Chapter 6
Fuzzy Extent Analysis for Food Risk Assessment

6.1 Introduction

The analytical hierarchy process (AHP) provides an effective way to deal with complex decision making. However, AHP requires decision makers to determine the relative importance of each criterion/factor by means of pairwise comparisons between the relevant criteria/factors included in the analysis. The decision maker may feel uncertain about the pairwise comparison or may consider that it is not a method capable of reflecting a human being's vague thoughts (Kahraman et al. 2003). Often, the uncertainty inherent in some situations and in some problems cannot be expressed simply by using crisp values from the nine-point scale. To address the limitations of AHP, some scholars have made use of fuzzy set theory, as introduced by Zaddeh (1965), to create the fuzzy AHP approach. The main benefit introduced by fuzzy AHP is that it enables a more accurate description of the decision-making process that takes place in real applications where ill-defined uncertainties are not uncommon (Huang et al. 2008).

Different methods for the fuzzification of AHP have been proposed since Van Laarhoven and Pedrycz (1983) and Buckley (1985) presented their preliminary work in fuzzy AHP. Van Laarhoven and Pedrycz (1983) used fuzzy ratios based on triangular fuzzy number. Buckley (1985) determined fuzzy priorities for comparison ratios which were defined by trapezoidal membership functions. The previous chapter demonstrates the operations of fuzzy AHP via a case study. In addition, many approaches have been developed to refine fuzzy AHP models on multiple criteria decision-making (MCDM) problems (Chang 1996; Xu 2000; Csutora and Buckley 2001; Mikhailov 2003; Wang et al. 2006). Amongst these, fuzzy extent analysis introduced by Chang (1996) is a relatively easier and less computational exercise compared with the other approaches to fuzzy AHP. In this approach, triangular fuzzy numbers are used to construct pairwise comparison scales for fuzzy AHP, and then the fuzzy extent analysis method is deployed to determine the synthetic extent values of the pairwise comparison.

In this chapter, fuzzy extent analysis is integrated with the hierarchical model to provide aggregative risk assessment. An application of the aggregative risk assessment model in the food supply chain is presented. Quality and safety are

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always the top priorities in the industry. The fuzzy hierarchical model provides a practical and easy-to-use risk assessment model that will help in conducting risk analysis and in quantifying risk in such a way that different operational processes and material batches can be compared in terms of food safety and quality. The model is able to effectively analyse, quantify and enable comparative assessment of the risks of the different processes along a food supply chain, and thereby support the decision-making process at critical control points.

6.2 Fuzzy Extent Analysis

Here, the fuzzy synthetic extent analysis method is introduced to calculate the synthetic extent value of the pairwise comparison. An extent analysis adaptation to fuzzy AHP was proposed by Chang (1996), in order to obtain a crisp priority vector from a triangular fuzzy comparison matrix. The triangular fuzzy scale of preferences is given in Fig. 6.1, in which TFNs' M_1, M_3, M_5, M_7 and M_9 are used to represent the pairwise comparison of decision variables in the range from "Equal" to "Absolute", when these are employed as descriptive terms attached to the level of importance of paired variables, and TFNs' M_2, M_4, M_6 and M_8 represent the mid-point preference values lying between them.

In terms of an equation-based approach, let $P = \{p_1, p_2, \ldots p_n\}$ be an object set, and $Q = \{q_1, q_2, \ldots q_m\}$ be a goal set. According to the method of extent analysis (Chang 1996), each object is taken and extent analysis is performed for each goal, respectively. Therefore, the m extent analysis values for each object are obtained as $M_{g_i}^1, M_{g_i}^2, \ldots M_{g_i}^m, i = 1, 2, \ldots, n$, where all the $M_{g_i}^j (j = 1, 2, \ldots, m)$ are TFNs. The value of fuzzy synthetic extent with respect to the ith object is defined as:

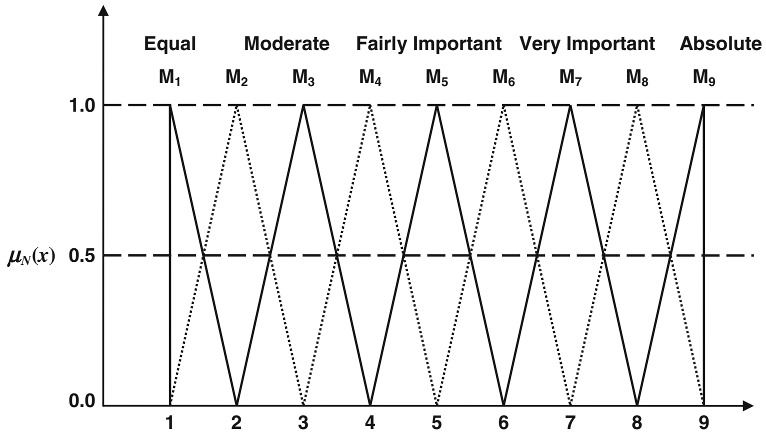


Fig. 6.1 Membership functions of TFN

$$S_i = \sum_{j=1}^{m} M_{g_i}^{j} \otimes \left[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{g_i}^{j}\right]^{-1} \tag{6.1}$$

and $\left[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{g_i}^{j}\right]^{-1}$ can be calculated as:

$$\left[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{g_i}^{j}\right]^{-1} = \left(\frac{1}{\sum\limits_{i=1}^{n} m_{3i}}, \frac{1}{\sum\limits_{i=1}^{n} m_{2i}}, \frac{1}{\sum\limits_{i=1}^{n} m_{1i}}\right) \tag{6.2}$$

The degree of possibility of $M_1 \geq M_2$ is defined as:

$$V(M_1 \geq M_2) = \sup_{x \geq y}\left[\min(u_{M_1}(x), u_{M_2}(y))\right] \tag{6.3}$$

When a pair (x, y) exists, such that $x \geq y$ and $u_{M_1}(x) = u_{M_2}(y) = 1$, then we have $V(M_1 \geq M_2) = 1$. Since M_1 and M_2 are convex fuzzy numbers, we have that

$$\begin{aligned} &V(M_1 \geq M_2) = 1 \text{ if } m_{12} \geq m_{22}, \\ &V(M_1 \geq M_2) = hgt(M_1 \cap M_2) = u_{M_1}(d) \end{aligned} \tag{6.4}$$

where d is the ordinate of the highest intersection point D between u_{M_1} and u_{M_2} (see Fig. 6.2). When $M_1 = (m_{11}, m_{12}, m_{13})$ and $M_2 = (m_{21}, m_{22}, m_{23})$, then ordinate of D is computed by

$$\begin{aligned} V(M_2 \geq M_1) &= hgt(M_1 \cap M_2) \\ &= \frac{m_{11} - m_{23}}{(m_{22} - m_{23}) - (m_{12} - m_{11})} \end{aligned} \tag{6.5}$$

