55], and Chen and Weng [56].

Chen et al. [57] also used fuzzy ideal programming for QFD optimization. Other studies have revolved around the application of mathematical programming in the optimization of technical characteristics. Examples include the studies by Dawson and Askin, [58] and Belhe and Kusiak,[59] . Furthermore, Lai et al. [4] used LPP to optimize customer requirements to maximize overall customer satisfaction in the QFD method. Given that competition is multidimensional, organizations must always attempt to maximize overall customer satisfaction by optimizing their product design.

Moreover, all constraints (the product development time, development cost, production cost, human resources in design and production, etc.) must be taken into account. In all of the aforementioned methods, a multi-objective problem is converted into a single-objective problem and then a satisfactory solution to the single-objective problem is obtained. Therefore, the design team has to first assign a weight to each objective. These weights are in different importance levels and must be fit in terms of the description of the optimization problem. The decision maker can consider multiple criteria by dint of LPP and express the level of utility for each criterion considering different preference ranges. It is difficult for the design team and the customers to rank the customer requirements. However, it is easier to identify levels of satisfaction for a particular customer requirement as ideal, desirable, tolerable, undesirable, highly undesirable, or unacceptable. Using this information, LPP can extract the importance weights and optimal results. In fact, LPP makes it possible to use competitive information with a systematic and measured approach. Therefore, there is no need to separately calculate the weight of each objective.

In most conventional methods, the weights are constant, which may in some cases lead to deviation. LPP is a different and systematic approach to calculate the weights both locally and globally. Furthermore, it integrates the weight calculation process with the optimization process to obtain the optimal solution, and it is relatively easier to obtain the data used in LPP as compared to other methods.

Table 3 lists the recent studies of supply chain that used various techniques.

Insert Table 3

Based on the literature review in the field of resilience supply chain, we realized that although there is growing trend in resilient supply chain, considering some practical approaches such as QFD and LPP is limited. Therefore, the research gap and significant contribution of this study can be as follow:

First, a limited number of studies have been focused on resilient supply chain by applying multi-criteria decision-making techniques such as, AHP, ANP and TOPSIS which are less practical in real world. Thus, we fill this gap by utilizing a new approach, namely QFD.

Second, Multi-objective optimization methods require the determination of the objective weights; so, the main challenge in solving these problems is weighting the objectives correctly during the optimization process. Therefore, the design team needs to both locally and globally determine the accurate weights in the objective space with a flexible and easy approach. LPP offers a systematic yet different approach to the achievement of the objective weights both locally and globally. It also integrates the weight calculation method with the optimization process to obtain optimal results.

Third, the occurrence of the COVID-19 pandemic is a disruption that has adversely affected many supply chains (SCs) around the world. Therefore, in this paper, we strive to minimize supply chain risks and develop the resilience of a supply chain by applying some resilient strategies during COVID-19 pandemic.

Fourth, the position of the current study compared to other works is that many previous studies tried to devise a comprehensive or actual network for other products. This was done with the same purpose of filling the presented gap when dealing with pharmaceutical products.

3. Proposed research methodology

The decision algorithm in this study determines the estimation level of each resilience strategy with regard to supply chain resilience development and predetermined objectives. In general, the proposed algorithm consists of three general parts: first, based on literature review, supply chain risks and resilient strategies to address the risks were identified and prioritized. Second, by employing HOQ, which is known as one of the QFD method tools, the relationships between risks and strategies were determined. Eventually, mathematical modeling is formulated using the LPP approach to design a resilient supply chain.

In this study, after collecting general information by studying the research literature and considering the opinions of the QFD team members, a list of supply chain risks is prepared. Thereafter, using the Delphi method, ten risks are selected and placed in the customer requirements section of the house of quality. Likewise, a list of resilient strategies is selected and placed in the technical characteristics section of the house of quality. Each resilient strategy directly affects one or several supply chain risks and has to be expressed in a measurable and practical format. It is again worth mentioning that the data input in the QFD process is obtained through subjective assessments made by decision makers or experts based on professional knowledge, experience and available information.

In brief, the steps of the proposed research algorithm are shown in Figure 3:

Insert Figure 3

4. Case Study

The framework proposed for resilience development is a supply chain of a pharmaceutical company. This company is located in Iran, and its vision is to become a leading global human healthcare organization. Based on the value of this company, which is to create an environment that can foster creativity and openness to new ideas, we collaborated with a four-member team consisting of supply chain manager, Research and Development (R&D) manager, market research manager and production manager, who serve as the QFD team in the case study company.

First, a relatively long list of supply chain risks was prepared. In the next step, they were identified considering the recommendation by the supply chain manager and the opinion of the QFD team members and the fact that some of these characteristics overlapped with each other. Table 4 shows these risks.

Insert Table 4

Besides, Table 5 shows the resilience strategies influencing these risks.

Insert Table 5

The relationships between the resilience strategies and supply chain risks as well as the interactions between technical requirements were identified through discussions and interviews with QFD team experts. Afterward, the House of Quality relationships were normalized using the aforementioned relationships. Fig. 4 presents the basic relationships between the supply chain risks and resilience strategies along with the correlations between the resilience strategies. Figure 5 also shows the normalized relationships of the house of quality.

Insert Figure 4

To take into account the correlation between technical characteristics, Wasserman [77] proposed the following formula to normalize the relationships between the customer demands and technical characteristics.

Y_{jk}: The degree of dependence of the *j-th* and *k-th* of the technical characteristics

R_{ij}: The relationship between the *i-th* customer requirement and the *j-th* technical characteristic of the product

m: Number of customer requirements

n: Number of technical characteristics

$$R_{ij}^{norm} = \frac{\sum_{k=1}^{n} R_{ik} * Y_{kj}}{\sum_{j=1}^{n} \sum_{k=1}^{n} R_{ij} * Y_{jk}} \qquad i = 1.2.3.....m, \quad j = 1.2.3.....n \qquad (13)$$

Where R_{ij}^{norm} denotes the normalized relationship between $CR_i$and TR_j, $(i = 1,2,3,..,I)$ and $(j = 1,2,3,\dots,J)$. In previous research, the 1-3-9 or 1-5-9 scales were usually used to show the weak, moderate, and strong relationships between *TRs* and *CRs* as well as between the TRs.

In Figure 5, the house of quality relationships is normalized using Wasserman [77]'s equation.

Insert Figure 5

After identifying the supply chain risks, the resilience strategies and the relationships between them, the type of the class function of supply chain risks is extracted and the utility limits for each class function are determined.

Table 6 shows the class function type and the utility limits of supply chain risks.