To compare M_1 and M_2, both the values of $V(M_1 \geq M_2)$ and $V(M_2 \geq M_1)$ are required. The degree of possibility for a convex fuzzy number to be greater than k convex fuzzy numbers M_i $(i = 1, 2,\ldots,k)$ can be defined by

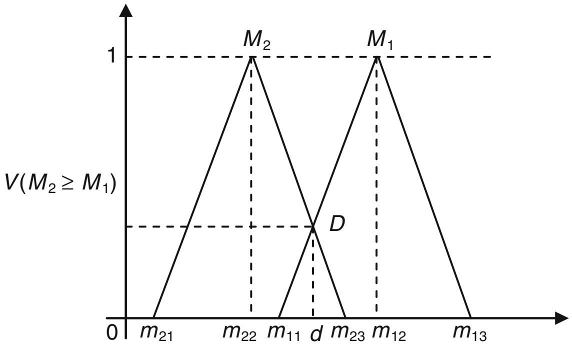


Fig. 6.2 Membership functions of the set of importance ratings

$$\begin{aligned} &V(M \geq M_1, M_2, \ldots, M_k) \\ &= V[(M \geq M_1)\, and\, (M \geq M_2) \text{ and}, \ldots, \text{and } (M \geq M_2)] \\ &= \min V(M \geq M_i), i = 1, 2, \ldots, k \end{aligned} \tag{6.6}$$

If

$$d(X_i) = \min\, V(S_i \geq S_k), \tag{6.7}$$

For $k = 1, 2, \ldots, n$; $k \neq i$, then the rating vector is given by

$$W' = (d(X_1), d(X_2), \ldots, d(X_n))^T \tag{6.8}$$

where X_i ($i = 1, 2, \ldots, n$) are n different criteria. Via normalisation, the normalised rating vectors are:

$$W = (R(X_1), R(X_2), \ldots, R(X_n))^T \tag{6.9}$$

where W is a non-fuzzy number that provides priority weights of an uncertainty criterion or sub-criterion over others.

For the accuracy of the method to be verified, the consistency measure is performed to screen out inconsistency between responses. Since M_i is a triangular number, it has to be defuzzified into a crisp number to compute the consistency ratio (CR). The centre of area (COA) approach is used here for defuzzifying M_i. According to the COA approach discussed earlier in Chap. 5, a TFN $\tilde{M} = (m_1, m_2, m_3)$ can be defuzzified into a crisp value by:

$$P(\tilde{M}) = [(m_3 - m_1) + (m_2 - m_1)]/3 + m_1 \tag{6.10}$$

Therefore, the CR of each judgment can be calculated and checked to ensure that it is lower than or equal to 0.1.

Chang's extent analysis has been widely applied in different problem environments in the literature: Weck et al. (1997) applied this method to evaluate alternative production cycles and rank them in terms of the main objective set; Kwong and Bai (2003) used fuzzy extent analysis to prioritise customer requirements in quality function deployment (QFD); Kahraman et al. (2004) developed an analytical selection tool to measure the customer satisfaction in catering firms in Turkey; Chan and Kumar (2007) applied fuzzy AHP to investigate the risk associated with various options for global supplier selection; Celik et al. (2009) developed fuzzy AHP methodology based on Chang's extent analysis to model shipping registry selection; Cho et al. (2012) employed extended fuzzy AHP to measure the performance of service supply chain management; Lee et al. (2012) used fuzzy extent analysis to determine the criteria for green supplier selection; Kutlu and Ekmekçioğlu (2012) integrated fuzzy extent analysis with fuzzy technique for order of preference by similarity to Ideal solution (TOPSIS) for failure mode and effects analysis; and Wang et al. (2012) applied fuzzy extent analysis to develop a risk assessment model that enabled a structured analysis of aggregative risk in the food supply chain. The trends in utilising fuzzy extent analysis in fuzzy

AHP evident in the literature have been continued in many of the operational disciplines due to its ease of use and computational simplicity. There is, however, criticism of its accuracy in estimating the respective weights of variables from a fuzzy comparison matrix. Further, Wang et al. (2008) stated that the fuzzy extent analysis method is not a method appropriate for deriving priorities from a fuzzy comparison matrix, demonstrating this through three numerical examples. Nevertheless, they also acknowledged that it is useful for showing to what degree the priority of one decision criterion or its alternative in a pair is greater than others in a fuzzy comparison matrix. The purpose of this research is to assess risk in different supply chains and highlight those risk factors that are significant, in order for organisations to take appropriate actions to address them. The fuzzy extent analysis approach to AHP allows a more accurate evaluation of the uncertainty inherent in the decision-making process and, therefore, merits inclusion in this book.

6.3 Risk Assessment in the Food Industry

Food contamination incidents, food quality concerns and outbreaks of animal diseases of all kinds are frequently reported in the media, and these have been responsible for spreading significant anxiety amongst consumers over food safety. To ensure consumers' confidence is retained, a series of food safety policies and regulations have been created and adopted, to varying degrees, all over the world. Along these same lines, the application of risk assessment techniques to food safety issues is being promoted strongly by international organisations (WHO/FAO 1999). Risk assessment is but one of three parts of the food risk analysis process, which also includes risk management and risk communication.

6.3.1 Hazard Analysis and Critical Control Points

Alongside the series of global food safety policies and regulations, the preventative approach of hazard analysis and critical control points (HACCP) is increasingly used as a means of providing enhanced food safety assurance. HACCP principles can be applied throughout the food chain from the primary producer to final consumer, and the application of HACCP systems can also aid inspection by regulatory authorities, as well as promote international trade, by increasing confidence in food safety (Codex Alimentarius Commission 1997). Most food manufacturers are now required to apply the principles of HACCP to ensure the safety of their products. Consequently, HACCP principles have been internationally accepted and approved.

The goal of a HACCP plan is to minimise risks by establishing control procedures at certain critical points during food processing. Walker and Jones (2002) stated that the use of HACCP is an approach for prevention and control of foodborne disease, by identifying hazards and risks at every stage of food production and determining where controls are required. Sun and Ockerman (2005) discussed the needs, current applications and the prospects of HACCP in food service areas in their research and suggested that the development of a HACCP in all food businesses is essential to ensure the safety of the whole production line in the food chain.