Insert Table 6

Based on the LPP method, Eqs. (1) to (8), and the fact that the number of considered risks is 12, the importance weights of each area of utility are calculated. For instance, the calculations for the first risk (losing customers) for extracting the importance weights of each different utility range are listed in Table 7.

Insert Table 7

Likewise, the importance weights of other risks can also be calculated. Table 8 presents the importance weights calculated for different ranges of supply chain risks.

Insert Table 8

Ultimately, based on the case study data and Eqs. (9) to (12), LPP model is formulated as follow:

$$\min J = 0.40d_{12}^{+} + 4.10d_{13}^{+} ...... + 32.66d_{104}^{+} + 462d_{105}^{+} \qquad (14\text{-}1)$$

$s.t:$

$1.criteria$

$$g_1 = 0.036x_1 + 0x_2 + 0.145x_3 + 0.217x_4 + 0.229x_5 + 0x_6 + 0.337x_7 + 0.036x_8$$

.

. (14-2)

.

$$g_{10} = 0.231x_1 + 0x_2 + 0x_3 + 0.692x_4 + 0.077x_5 + 0x_6 + 0x_7 + 0x_8$$

$2.goalconstra\,\text{int}$

$$g_1 - d_{12}^{+} \leq 0.1$$

(14-3)

$$g_1 - d_{13}^{+} \leq 0.35$$

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$$g_{10} - d_{105}^{+} \leq 0.79$$

(14-4)

$$d_{is}^{+} \geq 0 i = 1.2....10 s = 2.3.4.5$$

$$g_i \geq 0$$

$$x_j = 0 \ \ or \ \ 1$$

After solving the Eq (14) in GAMS software, the results show the level of estimation of technical requirements, which are basically the resilience strategies in a supply chain.

In the LPP algorithm, the coefficient β and the value of $\tilde{z}^2$were selected arbitrarily. Besides, as the convexity parameter, β had to be greater than 1 and $\tilde{z}^2$had to be a small positive number. In this study, weights were generated assuming β = 1.1 and $\tilde{z}^2 = 1$ and the results presented were obtained based on these assumptions. The question here is whether the results are affected by these values. To answer this question, the weights were once calculated with $\beta = 1.1$ and were once again calculated with $\beta = 3$ and $\beta = 7$ and the model was implemented based on the new weights. In both cases, the results were fully similar to the results obtained earlier. Tables 9 and 10 present estimation level of resilience strategies and reduction level of supply chain risks by employing specified resilience strategies respectively.

Insert Table 9

Insert Table 10

5. Conclusion

Today's business environment has created a high level of uncertainty and turbulent behaviors in the supply chain which are the results of factors such as globalization, increased level of outsourced activities, increased demand fluctuations, reduced life cycle of products, a drastic decrease in inventories, and reduced number of suppliers of companies. Besides, supply chains face major challenges and threats such as natural disasters (flood, earthquake, hurricane, and fire), cyber attacks, sanctions, supply, production, and distribution system disruptions, etc. The aforesaid factors increase the supply chain risk. Hence, one of the challenges in today's business is risk management and risk reduction for creating a resilient supply chain.

In this study, Utilizing QFD and LPP methods, supply chain in this study in three steps is designed. In this regard, the supply chain risks and appropriate strategies to address the risks were identified and prioritized in the first stage. In the next stage, the relationships between risks and strategies were determined by implementing the house of quality, which is known as one of the QFD method tools.

The correlation rate between each of the strategies was then determined. Ultimately, the Wasserman [77]'s method was used to normalize the relationships between risks and strategies. In the final step, the type of class function of each of the supply chain risks was first defined according to the type of risk followed by determining the range of limits for each class function. Then, the weight of the importance of different utility ranges for each supply chain risk was calculated to provide a physical programming model by adhering to the principle of minimizing the weighted sum of deviations from the estimation levels of the strategies.

Revealed by the findings of the case study, applying appropriate policies in determining the number and choice of suppliers, employing up-to-date methods in pricing and market analysis, and enhancing the level of supply chain agility to address natural disasters play a crucial role in reducing the supply chain risks of the pharmaceutical company and the supply chain resilience. Thus, focusing on the strategies mentioned and providing a proper context to adopt these strategies, the supply chain managers would be able to design and implement a resilient supply chain. However, the provision of this context can be challenging for some main reasons. First, lack of easy access to supply chain data to define supply chain risks and resilience strategies in order to reduce supply chain risks. Second, difficulty converting qualitative data to quantitative data. Finally, determining the relationships between the resilience strategies and supply chain risks as well as the interactions between resilience strategies accurately were challenging.

The following suggestions can also be considered for future research:

- The research conducted is performed using a combination of fuzzy AHP, QFD and LPP techniques to improve supply chain resilience. There are two main advantages to using these methods, first, the use of verbal words to collect data that is fuzzy in nature, allows team members of QFD to evaluate their relationships inhouse of quality with more freedom and flexibility. Second, since individuals' judgments of relationships are different, applying this method allows for a more accurate assessment of house of quality relationships.

- It is possible to add any system constraint such as budget constraints to the model depending on the study product or company’s policies.
- It can be considered in various industries, such as food and beverage industry, banking industry automotive industry, defense industry and aviation industry in order to better responsiveness and developing resilience.

References

[1] Farahani, R.Z., Rezapour, S., Drezner, T., et al. “Competitive supply chain network design: An overview of classifications, models, solution techniques and applications”, Omega, 45, pp.92-118 (2014).

[2] Akao, Y. and King, B. “Quality function deployment: integrating customer requirements into product design” Vol. 21 (1990).

[3] Fung, R.Y., Tang, J., Tu, P.Y., et al. “Modelling of quality function deployment planning with resource allocation”, Research in Engineering Design, 14(4), pp.247-255 (2003).

[4] Lai, X., Xie, M. and Tan, K.C. “QFD optimization using linear physical programming”, Engineering optimization, 38(5), pp.593-607 (2006).

[5] Maria, A., Mattson, C., Ismail-Yahaya, A. and Messac, A.” Linear physical programming for production planning optimization”, Engineering Optimization, 35(1), pp.19-37 (2003).

[6] Hamdi-Asl, A., Amoozad-Khalili, H., Tavakkoli-Moghaddam, R., et al. “Toward sustainability in designing agricultural supply chain network: A case study on palm date”, Scientia Iranica (2021).

[7] Taleizadeh, A.A., Safaei, A.Z., Bhattacharya, A., et al. “Online peer-to-peer lending platform and supply chain finance decisions and strategies”, Annals of Operations Research, pp.1-31 (2022).

[8] Amjadian, A. and Gharaei, A.” An integrated reliable five-level closed-loop supply chain with multi-stage products under quality control and Green policies: Generalised outer approximation with exact penalty”, International Journal of Systems Science: Operations & Logistics, pp.1-21 (2021).

[9] Taleizadeh, A.A., Noori-daryan, M., Soltani, M.R., et al.” Optimal pricing and ordering digital goods under piracy using game theory”, Annals of Operations Research, pp.1-38 (2021).

[10] Askari, R., Sebt, M.V. and Amjadian, A. “A multi-product EPQ model for defective production and inspection with single machine, and operational constraints: Stochastic programming approach”, In International conference on logistics and supply chain management (pp. 161-193). Springer, Cham (2020).

[11] Taleizadeh, A.A., Askari, R. and Konstantaras, I. “An optimization model for a manufacturing-inventory system with rework process based on failure severity under multiple constraints”, Neural Computing and Applications, 34(6), pp.4221-4264 (2022).

[12] Rice, J.B. and Caniato, F. Building a secure and resilient supply network, SUPPLY CHAIN MANAGEMENT REVIEW, V. 7, NO. 5 (SEPT./OCT. 2003), P. 22-30: ILL (2003).

[13] Ritchie, B. and Brindley, C. “Supply chain risk management and performance: a guiding framework for future development”, International Journal of Operations & Production Management (2007).

[14] Silva, M.E., Pereira, S.C. and Gold, S. “The response of the Brazilian cashew nut supply chain to natural disasters: A practice-based view”, Journal of cleaner production, 204, pp.660-671 (2018).

[15] Perrin, A. and Martin, G.” Resilience of French organic dairy cattle farms and supply chains to the Covid-19 pandemic”, Agricultural Systems, 190, p.103082 (2021).

[16] Kleindorfer, P.R. and Saad, G.H. “Managing disruption risks in supply chains”, Production and operations management, 14(1), pp.53-68 (2005).

[17] Blackhurst, J.V., Scheibe, K.P. and Johnson, D.J. “Supplier risk assessment and monitoring for the automotive industry”, International journal of physical distribution & logistics management (2008).

[18] Blos, M.F., Quaddus, M., Wee, H.M., et al. “Supply chain risk management (SCRM): a case study on the automotive and electronic industries in Brazil”, Supply Chain Management: An International Journal, 14(4), pp.247-252 (2009).

[19] Chowdhury, M.M.H. and Quaddus, M. “Supply chain resilience: Conceptualization and scale development using dynamic capability theory”, International Journal of Production Economics, 188, pp.185-204 (2017).

[20] Scheibe, K.P. and Blackhurst, J.” Supply chain disruption propagation: a systemic risk and normal accident theory perspective”, International Journal of Production Research, 56(1-2), pp.43-59 (2018).

[21] Fan, Y. and Stevenson, M.” A review of supply chain risk management: definition, theory, and research agenda”, International Journal of Physical Distribution & Logistics Management (2018).

[22] Colicchia, C., Creazza, A., Noè, C., et al. “Information sharing in supply chains: a review of risks and opportunities using the systematic literature network analysis (SLNA)”, Supply chain management: an international journal (2018).

[23] Tiwari, S., Kazemi, N., Modak, N.M., et al. “The effect of human errors on an integrated stochastic supply chain model with setup cost reduction and backorder price discount”, International Journal of Production Economics, 226, p.107643 (2020).

[24] Kumar, P., Singh, R.K. and Kumar, V. “Managing supply chains for sustainable operations in the era of industry 4.0 and circular economy: Analysis of barriers”, Resources, Conservation and Recycling, 164, p.105215 (2021).

[25] Kamalahmadi, M. and Parast, M.M. “A review of the literature on the principles of enterprise and supply chain resilience: Major findings and directions for future research”, International Journal of Production Economics, 171, pp.116-133 (2016).

[26] de Oliveira, U.R., Espindola, L.S., da Silva, I.R., et al. “A systematic literature review on green supply chain management: Research implications and future perspectives”, *Journal of cleaner production*, *187*, pp.537-561 (2018).

[27] Wieland, A. and Wallenburg, C.M. “Dealing with supply chain risks: Linking risk management practices and strategies to performance”, *International journal of physical distribution & logistics management* (2012).

[28] Hao, S., Hong, W., Xu, H., et al. “Relationship between resilience, stress and burnout among civil servants in Beijing, China: Mediating and moderating effect analysis”, *Personality and Individual Differences*, *83*, pp.65-71 (2015).

[29] Linnenluecke, M.K. “Resilience in business and management research: A review of influential publications and a research agenda”. *International Journal of Management Reviews*, *19*(1), pp.4-30 (2017).

[30] Ivanov, D., Dolgui, A. and Sokolov, B. “The impact of digital technology and Industry 4.0 on the ripple effect and supply chain risk analytics”, *International Journal of Production Research*, *57*(3), pp.829-846 (2019).

[31] Mensah, P., Merkuryev, Y. and Longo, F. “Using ICT in developing a resilient supply chain strategy”, *Procedia Computer Science*, *43*, pp.101-108 (2015).

[32] Ghavamifar, A., Makui, A. and Taleizadeh, A.A. “Designing a resilient competitive supply chain network under disruption risks: A real-world application”, *Transportation research part E: logistics and transportation review*, *115*, pp.87-109 (2018).

[33] Charles, A., Lauras, M. and Van Wassenhove, L. “A model to define and assess the agility of supply chains: building on humanitarian experience”, *International Journal of Physical Distribution & Logistics Management* (2010).

[34] Akdogan, A.A. and Demirtas, O. “Managerial role in strategic supply chain management”, *Procedia-Social and Behavioral Sciences, 150,* pp.1020-1029 (2014).

[35] Mancheri, N.A., Sprecher, B., Bailey, G., et al. “Effect of Chinese policies on rare earth supply chain resilience”, *Resources, Conservation and Recycling*, *142*, pp.101-112 (2019).

[36] Fu, W. and Chien, C.F. “UNISON data-driven intermittent demand forecast framework to empower supply chain resilience and an empirical study in electronics distribution”, *Computers & Industrial Engineering, 135,* pp.940-949 (2019).

[37] Dubey, R., Gunasekaran, A., Childe, S.J., et al. “Empirical investigation of data analytics capability and organizational flexibility as complements to supply chain resilience”, *International Journal of Production Research, 59*(1), pp.110-128 (2021).

[38] Hawkins, T.G., Gravier, M.J. and Muir, W.A. “The role of supplier performance evaluations in mitigating risk: Assessing evaluation processes and behaviors”, *Industrial Marketing Management, 87,* pp.2-17 (2020).