There are seven standard principles underpinning the HACCP system, as recommended by the US Food and Drug Administration's Food Code (McSwame et al. 2003). They are (1) hazard analysis, (2) identification of the critical control points (CCPs) in food preparation, (3) establishment of critical control limits (thresholds) which must be met at each identified critical control point, (4) establishment of procedures to monitor CCPs, (5) establishment of the corrective action procedures to be taken when monitoring indicates that a critical limit has been exceeded, (6) establishment of procedures to verify that the HACCP system is working and (7) implementation of effective record keeping systems that document the HACCP system. Hazard analysis is the collection and evaluation of information regarding the characteristics and extent of contaminants and other conditions leading to threats to food safety. Hazard identification is a qualitative approach of systematically identifying potential adverse health effects of the hazard. The impacts of hazardous agents vary in terms of the materials quality, process environment, composition, packaging and storage conditions of the product.

6.3.2 Food Risk Assessment

The application of risk assessment methods to food safety has been reported extensively in the literature. It is a scientific evaluation of known or potential adverse health effects resulting from exposure to biological, chemical or physical factors in food (Codex Alimentarius Commission 2002). The ultimate goal of a risk assessment process is to estimate the probability of occurrence, and this may be based on qualitative and/or quantitative information (Davidson et al. 2006).

Risk is defined as a function of the probability of an adverse health effect happening and the severity of that effect and is consequential to a hazard (European Commission 2002). Here, hazard means a biological, chemical or physical agent in, or the overall condition of, food with the potential to cause an adverse health effect (European Commission 2002). The risk assessment process consists of four steps: hazard identification, hazard characterisation, exposure assessment and risk characterisation. Hazard identification is the identification of biological, chemical and physical agents capable of causing adverse health effects and which may be present in a particular food or group of foods (Codex Alimentarius Commission 1999). Hazard characterisation is the qualitative and/or quantitative evaluation of the nature of the adverse health effects associated with these biological, chemical and physical agents, which may be presented in food (Codex Alimentarius Commission 1999). It is, therefore, the process of obtaining quantitative information (dose–response assessment) on the magnitude of adverse effects on human health following exposure to a hazardous entity. Exposure assessment is defined as the qualitative and/or quantitative evaluation of the likely intake of biological, chemical and physical agents via food, as well as exposures to other sources, if relevant (Codex Alimentarius Commission 1999). Risk characterisation is the qualitative and/or quantitative estimation, including any attendant uncertainties, of the probability of occurrence and severity of known, or potential, adverse health effects in a given population based on hazard identification, hazard characterisation and exposure assessment (Codex Alimentarius Commission 1999).

Various risk assessment methodologies and approaches have been developed and are used increasingly to quantitatively assess risks to human health presented by the food chain (Serra et al. 1999; Hoornstra et al. 2001; Parsons et al. 2005). Sperber (2001) indicated that risk assessment is a quantitative and globally applicable process in which a numerical degree of risk can be calculated for a particular hazard. Quantitative risk assessment, in particular when using stochastic models, is a specialised task that requires skills in mathematics and statistics, in addition to microbiological and technological knowledge (European Commission 2002). As a consequence, it is usually conducted by a large consortium of experts that normally involves regulatory, public health, academic and industry participation.

Traditionally, risk assessment has mainly focused on assessing the risk of the end product impacting adversely on consumers' health and on making decisions about food safety objectives that comply with regulatory and customer requirements (Hoornstra et al. 2001; European Commission 2002). End point testing of products is not a good way of ensuring food safety (Walker et al. 2003). By the time the results are obtained, the food has been served and consumed, and it is subsequently hard to trace effects, or even conduct a recall in the event of product safety being compromised. The question of the level of application of risk assessment is related to the reason for conducting the risk assessment in the first place, that is, to provide information sufficient to make robust risk management decisions. There is also a need to provide an additional focus on risk assessment application from a production perspective, and so more risk assessment procedures must be carried out during the processing itself. For example, "Pre-screening" of the risk by simpler qualitative methods can aid decisions about the value of investing resources in fully quantitative risk assessment (Ross and Sumner 2002). From a company's perspective, by using elements of quantitative risk assessment, the HACCP system can be transformed into a more meaningful managerial tool. In reality, many companies, and particularly small- and medium-sized enterprises (SMEs), struggle with the practical application of HACCP, because of a lack of expertise, training, time, motivation and commitment, all compounded by their lack of ability to implement a systematic and quantitative risk assessment.

In the food supply chain, the risk assessment process needs both sufficient information and effective tools. As previously discussed, HACCP is broadly established as a tool for promoting food safety assurance. Walker and Jones (2002) stated that HACCP is an approach for prevention and control of foodborne disease by identifying hazards and risks at every stage of food production and determining where controls are required. An important principle of HACCP is hazard analysis, but it should be emphasised that hazard analysis and risk assessment are fundamentally different and independent processes (Sperber 2001). However, both contain a common step: hazard identification, which is a qualitative approach of systematically identifying the potentially adverse health effects of the hazard. The main basis of hazard identification is starting from the knowledge of existing hazards, established either from an analysis of ingredient lists or from brainstorming by the HACCP team.

6.3.3 Using Fuzzy Theory in Food Risk Assessment

The process of conducting risk assessments is well described as a formal, structured process that is both complex and evolving. More and more extended quantitative risk assessments are being carried out. However, the outputs represent only those hazards incorporated in the original design of the assessment. In reality, many companies, particularly SMEs, struggle with their application in implementing systematic and quantitative risk assessment, due to lack of expertise, training, time, motivation, commitment and funding. Furthermore, tailor-made quantitative risk assessments are not always possible, either because of a lack of specific quantitative data or because of a lack of understanding of the available models or the implications of each model's parameter. However, these obstacles do not necessarily prevent risk estimation entirely. In such situations, qualitative risk assessment can assist risk managers in priority setting, policy decision making and allocating risk resources to sampling (Coleman and Marks 1999) while acknowledging that the assessment is often carried out with inadequate data for comprehensive numerical risk estimation (Codex Alimentarius Commission 2001). Accordingly, various semi-quantitative scoring systems and decision trees, etc., have also been introduced to bridge the gap between qualitative and fully quantitative methods (Marks et al. 1998; Huss et al. 2000; Ross and Sumner 2002, Davidson 2006).

In many cases, however, problems with a significant degree of uncertainty cannot be addressed simply by using the concept of probability, let alone crisp values. Since fuzzy set theory was introduced by Zadeh (1965), it has been frequently used to solve such problems of an uncertain nature. The fuzzy set theory resembles human reasoning, in its use of approximate information and allowance of uncertainty, as a tool to support decision making. It has the advantage of mathematically representing uncertainty and vagueness. The use of fuzzy methods in risk assessment has covered a range of applications: earthquake risks (Huang 1996), environmental risk (Sadiq and Husain 2005), contaminated groundwater (Li et al. 2007) and software development (Lee 1996; Lee et al. 2003). More recently, Davidson et al. (2006) proposed a general framework that allows simple computations (for microbial risk assessment) using fuzzy values to represent uncertainty and/or lack of knowledge of associated values. However, similar to most risk assessment models, the research only focuses on individual hazards and still requires some degree of knowledge to properly construct a food hazard identification system.