[39] Bader, L., Pennekamp, J., Matzutt, R., et al. “Blockchain-based privacy preservation for supply chains supporting lightweight multi-hop information accountability”, *Information Processing & Management*, *58*(3), p.102529 (2021).

[40] Alikhani, R., Torabi, S.A. and Altay, N. “Retail supply chain network design with concurrent resilience capabilities”, *International Journal of Production Economics*, *234*, p.108042 (2021).

[41] Shin, N. and Park, S. “Supply chain leadership driven strategic resilience capabilities management: A leader-member exchange perspective”, *Journal of Business Research*, *122*, pp.1-13 (2021).

[42] Bergquist, K. and Abeysekera, J. “Quality function deployment (QFD)—A means for developing usable products”, *International journal of industrial ergonomics*, *18*(4), pp.269-275 (1996).

[43] Partovi, F.Y. and Corredoira, R.A. “Quality function deployment for the good of soccer”, *European journal of operational research*, *137*(3), pp.642-656 (2002).

[44] Chou, S.M. “Evaluating the service quality of undergraduate nursing education in Taiwan–using quality function deployment”, *Nurse Education Today*, *24*(4), pp.310-318 (2004).

[45] Dikmen, I., Birgonul, M.T. and Kiziltas, S. “Strategic use of quality function deployment (QFD) in the construction industry”, *Building and environment*, *40*(2), pp.245-255 (2005).

[46] Wang, H., Fang, Z., Wang, D., et al. “An integrated fuzzy QFD and grey decision-making approach for supply chain collaborative quality design of large complex products”, *Computers & Industrial Engineering*, *140*, p.106212 (2020).

[47] Ocampo, L.A., Labrador, J.J.T., Jumao-as, A.M.B., et al. “Integrated multiphase sustainable product design with a hybrid quality function deployment–multi-attribute decision-making (QFD-MADM) framework”, *Sustainable Production and Consumption*, *24*, pp.62-78 (2020).

[48] Messac, A. “Physical programming-effective optimization for computational design”, *AIAA journal*, *34*(1), pp.149-158 (1996).

[49] Messac, A. and Ismail-Yahaya, A. “Multiobjective robust design using physical programming”, *Structural and multidisciplinary optimization*, *23*(5), pp.357-371 (2002).

[50] Chen, L.H. and Ko, W.C. “Fuzzy linear programming models for NPD using a four-phase QFD activity process based on the means-end chain concept”, *European Journal of Operational Research*, *201*(2), pp.619-632 (2010).

[51] Zhou, M. “Fuzzy logic and optimization models for implementing QFD”, *Computers & Industrial Engineering, 35*(1-2), pp.237-240 (1998).

[52] Joos, H.D. “A methodology for multi-objective design assessment and flight control synthesis tuning”, *Aerospace Science and Technology, 3*(3), pp.161-176 (1999).

[53] Chowdhury, M.M.H. and Quaddus, M.A. “A multi-phased QFD based optimization approach to sustainable service design”, *International Journal of Production Economics, 171*, pp.165-178 (2016).

[54] Karsak, E.E., Sozer, S. and Alptekin, S.E. “Product planning in quality function deployment using a combined analytic network process and goal programming approach”, *Computers & industrial engineering, 44*(1), pp.171-190 (2003).

[55] Han, S.B., Chen, S.K., Ebrahimpour, M., et al. “A conceptual QFD planning model”, International *Journal of Quality & Reliability Management, 18*(8), pp.796-812 (2001).

[56] Chen, L.H. and Weng, M.C. “An evaluation approach to engineering design in QFD processes using fuzzy goal programming models”, *European Journal of Operational Research, 172*(1), pp.230-248 (2006).

[57] Chen, L.H., Ko, W.C. and Yeh, F.T. “Approach based on fuzzy goal programing and quality function deployment for new product planning”, *European Journal of Operational Research, 259*(2), pp.654-663 (2017).

[58] Dawson, D. and Askin, R.G. “Optimal new product design using quality function deployment with empirical value functions”, *Quality and Reliability Engineering International, 15*(1), pp.17-32 (1999).

[59] Belhe, U. and Kusiak, A. “The house of quality in a design process”, *International journal of production research, 34*(8), pp.2119-2131 (1996).

[60] Gencer, C. and Gürpinar, D. “Analytic network process in supplier selection: A case study in an electronic firm”, *Applied mathematical modelling, 31*(11), pp.2475-2486 (2007).

[61] Kovach, J., Cho, B.R. and Antony, J. “Development of an experiment-based robust design paradigm for multiple quality characteristics using physical programming”, *The International Journal of Advanced Manufacturing Technology, 35*(11), pp.1100-1112 (2008).

[62] Pochampally, K.K., Gupta, S.M. and Govindan, K. “Metrics for performance measurement of a reverse/closed-loop supply chain”, *International Journal of Business Performance and Supply Chain Modelling, 1*(1), pp.8-32 (2009).

[63] Losada, C., Scaparra, M.P. and O’Hanley, J.R. “Optimizing system resilience: a facility protection model with recovery time”, *European Journal of Operational Research, 217*(3), pp.519-530 (2012).

[64] Shaw, K., Shankar, R., Yadav, S.S., et al. “Supplier selection using fuzzy AHP and fuzzy multi-objective linear programming for developing low carbon supply chain”, *Expert systems with applications, 39*(9), pp.8182-8192 (2012).

[65] Soni, U., Jain, V. and Kumar, S. “Measuring supply chain resilience using a deterministic modeling approach”, *Computers & Industrial Engineering, 74*, pp.11-25 (2014).

[66] Mari, S.I., Lee, Y.H. and Memon, M.S. “Sustainable and resilient supply chain network design under disruption risks”, *Sustainability, 6*(10), pp.6666-6686 (2014).

[67] Lam, J.S.L. and Lai, K.H. “Developing environmental sustainability by ANP-QFD approach: the case of shipping operations”, *Journal of Cleaner Production, 105*, pp.275-284 (2015).

[68] Chowdhury, M.M.H. and Quaddus, M.A. “A multiple objective optimization based QFD approach for efficient resilient strategies to mitigate supply chain vulnerabilities: The case of garment industry of Bangladesh”, *Omega, 57*, pp.5-21 (2015).

[69] Dixit, V., Seshadrinath, N. and Tiwari, M.K. “Performance measures based optimization of supply chain network resilience: A NSGA-II+ Co-Kriging approach”, *Computers & Industrial Engineering, 93*, pp.205-214 (2016).

[70] Rezapour, S., Farahani, R.Z. and Pourakbar, M. “Resilient supply chain network design under competition: A case study”, *European Journal of Operational Research*, *259*(3), pp.1017-1035 (2017).