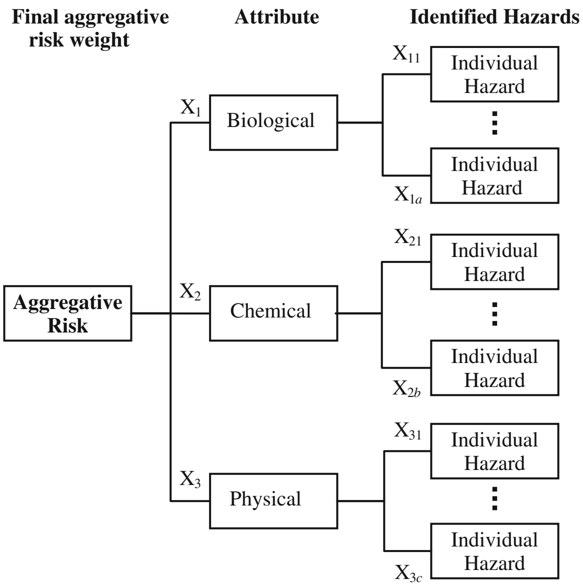
6.4 Fuzzy Hierarchical Model for Aggregative Food Risk Assessment

In a food production network, risk can be accumulated as food passes through the different stages in supply chains (Li et al. 2001; Parsons et al. 2005). The application of quality assurance (QA) systems is required at each step in the food supply chain to ensure safety of food and to show compliance with regulatory and customer requirements (Domenech et al. 2007). In order to enable a structured analysis of food safety risk in food supply chains to be carried out, a hierarchical structure model for aggregative risk assessment needs to be established, based on the input of hazards obtained through a hazard identification process. As previously stated, knowledge of existing or potential hazards may come from commonly used methods, for example, brainstorming by the HACCP team or the analysis of sensitive ingredient lists. Individual hazards in the hierarchical structure are then assessed using the fuzzy enabled risk assessment method. Fuzzy extent analysis is used to determine the weights of identified hazards. After that, fuzzy values are computed and it is possible to move on to establish an aggregative food safety risk indicator (AFSRI).

6.4.1 Hierarchical Structure

Contrary to current risk assessment techniques that focus on classifying particular types of hazards, this research aims to establish an aggregative food safety risk indicator (AFSRI) which provides a single value representing the risk rating. Risk assessment, according to the Codex Alimentarius Commission (2002), is a scientific evaluation of known or potentially adverse health effects resulting from exposure to hazardous agents. Impacts of hazardous agents vary in terms of material quality, process environment, packaging and storage conditions of the product, etc. Hazards can be classified into three categories: biological, chemical and physical hazards (Codex Alimentarius Commission 2002). To determine a value for the aggregative risk, biological, chemical and physical hazards (and all the severity factors associated with them) have to be incorporated into the calculation. Figure 6.3 represents a hierarchical model for the aggregative risk involving these three categories. Then, all the known and/or potential hazards in each category should be identified and listed. For example, physical hazards could be glass, bone, metal, wire, sand, dirt and stones, pits or shells, and pests or parts of pests, etc. The fuzzy set theory is then used to evaluate the identified individual hazards.

Fig. 6.3 Hierarchical structure model of aggregative food safety risk



6.4.2 *Use of Fuzzy Theory in the Evaluation of Food Risk*

In many cases, constraints in data quality, time, personnel or resources may not permit a full systematic and quantitative risk assessment. In this chapter, the fuzzy theory approach is adopted as a basis for the transformation of the qualitative risk evaluation factors into fuzzy values and, consequently, the use of more refined quantitative assessment outcomes in the development of the supply chain–oriented risk assessment model. Here, the commonly used concept of the triangular fuzzy number (TFN) is employed to characterise the fuzzy values of quantitative data, and additionally, linguistic terms are used in approximate reasoning. There are many other fuzzy theory representations, such as standardised trapezoidal fuzzy number and the Gaussian method, which are used to capture and convert experts' fuzzy information and subjective judgements into quantitative values. Trapezoidal, Gaussian and triangular membership functions are all popularly used representations. Trapezoidal and triangular membership functions describe the fuzzy membership linearly. On the other hand, the Gaussian function describes fuzzy membership nonlinearly and more flexibly, with a smoothed presentation in variations of membership by degrees. With more parameters characterising the function, the Gaussian method may describe the membership more accurately in some situations, particularly when the function of an item can be quantitatively defined and calculated. However, it is more complex than the methods employing linear functions, in terms of definition of a membership function. When an item is subjectively measured, the complexity of the definition may generate even more inaccuracy. Additionally, Gaussian membership functions are not normal, and they do not have the consistency property (Zeng and Singh 1994). Besides these complications, the triangular membership functions are easier to generate and are, thus, the most frequently used functions in applications (Lee 1996; Lee et al. 2003; Sadiq and Husain 2005).

Lee (1996) has developed an 11-level ranking system by which grade and importance of risk factors are classified. This approach was also used by Sadiq and Husain (2005) in estimating aggregative risk of various environmental activities. In Lee's approach, the linguistic values from 1 to 11 were used to represent corresponding fuzzy numbers with triangular membership functions, as listed in Table 6.1. The membership functions of triangular fuzzy numbers for the 11-level qualitative scales in Table 6.1 are described in Eq. 6.11.

$$\mu_{N1}(x) = \begin{cases} 1 - 10x, & 0 \le x < 0.1, \\ 0, & 0.1 \le x \le 1, \end{cases}$$

$$\mu_{Nn}(x) = \begin{cases} 0, & 0 \le x < \frac{n-2}{10} \\ 10x - (n-2), & \frac{n-2}{10} \le x \le \frac{n-1}{10} \\ n - 10x, & \frac{n-1}{10} \le x \le \frac{n}{10} \\ 0, & \frac{n}{10} \le x \le 1 \end{cases} \tag{6.11}$$

$$(n = 2, 3, \cdots 10)\text{and}$$

$$\mu_{N11}(x) = \begin{cases} 0, & 0 \le x < 0.9, \\ 10x - 9, & 0.9 \le x \le 1, \end{cases}$$

Once the linguistic values from 1 to 11 had been made into corresponding fuzzy numbers with triangular membership functions, two fuzzy numbers N_r and N_i with membership functions $u_{N_r}(x)$ and $u_{N_i}(x)$ were used to represent the grade of risk and the grade of importance, respectively. The next stage of the conversion of the

Table 6.1 Linguistic classifications of grades of risk and importance and their corresponding TFNs [Modified after Lee (1996)]

Grade of risk	Eleven ranks of grade of risk (*r*)	Eleven ranks of grade of importance (*i*)	Triangular fuzzy numbers (TFNs)
1	Definitely low	Definitely unimportant	(0.0, 0.0, 0.1)
2	Extremely low	Extremely unimportant	(0.0, 0.1, 0.2)
3	Very low	Very unimportant	(0.1, 0.2, 0.3)
4	Low	Unimportant	(0.2, 0.3, 0.4)
5	Slightly low	Slightly unimportant	(0.3, 0.4, 0.5)
6	Middle	Middle	(0.4, 0.5, 0.6)
7	Slightly high	Slightly important	(0.5, 0.6, 0.7)
8	High	Important	(0.6, 0.7, 0.8)
9	Very high	Very important	(0.7, 0.8, 0.9)
10	Extremely high	Extremely important	(0.8, 0.9, 1.0)
11	Definitely high	Definitely important	(0.9, 1.0, 1.0)

resulting combined fuzzy values into a non-fuzzy form is called defuzzification. The COA approach (see Eq. 6.10) is used for this defuzzification.

When assessing risks, the nature of the hazard, the likelihood that an individual or population will be exposed to the hazard and the likelihood that exposure will result in an adverse health effect have all to be considered (Walls 2006). As the assessment results are used as a comparative measure of risk and the same population target is contained in the assessment, the risk is assumed to be independent of population size. Therefore, the following factors are instead considered when the risk assessment is carried out:

1. Severity of the hazard
2. Likelihood of the hazard
3. Effect of the hazard

Here, the *severity* indicates the nature of the hazard; the *likelihood* refers to the probability of the hazard occurring and its consequent effects based on known history of performance and complaints; and the *effect* includes the potential numbers exposed, as well as the age and vulnerability of those exposed.

In practice, companies have difficulty in evaluating these factors due to uncertainty and lack of both knowledge and information. Instead, risk assessors and QA managers generally rank these risk factors qualitatively in terms of linguistic variables such as high, moderate and low. In the fuzzy theory approach, the qualitative scales are expressed as TFNs to capture the vagueness in the linguistic subjectivity of risk definitions. Table 6.2 describes this qualitative scaling system for severity of the hazard, likelihood of an adverse health effect consequential to the hazard, and probability of exposure. Three fuzzy numbers N_s, N_l and N_e with membership functions, $u_{N_s}(x)$, $u_{N_l}(x)$, and $u_{N_e}(x)$ represent the grading of these three factors, respectively. To determine the magnitude and intensity of the risk, these three factors are multiplied by themselves to produce the risk evaluation:

$$\text{Risk} = \text{Hazard Severity} \times \text{Hazard likelihood} \times \text{Hazard Effect} \tag{6.12}$$

All the calculations in this risk assessment involve multiplication. Note that the product of two TFNs is also a fuzzy number, which itself is not necessarily a triangle. To simplify the multiplication calculations, a standard approximation is used. The standard approximation has been defined by authors such as Chen and Hwang (1993) and Giachetti and Young (1997) in the forms described in Eq. 6.13.

$$\begin{aligned} &A \rightarrow \langle a_1, a_2, a_3 \rangle \\ &B \rightarrow \langle b_1, b_2, b_3 \rangle \\ &C = A \otimes B \\ &C \rightarrow \langle a_1 b_1, a_2 b_2, a_3 b_3 \rangle \end{aligned} \tag{6.13}$$

Generally, the product calculated by standard approximation is a conservative estimate, as the error introduced by the standard approximation is the difference between the membership function of the actual product and the membership

Table 6.2 Linguistic classification of grades of hazard factors and their corresponding TFNs

Ranking level	A qualitative explanation for grade of hazard severity (*s*)	A qualitative explanation for grade of likelihood of the hazard (*l*)	A qualitative explanation for grade of number of product exposed (*e*)	Triangular fuzzy numbers (TFNs)
1	Definitely mild	Definitely low	Minimal	(0.0, 0.0, 0.1)
2	Extremely mild	Extremely low	Extremely few	(0.0, 0.1, 0.2)
3	Quite mild	Quite low	Quite few	(0.1, 0.2, 0.3)
4	Mild	Low	Few	(0.2, 0.3, 0.4)
5	Slightly mild	Slightly low	Slightly few	(0.3, 0.4, 0.5)
6	Moderate	Moderate	Some	(0.4, 0.5, 0.6)
7	Slightly severe	Slightly high	Slightly many	(0.5, 0.6, 0.7)
8	Severe	High	Many	(0.6, 0.7, 0.8)
9	Quite severe	Quite high	Quite many	(0.7, 0.8, 0.9)
10	Extremely severe	Extremely high	Extremely many	(0.8, 0.9, 1.0)
11	Definitely severe	Definitely high	All	(0.9, 1.0, 1.0)

function of the standard approximation. However, it had been argued that the approximation is only appropriate for early-stage risk assessment (Davidson et al. 2006). In this chapter, the product of three TFNs is calculated by this standard approximation as shown in Eq. 6.14.

$$\begin{aligned} N_s &\to \langle a_s, m_s, b_s \rangle, a_s < m_s < b_s \\ N_l &\to \langle a_l, m_l, b_l \rangle, a_l < m_l < b_l \\ N_e &\to \langle a_e, m_e, b_e \rangle, a_e < m_e < b_e \\ N_g &= N_s \times N_l \times N_e \to \langle a_s\, a_l\, a_e,\ m_s\, m_l\, m_e,\ b_s\, b_l\, b_e \rangle \end{aligned} \tag{6.14}$$

Fuzzy mathematics is then used to determine the risk of a given magnitude and intensity. The COA method is exploited to transform the TFNs into a numerical value for the computation. We define these as follows:

$$P(N_g) = \left[(b_g - a_g) + (m_g - a_g) \right] / 3 + a_g \tag{6.15}$$

where a and b are the lower and upper limits of the integral, respectively. $\mu_{\mathrm{Ng}}(x)$ is the new membership function of multiplication result as:

$$\mu_{N_g}(x) = \begin{cases} 0, & x \le a_g \\ \frac{x - a_g}{m_g - a_g}, & a_g \le x \le m_g \\ \frac{b_g - x}{b_g - m_g}, & m_g \le x \le b_g \\ 0, & x \ge b_g. \end{cases} \tag{6.16}$$

For $a_g = a_s\, a_l\, a_e,\ m_g = m_s\, m_l\, m_e,\ b_g = b_s\, b_l\, b_e$

The grades of the three main risk factors for each hazard can be determined by a risk manager or a risk assessor in this manner, according to their analysis of the hazard. A set of integers between 1 and 11 are assigned to the individual hazard.