[71] Fargnoli, M. and Haber, N. “A practical ANP-QFD methodology for dealing with requirements’ inner dependency in PSS development”, *Computers & Industrial Engineering*, *127*, pp.536-548 (2019).

[72] Margolis, J.T., Sullivan, K.M., Mason, S.J., et al. “A multi-objective optimization model for designing resilient supply chain networks”, *International Journal of Production Economics*, *204,* pp.174-185 (2018).

[73] Kinoshita, Y., Yamada, T. and Gupta, S.M. “Problem of Disassembly-To-Order System for Recycling Rate and Profit using Linear Physical Programming”, *Procedia Manufacturing*, *39,* pp.1597-1606 (2019).

[74] Yatsuka, T., Ishigaki, A., Kinoshita, Y., et al. and Inoue, M. “Linear physical programming iteration method of multi-player multi-objective decision making supply chain”, *Procedia Manufacturing*, *39*, pp.1649-1657 (2019).

[75] Mohammed, A., Harris, I., Soroka, A., et al. “A hybrid MCDM-fuzzy multi-objective programming approach for a G-resilient supply chain network design”, *Computers & Industrial Engineering*, *127*, pp.297-312 (2019).

[76] Mistarihi, M.Z., Okour, R.A. and Mumani, A.A.” An integration of a QFD model with Fuzzy-ANP approach for determining the importance weights for engineering characteristics of the proposed wheelchair design”, *Applied soft computing*, *90*, p.106136 (2020).

[77] Wasserman, G.S. “On how to prioritize design requirements during the QFD planning process”, *IIE transactions*, *25*(3), pp.59-65 (1993).

Table 1. Common risks in the supply chain

Supply chain risks	Reference
Natural risks	
Silva et al. [14]	Natural disasters
Perrin and Martin [15]	Infectious diseases (such as COVID-19)
Operating risks	
Kleindorfer and Saad [16]	Operating failure due to the inappropriate use of machinery and equipment
Blackhurst et al. [17]	Production capacity limitation
Blos et al. [18]	Product qualitative problems
Chowdhury and Quaddus [19]	Inadequacy of skills in human's resources
Scheibe and Blackhurst [20]	Infrastructural problems such as inefficient distribution, storage, and information
Fan and Stevenson [21]	Lack of access to information
Scheibe and Blackhurst	Worker conflicts and strikes
Colicchia et al. [22]	Transportation disruptions
Tiwari et al. [23]	Human error
Kumar et al. [24]	Management weakness
Financial risks	
Kamalahmadi and Parast, [25]	Bankruptcy
Kamalahmadi and parast	Economic conditions (recession and prosperity)
de Oliveira et al. [26]	Inflation
Supply and demand risks	
Wieland and Wallenburg [27]	Supplier disruption (opportunism, timely delivery)
Hao et al. [28]	Shortage of available raw materials
Linnenluecke [29]	Losing customers
Ivanov et al. [30]	Number of suppliers

Table 2. Common resilience strategies in the supply chain

Reference	Resilience strategies
Charles et al. [33]	Improving supply chain agility for dealing with unexpected natural accidents
Akdogan and Demirtas [34]	Improving knowledge and management performance in different chain sections
Mancheri et al. [35]	Having a coherent relationship with shareholders and monitoring the chain economic conditions
Fu and Chin [36]	Utilizing the appropriate methods for forecasting and analyzing demand and capacity
Dubey et al. [37]	Concentrating on the customer services and customer satisfaction
Hawkins et al. [38]	Enforcing the appropriate policies on determining the number and selecting suppliers
Bader et al. [39]	Utilizing the information sharing policies in and out of the supply chain
Alikhani et al. [40]	Using state-of-the-art methods of pricing and analyzing the market
Shin and Park [41]	Monitoring and improving the process and product components

Alikhani et al. [40]	Increasing inventories and improving the inventory and raw materials sections

Table 3. Literature review

Authors	Techniques								
	Resilient supply chain	Mathematical modeling	Multi-objective optimization	AHP	ANP	TOPSIS	QFD	Physical Programming	
								Non-linear	Linear
Lai et al. [4]			✓				✓		✓
Gencer and Gurpinar [60]					✓				
Kovach et al. [61]								✓	
Pochampally et al. [62]							✓		✓
Losada et al. [63]	✓	✓							
Shaw et al. [64]			✓	✓					
Soni et al. [65]	✓	✓							
Mari et al. [66]	✓		✓						
Lam and Lai [67]					✓		✓		
Chowdhury and Quaddus [68]	✓			✓		✓			
Dixit et al. [69]	✓		✓						
Rezapour et al. [70]	✓	✓							
Fargnoli and Haber [71]					✓		✓		
Ghavamifar et al. [32]	✓		✓						
Margolis et al. [72]	✓		✓						
Sabouhi et al.	✓	✓							
Kinoshita et al. [73]									✓
Yatsuka et al. [74]			✓						✓
Mohammed et al. [75]	✓		✓	✓		✓			
Mistarihi et al. [76]					✓		✓		
This paper	✓	✓	✓				✓		✓

Table 4. Supply chain risks

Risk name		Symbol
Supply and demand risks (SDR)	Lack of raw materials	SCR_1
	The number of suppliers	SCR_2

Operational risks (OR)	Limits of production capacity	SCR_3
	Lack of access to information	SCR_4
	Weakness in management	SCR_5
	Product quality issues	SCR_6
Financial risks (FR)	Economic conditions (recession and prosperity)	SCR_7
	Bankruptcy	SCR_8
Natural risks (NR)	Infectious diseases (such as COVID-19)	SCR_9
	Natural disasters such as floods, earthquakes, etc.	SCR_{10}

Table 5. Resilience strategies

Strategies name	**Symbol**
Implementing appropriate and relevant policies in terms of the number and selection of suppliers	RS_1
Taking advantage of appropriate methods for predicting and analyzing demand and capacity	RS_2
Taking advantage of information sharing policy in the supply chain and beyond it	RS_3
Upgrading the level of knowledge and managerial performance in different parts of the chain	RS_4
Employing up-to-date procedures in pricing and market analysis	RS_5
Monitoring and enhancing product and process components	RS_6
Cohesive communication with shareholders and monitoring economic conditions of the chain	RS_7
Upgrading supply chain agility to cope with natural disasters	RS_8