With the transformation of these descriptive scales into TFN values, the risk of identified hazards can be calculated.

6.4.3 Analysis of Aggregative Food Safety Risk Indicator with Fuzzy Analytical Hierarchy Process

To incorporate all of the identified hazards into an aggregated risk indicator, it is essential to know how important one hazard is over another for any given product in a particular process environment. In other words, risk assessors have to determine the respective variance in weighting between individual hazards. AHP has been widely used to address such multi-criteria decision-making (MCDM) problems. However, it has been generally criticised in the literature because of the use of a scale with discrete steps in value of 1 to 9, which in turn cannot handle the uncertainty and vagueness present in representing the relative importance of different decision criteria. Here, fuzzy AHP, which is an important extension of the typical AHP method, is used to rank how important one hazard is over another for a product in a particular process environment. The approach adopts the fuzzy synthetic extent analysis method (Chang 1996) and uses the triangular fuzzy numbers (TFNs) as a pairwise comparison scale for deriving the weights of identified hazards.

As discussed in Sect. 6.4.1, a two-stage hazard classification structure has been developed (see Fig. 6.3). At the first stage, there are three main hazard categories: biological, chemical and physical hazards. At the second stage, all the known and/or potential hazards within these three categories should be identified and listed. For each identified hazard, there are three risk factors: hazard severity, hazard likelihood and hazard effect. In converting these considerations to an equation, let N be the total number of identified hazards in the hierarchy model. For each identified hazard, we denote $w(X_i)$ as the comparative weight of hazard X_i. (where $0 \leq w(X_i) \leq 1$ and $\sum_{i=1}^{N} w(X_i) = 1$ for $i = 1, 2, \ldots N$). The hierarchical structure for above statements is given in Table 6.3.

Members of the company's risk assessment team are required to provide their value judgements on the basis of their knowledge and experience for each identified hazard. Assessors can either provide a precise numerical value or a linguistic term or a fuzzy number. They are encouraged to give fuzzy scales where they are not sure about the exact numerical values. The membership functions of the TFNs are shown in Fig. 6.1, $M_i = (m_{i1}, m_{i2}, m_{i3})$, where $i = 1, 2, \ldots, 9$. Here, m_{i1}, m_{i2}, m_{i3} are the lower, middle and upper values of the fuzzy number m_i, respectively, where m_1, and m_{i3} represent a fuzzy degree of judgement. The greater m_{i3}–m_{i1} is, the greater the fuzziness of the judgement. When $m_{i1} = m_{i2} = m_{i3}$, the judgment is a non-fuzzy number.

Table 6.3 The structure model of aggregative food safety risk

Individual hazard	Weight of hazards	Hazard severity (s)	Likelihood of hazard (l)	Effect of hazard (e)	Rate of risk $g(s, l, e)$
X_1	$w(X_1)$	s_1	l_1	e_1	$g(s_1, l_1, e_1)$
X_2	$w(X_2)$	s_2	l_2	e_2	$g(s_2, l_2, e_2)$
…	…	…	…	…	…
X_n	$w(X_n)$	s_n	l_n	e_n	$g(s_n, l_n, e_n)$

Through this fuzzy extent analysis, the relative importance and weight of identified hazards can be obtained. The final value of aggregative risk is then calculated by the weighted average method as:

$$\mathrm{AFSRI} = [w(X_1), w(X_2), \ldots, w(X_n)]_{1\times n} \times g_n(s.l, e) \tag{6.17}$$

This index is useful in evaluating the aggregative risk of different production processes, and the identification of the highest AFSRI value implies that the associated process has the highest risk level.

6.5 Case Study

In this section, an application of the proposed model is presented based on a case study of a medium-sized food manufacturer in the UK. Numerical examples are provided to show how the model was applied and tested.

6.5.1 *The Existing Risk Assessment Methodology in the Case Study Company*

The case study is based on a supplier of ready-to-eat cooked meats (beef, pork, lamb, chicken and turkey) to major UK supermarkets. Due to the nature of cooked meat products, a strict QA scheme is currently deployed to ensure compliance with relevant legislation and industrial hygiene codes. Raw materials are purchased in chilled or frozen condition and stored appropriately within the factory. All production and associated chilled and frozen work-in-progress storage areas are temperature controlled throughout manufacturing. All finished cooked products are stored at chilled temperatures in designated facilities where a high-risk control environment can be maintained through measures such as air conditioning, separate drain systems and strict control of work wear.

The current risk assessment process in the company is integrated with the HACCP scheme. Table 6.4 shows an example of the risk assessment of the injection process currently conducted in the case company. For each process,

Table 6.4 Current risk assessment practice for injection process

Hazard		Severity	Likelihood	Effect
Biological hazards	Growth of pathogenic and spoilage bacteria caused by inadequate temperature control of brine solution	Moderate	Rare	Some
	Growth of pathogenic and spoilage bacteria caused by inadequate nitrite addition for cured meat products	Moderate	Rare	Some
Chemical hazards	Chemical contamination of brine solution or ingredients caused by insufficient control of hygiene chemicals	*Severe*	Rare	*All*
	Excessive quantity of nitrite added	Moderate	Rare	Some
Physical hazards	Metal contamination from needles/knives	Moderate	Occasional	Some

all known or potential hazards are identified and their causes are listed. The identified hazards are put into three categories: biological, chemical and physical hazards. Each hazard is measured by factors: **severity** (mild, moderate and severe), **likelihood** (rare, occasional and frequent) and **effect** (minimal, some and all). Each factor is ranked by the HACCP team. Control measures are then decided.

6.5.2 An Application of the Proposed Approach

Here, the aggregative risk assessment model is applied to perform a structured analysis of safety risk for specific products along their production process path. Firstly, the process flow in the manufacturing plant for a specific product is constructed including the stages of intake, storage, defrosting, meat preparation, brine make-up, injection, tumbling, filling and netting, cooking, cooling, roasting, slicing, and packing, etc. Data from each process stage are input into the analysis. In each process stage, all known or potential hazards are identified and the main potential sources inducing these hazards are listed and placed into the three categories: biological, chemical and physical. A hierarchical structure is then developed for these hazards, with the grades of severity (s), likelihood (l) and effect (e) of the hazard decided. After the s, l and e values for each hazard are estimated, risk grading $g(s, l, e)$ is evaluated through the fuzzy method discussed earlier to give a value for each hazard. As an example, the assessment results for the injection process of a selected product are presented in Table 6.5. Here, the scales of s, l and e values are estimates taken from the existing qualitative risk assessment gradings in the HACCP record (see Table 6.4). Compared with the current practice shown in Table 6.4, more options are provided with which to rank a particular risk factor, which allows users to better estimate the uncertainty inherent in input values. Furthermore, this provides a numerical value more accurately differentiating the risk level of individual hazards.

Table 6.5 Fuzzy-based risk assessment for injection process

Processes	Hazards category	Individual hazard		s	l	e	$g(s, l, e)$
Injection	Biological	Growth of pathogenic and spoilage bacteria caused by inadequate temperature control of the brine solution	X_1	6	3	6	0.127
		Growth of pathogenic and spoilage bacteria caused by inadequate nitrite addition for cured meat products	X_2	5	2	5	0.049
	Chemical	Chemical contamination of the brine solution or ingredients caused by insufficient control of hygiene chemicals	X_3	9	2	10	0.192
		Excessive quantity of nitrite added	X_4	5	2	4	0.039
	Physical	Metal contamination from needles/knives	X_5	8	4	4	0.156

Note The assessment is based on the information in Table 6.4 combined with the advice from the QA team in the case company

Then, the fuzzy AHP method is used to assign comparative weights to identified hazards for a particular process of the product under assessment. The different values of fuzzy synthetic extent with respect to the five different hazards are denoted by S_1, S_2, S_3, S_4 and S_5, respectively. By applying Eq. 6.1, we have

$$\begin{aligned}
S_1 &= (4.7, 5.8, 7.1) \otimes (1/43.4, 1/36.6, 1/30.4) \\
&= (0.11, 0.16, 0.23) \\
S_2 &= (2.9, 3.6, 4.4) \otimes (1/43.4, 1/36.6, 1/30.4) \\
&= (0.07, 0.10, 0.14) \\
S_3 &= (12.5, 15, 17.5) \otimes (1/43.4, 1/36.6, 1/30.4) \\
&= (0.29, 0.41, 0.58) \\
S_4 &= (2.4, 2.7, 3.3) \otimes (1/43.4, 1/36.6, 1/30.4) \\
&= (0.05, 0.07, 0.11) \\
S_5 &= (7.9, 9.5, 11.2) \otimes (1/43.4, 1/36.6, 1/30.4) \\
&= (0.18, 0.26, 0.37)
\end{aligned}$$

The degree of possibility of S_i over S_j $(i \neq j)$ can be determined by Eqs. 6.3–6.5.

$$\begin{aligned}
&V(S_1 \geq S_2) = 1, \\
&V(S_1 \geq S_3) = \frac{0.29 - 0.23}{(0.16 - 0.23) - (0.41 - 0.29)} = 0.28, \\
&V(S_1 \geq S_4) = 1, \\
&V(S_1 \geq S_5) = 0.34.
\end{aligned}$$

Similarly,

$$V(S_2 \geq S_1) = 0.37, V(S_2 \geq S_3) = 0.87, V(S_2 \geq S_4) = 0.37, V(S_2 \geq S_5) = 0.31;$$
$$V(S_3 \geq S_1) = 1, V(S_3 \geq S_2) = 1, V(S_3 \geq S_4) = 1, V(S_3 \geq S_5) = 1;$$
$$V(S_4 \geq S_1) = 0.02, V(S_4 \geq S_2) = 0.63, V(S_4 \geq S_3) = 1.13, V(S_4 \geq S_5) = 0.64;$$
$$V(S_5 \geq S_1) = 1, V(S_5 \geq S_2) = 1, V(S_5 \geq S_3) = 0.35, V(S_5 \geq S_4) = 1;$$

Based on Eq. 6.7, we obtain

$$\begin{aligned} d(X_1) &= \min V(S_1 \geq S_2, S_3, S_4, S_5) \\ &= \min(1,\ 0.28, 1,\ 0.34) \\ &= 0.28 \end{aligned}$$

Similarly, $d(X_2) = 0.31, d(X_3) = 1, d(X_4) = 0.02, d(X_5) = 0.35$

Therefore, $W' = (0.28, 0.31, 1, 0.02, 0.35)$ after the normalisation process, so the weight vector with respect to identified hazards, X_1, X_2, X_3, X_4, and X_5, can be expressed as:

$$W = (0.144, 0.160, 0.510, 0.008, 0.177)$$

The complete result is shown in Table 6.6. Now, the risk values of individual hazards, $g_n(s,l,e)$, are multiplied by W to determine the aggregative risk as follows

$$\begin{aligned} \text{AFSRI} = &(0.127 \times 0.144 + 0.049 \times 0.160 + 0.192 \times 0.510 + 0.039 \\ &\times 0.008 + 0.156 \times 0.177) \\ = &0.152 \end{aligned}$$

Therefore, in this example, 0.152 is the rate of aggregative safety risk for the injection process. The same procedure is repeated for the “raw material intake”, “brine make-up” and “tumbling processes” to further demonstrate the proposed approach. The calculation results for these processes are shown in Table 6.7. The main difference between the proposed aggregative risk assessment model and the company’s current practice is that the aggregative model does not only provide an assessment of individual hazards, but also gives an index of the overall food safety risk level for a particular process or product batch. More scoring options are also provided to rank a particular risk factor, which allow users to better estimate the uncertainty inherent in input values. In addition, this approach also provides an overview of the risk level for a particular process or product batch. Although the integrated risk index for a production or supply process does not scientifically measure a specific hazard, and though indices for different processes might only be slightly different, such a quantified AFSRI will be of significantly greater effectiveness in comparing the risk levels between different processes and product batches. Equally importantly, the aggregative risk assessment approach provides an opportunity for innovation in operations planning through incorporating safety factors associated with operational process change decisions in a quantitative manner. This is critical in properly taking

Table 6.6 Weights estimated through the fuzzy AHP

	X_1	X_2	X_3	X_4	X_5	W
X_1	(1, 1, 1)	(3/2, 2, 5/2)	(2/7, 1/3, 2/5)	(3/2, 2, 5/2)	(2/5, 1/2, 2/3)	0.144
X_2	(2/5, 1/2, 2/3)	(1, 1, 1)	(2/9, 1/4, 2/7)	(1, 3/2, 2)	(2/7, 1/3, 2/5)	0.160
X_3	(5/2, 3, 7/2)	(7/2, 4, 9/2)	(1, 1, 1)	(4, 5, 6)	(3/2, 2, 5/2)	0.510
X_4	(2/5, 1/2, 2/3)	(1/2, 2/3, 1)	(1/6, 1/5, 1/4)	(1, 1, 1)	(2/7, 1/3, 2/5)	0.008
X_5	(3/2, 2, 5/2)	(5/2, 3, 7/2)	(2/5, 1/2, 2/3)	(5/2, 3, 7/2)	(1, 1, 1)	0.177