Table 6. Type of class functions and utility limits of supply chain risks

	Risk name	**The type of class function**	**Utility Limits**									
			t_5^-	t_4^-	t_3^-	t_2^-	t_1^-	t_1^+	t_2^+	t_3^+	t_4^+	t_5^+
Supply and demand risks	Lack of raw materials	1S	-	-	-	-	-	0.1	0.35	0.57	0.71	1
	The number of suppliers	4S	0	0.1	0.2	0.35	0.5	0.65	0.75	0.85	0.9	1
Operational risks	Limits of production capacity	1S	-	-	-	-	-	0.2	0.36	0.55	0.79	1
	Lack of access to information	1S	-	-	-	-	-	0	0.28	0.49	0.82	1
	Weakness in management	1S	-	-	-	-	-	0.13	0.37	0.52	0.85	1
	Product quality issues	1S	-	-	-	-	-	0.09	0.24	0.56	0.7	1
Financial risks	Economic conditions (recession and prosperity)	1S	-	-	-	-	-	0.18	0.26	0.48	0.86	1

	Economic conditions (recession and prosperity)	1S	-	-	-	-	-	0.2	0.38	0.56	0.88	1
Natural risks	Infectious diseases (such as COVID-19)	4S	0	0.13	0.21	0.34	0.43	0.52	0.65	0.73	0.82	1
	Natural disasters such as floods, earthquakes, etc.	1S	-	-	-	-	-	0.1	0.25	0.49	0.79	1

Table 7. Calculations of the importance weights for SCR1

symbol	**Value**
$\tilde{z}^3$	0.99
$\tilde{z}^4$	9.8
$\tilde{z}^5$	97.02
$\tilde{t}_{12}$	0.25 = 0.35 - 0.1
$\tilde{t}_{13}$	0.22 = 0.57 - 0.35
$\tilde{t}_{14}$	0.14 = 0.71 - 0.57
$\tilde{t}_{15}$	0.29 = 1 - 0.71
w_{11}	0
w_{12}	0.4
w_{13}	4.5
w_{14}	70
w_{15}	334.5
$\widetilde{w}_{12}$	0.4 = 0.4 – 0
$\widetilde{w}_{13}$	4.1 = 4.5 - 0.4
$\widetilde{w}_{14}$	65.5= 70 - 4.5
$\widetilde{w}_{15}$	264.5= 334.5 - 70

Table 8. The calculated importance weights for different ranges of supply chain risks

	Risk name	**Importance weight of utility limits (ranges)**							
		w_{i2}^{-}	w_{i3}^{-}	w_{i4}^{-}	w_{i5}^{-}	w_{i2}^{+}	w_{i3}^{+}	w_{i4}^{+}	w_{i5}^{+}
Supply and demand risks	Lack of raw materials	-	-	-	-	0.4	4.1	65.5	264.5
	The number of suppliers	0.666	30	98	970.2	1	9.9	196	970.2
Operational risks	Limits of production capacity	-	-	-	-	0.625	5.21	40.83	462
	Lack of access to information	-	-	-	-	0.357	4.71	29.6	539
	Weakness in management	-	-	-	-	0.41	6.6	29.69	246.8
	Product quality issues	-	-	-	-	0.666	3.09	70	323.4
Financial risks	Economic conditions (recession and prosperity)	-	-	-	-	1.25	4.5	25.78	693
	Economic conditions (recession and prosperity)	-	-	-	-	0.555	5.5	30.62	808.5
Natural risks	Infectious diseases (such as COVID-19)	1.11	7.6	122.5	746.3	0.76	12.375	108.8	539
	Natural disasters such as floods, earthquakes, etc.	-	-	-	-	0.555	4.71	32.66	462

Table 9. Estimation level of resilience strategies

Resilience strategies	RS_1	RS_2	RS_3	RS_4	RS_5	RS_6	RS_7	RS_8
Estimation level	1	0	0	0	1	0	0	1

Table 10. Reduction level of supply chain risks by employing specified resilience strategies

Supply chain risks	**Satisfaction rate**	**Domain**
SCR_1	g_1 = 0.301	desirable
SCR_2	g_2= 0.408	desirable
SCR_3	g_3= 0.246	desirable
SCR_4	g_4= 0.204	desirable
SCR_5	g_5= 0.369	desirable
SCR_6	g_6= 0.150	desirable
SCR_7	g_7= 0.370	tolerable
SCR_8	g_8= 0.341	desirable
SCR_9	g_9= 0.308	tolerable
SCR_{10}	g_{10}= 0.308	tolerable

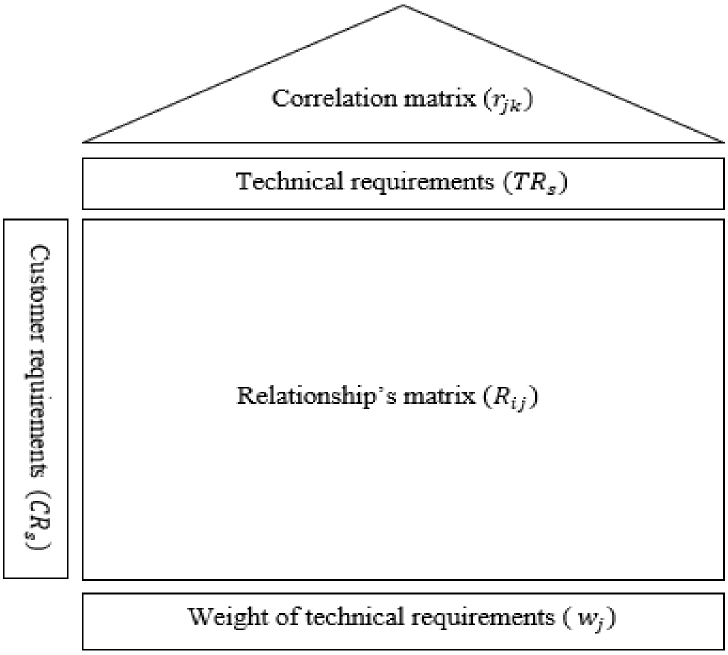


Figure 1. House of quality

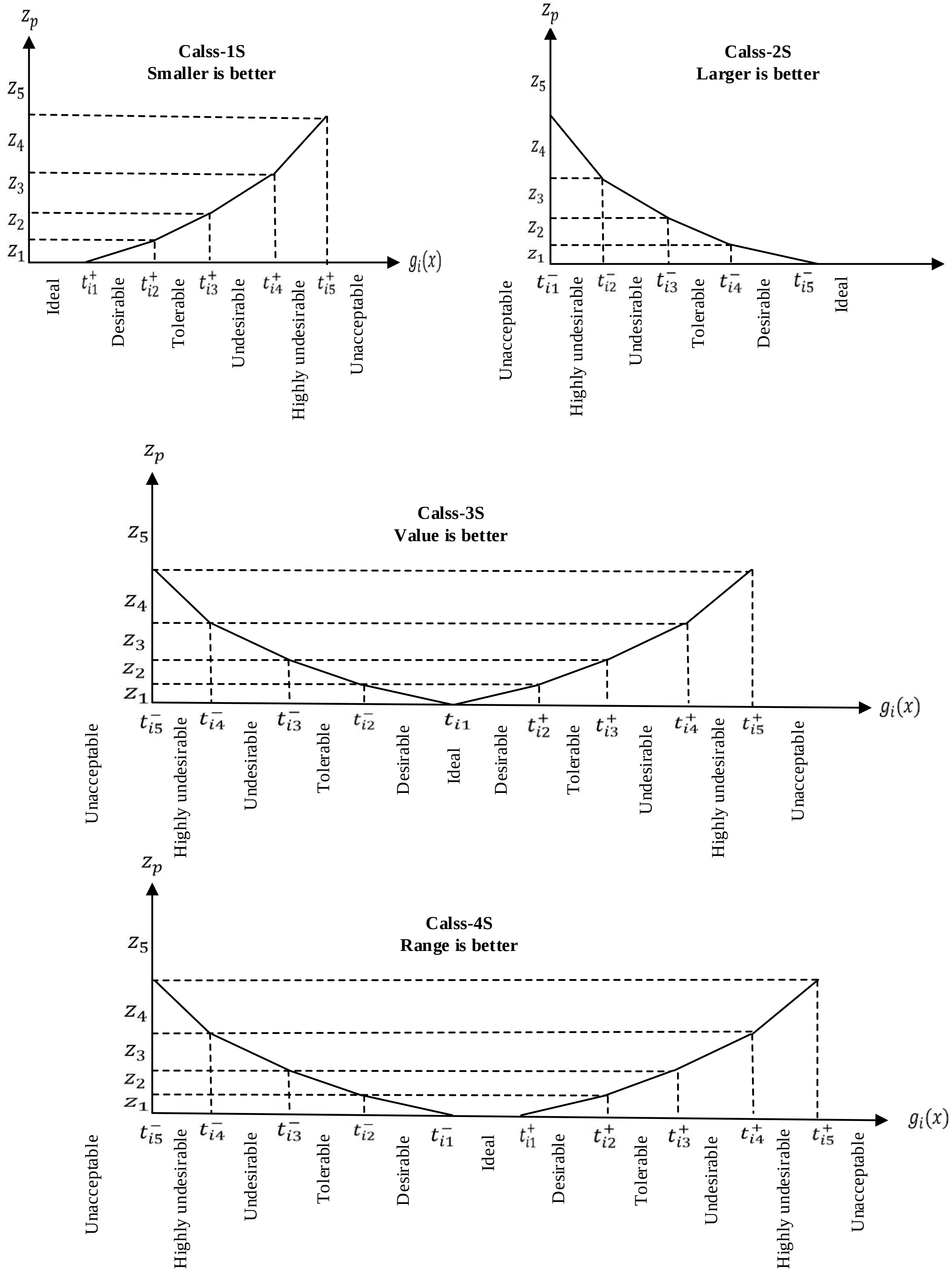


Figure 2. The four LPP classes

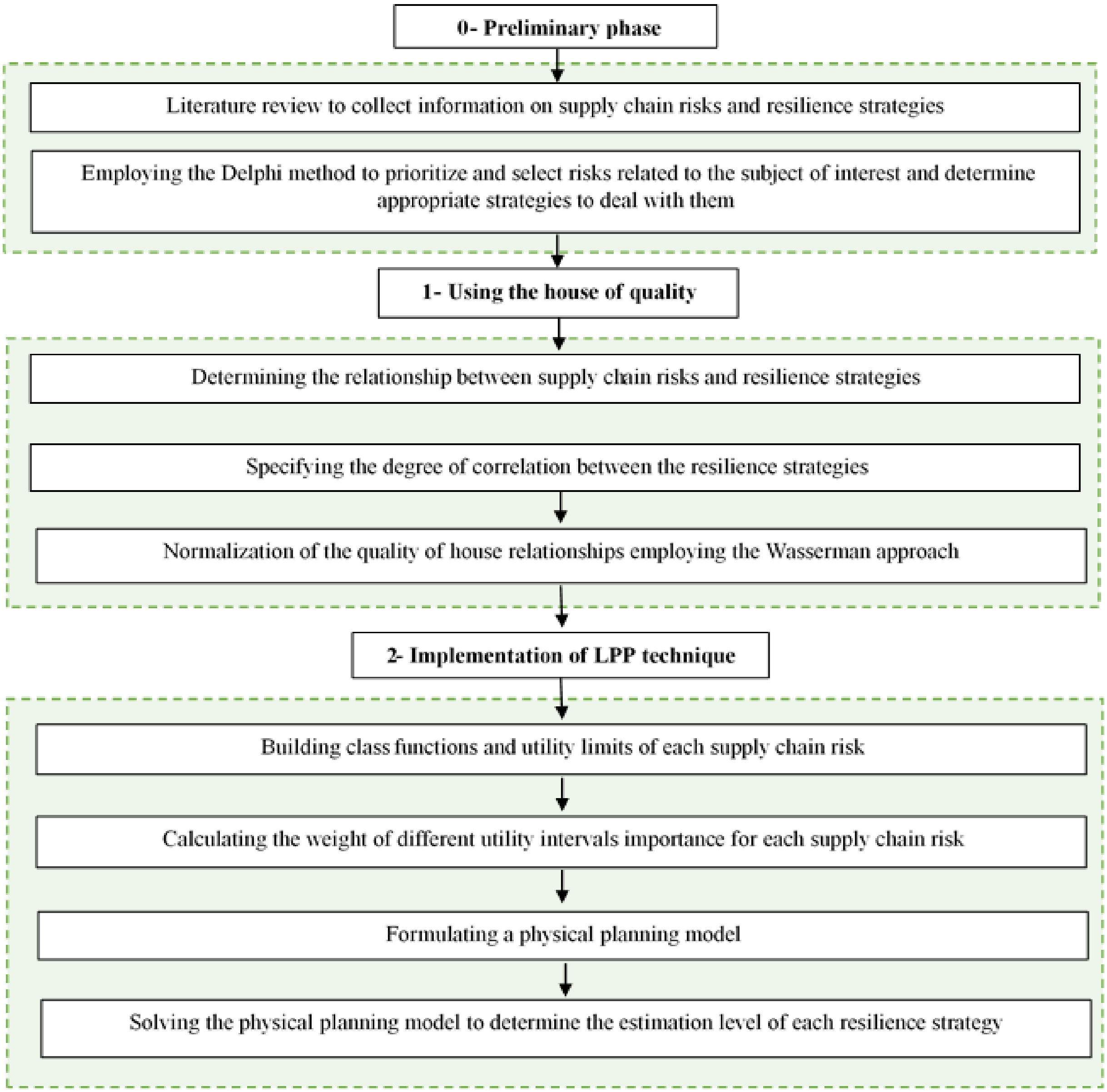
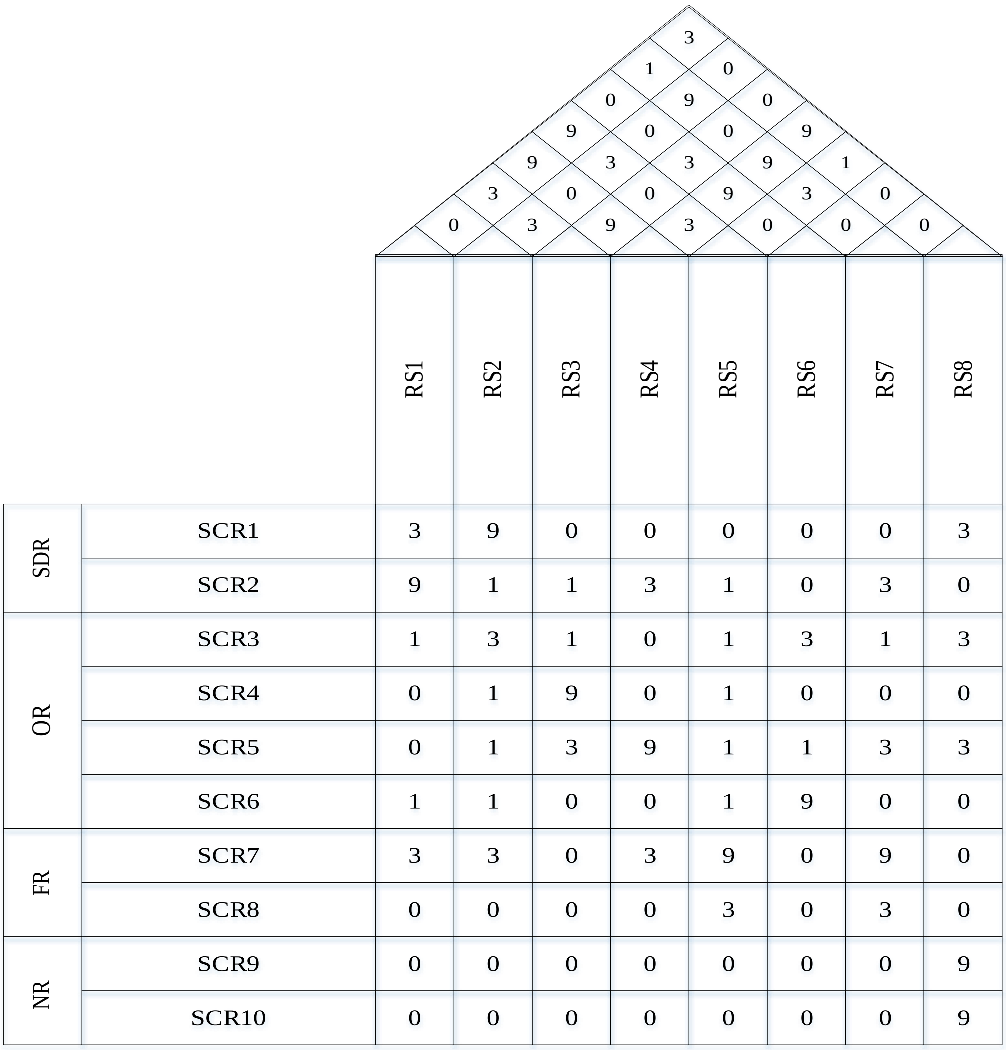


Figure 3. Proposed research methodology



		RS1	RS2	RS3	RS4	RS5	RS6	RS7	RS8
SDR	SCR1	3	9	0	0	0	0	0	3
	SCR2	9	1	1	3	1	0	3	0
OR	SCR3	1	3	1	0	1	3	1	3
	SCR4	0	1	9	0	1	0	0	0
	SCR5	0	1	3	9	1	1	3	3
	SCR6	1	1	0	0	1	9	0	0
FR	SCR7	3	3	0	3	9	0	9	0
	SCR8	0	0	0	0	3	0	3	0
NR	SCR9	0	0	0	0	0	0	0	9
	SCR10	0	0	0	0	0	0	0	9

Figure4. HOQ with basic relationships

		RS1	RS2	RS3	RS4	RS5	RS6	RS7	RS8
SDR	SCR1	0.036	0	0.145	0.217	0.229	0	0.337	0.036
	SCR2	0.086	0.068	0.117	0.246	0.209	0.062	0.099	0.113
OR	SCR3	0.108	0.074	0.103	0.412	0.118	0.015	0.152	0.020
	SCR4	0.184	0.153	0.015	0.429	0.015	0.138	0.061	0.005
	SCR5	0.174	0.061	0.137	0.146	0.066	0.141	0.146	0.129
	SCR6	0.054	0.018	0.198	0.557	0.072	0	0.078	0.024
FR	SCR7	0.185	0.171	0.071	0.213	0.114	0.043	0.133	0.071
	SCR8	0.244	0.293	0	0.293	0.073	0	0.073	0.024
NR	SCR9	0.231	0	0	0.692	0.077	0	0	0
	SCR10	0.231	0	0	0.692	0.077	0	0	0

Figure 5. Normalized HOQ

Biographies

Shahpar Sattar received her MSc degree in Industrial Engineering at the Department of Industrial Engineering, Khajeh Nasir Toosi University of Technology. After graduation, she started to work in Tohfe Food Production Group as a production planning expert. Her research inerests include supply chain management, risk management and operation research.

Address: No.7.Pardis Ave.Molasadra .Vanak Sq.Tehran.Iran.

E-mail: shahpar.ind.96@gmail.com

Phone: +98 9227826551

Emad Roghanian received his PhD degree from Iran University of Science and Technology, Tehran, Iran, in 2006. He is currently an Associate Professor in the Faculty of Industrial Engineering at K.N. Toosi University of Technology. His research interests include supply chain management, project management, probability models, and applied operations research. He has authored numerous papers presented at conferences and published in journals, including Applied Mathematical Modelling, Computers & Industrial Engineering and Applied Mathematics and Computation.

Office Address: No.7.Pardis Ave.Molasadra .Vanak Sq.Tehran.Iran.

E-mail: e_roghanian[@]kntu.ac.ir

Phone: +98 21 84063368 _ +98 9128387291