Note

(1) The consistency index $CI = 0.0088$, the random consistency index $RI = 1.12$ and the consistency ratio $CR = CI/RI = 0.0079$

(2) Since CR is 0.0079 that is less than 10 %, the consistency test is satisfied (Saaty and Vargas 2001)

Table 6.7 Estimation of the aggregative food safety risk for various processes

Processes	Raw material intake			Brine make-up			Tumbling		
		$g(s, l, e)$	W_i		$g(s, l, e)$	W_i		$g(s, l, e)$	W_i
	X_{11}	0.412	0.226	X_{21}	0.127	0.125	X_{31}	0.127	0.142
	X_{12}	0.316	0.138	X_{22}	0.049	0.125	X_{32}	0.17	0.142
	X_{13}	0.221	0.292	X_{23}	0.053	0.167	X_{33}	0.039	0.119
	X_{14}	0.049	0.129	X_{24}	0.017	0.083	X_{34}	0.125	0.358
	X_{15}	0.148	0.214	X_{25}	0.085	0.071	X_{35}	0.032	0.239
				X_{26}	0.257	0.265			
				X_{27}	0.032	0.165			
AFSRI	0.239			0.112			0.099		

account of potential safety-related costs (e.g. recall cost) into operational decisions, but has been notably absent in present supply chain management practice (Wang et al. 2009).

Managing risk plays a vital role in food supply chain management. Most food production processes contain a certain degree of risk. The magnitude of risk directly affects the safety of food in terms of public health and aims to identify the possibility of a resulting food crisis that may require a product recall. However, few researches simultaneously consider operational objective and risk in the production planning process. The aggregative risk assessment approach provides an overview of the risk level for a particular process or product batch. It is able to integrate with the estimation of other operational factors and be used to obtain an optimal production plan, so as to improve the overall manufacturing performance, for example, by avoiding the uneconomic mixing of high- and low-quality raw materials and thus reducing the risk of cross-contamination.

In operations research, a major interest in both theory and practice is to determine economic production batch size, meaning that various cost factors need to be incorporated in production planning models. In addition to the traditional cost factors such as set-up cost, inventory holding cost and product deteriorating cost, from within a risk management perspective, product recall cost emerges as another important cost factor. Some product recalls are so potentially costly they could even put food companies out of business. The batch size plays an important role in the potential recall cost. For example, a large production batch may require separate raw material batches from different suppliers to be mixed together in order to fulfil a batch production operation. In the event of a food safety incident resulting from a problem with one the raw material sources used in the production, all the products containing this contaminated raw material from the batch must be recalled. A large batch size will have much greater economic consequences in such an event. Another important element that affects the probability of such an event is the safety risk level of the raw materials used in the production. A high-risk level for raw materials used, and the mixing of these raw materials required in the production operation, will increase the probability of product recall. One origin of the food safety risk level is associated with the potential development of different kind of bacteria such as botulism, listeriosis and salmonella, meaning product quality could be compromised due to inappropriate production or storage conditions. As more investment is required to ensure that good quality production and storage conditions are maintained throughout the different supply chain processes, suppliers may, in turn, charge a premium price for good quality raw materials which contain a relatively lower food safety risk.

An aggregative and tangible risk assessment for the food supply chain processes would assist a manufacturer to minimise its overall operational costs while maintaining food safety standards, leading to reduced risk of product recall and incurring recall-related costs. The quantified AFSRI values for material batches can play an important role in the decision-making process of determining the best ways to constitute raw material batches (Wang et al. 2010). This is especially applicable to products with high vulnerability in quality and safety terms, where it could help manufacturers to choose the optimal raw material supplies, with the backup of an integrated view on economic and safety factors, and so reduce the cross-contamination risk by minimising unnecessary raw material mixing.

6.6 Discussion

The AFSRI aggregative food risk assessment model considers all hazard agents in an integrated way for the comprehensive assessment of food safety risks. It provides a practical solution by which enterprises can systematically assess the risk of supply chain processes. A step-by-step approach for conducting an aggregative food safety risk assessment is shown in the flow chart in Fig. 6.4.

Compared with the risk assessment approach presently used in the case study company, the proposed model provides more options with which to grade the hazard factors. The quantified risk for individual hazards through the fuzzy approach sets the relative significance level for identified hazards, and the AFSRI then builds on these to give an indication of overall risk level for different production processes. The results could be used to support the decision-making

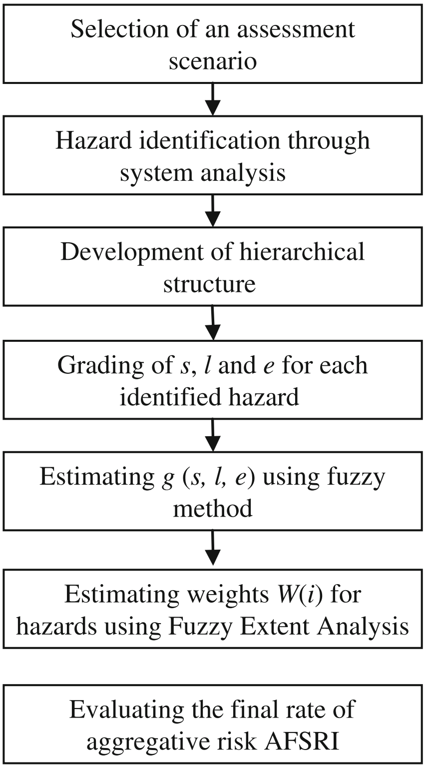


Fig. 6.4 Procedures for aggregative food safety risk assessment

process for the QA team, enabling them to focus on the most important hazards or processes, and take appropriate actions. The processes with higher AFSRI values highlight those containing higher-risk levels and indicate those areas where further in-depth risk assessment might be essential. Referring to the analysis in the case study application, the results derived through the aggregative risk assessment justify the perception of food safety risk from its raw materials as a critical control point for the case company. By comparison with other methods (Ross and Sumner 2002; Tuominen et al. 2003; Davidson et al. 2006) used for early-stage food risk assessment, the accuracy of the results in our model is considered sufficient to promote it as a more clearly focussed comparison of different products and processes. The AFSRI model could play a key complementary role in HACCP planning. All significant hazards identified in a process by this model can be further evaluated using more product-specific production analysis approaches. This helps food companies to focus on the factors that most affect food safety risk and to identify risks requiring more rigorous assessment. This will facilitate their quality control and provide the conditions likely to lead to a consistent supply of safe food products.

At present, the manual documentation process used in following the HACCP framework cannot be used to assess the overall risk level for a supply source, production process or a product batch. The proposed aggregative risk assessment method fills this gap by incorporating relevant multiple hazards and their associated risk factors into a quantified AFSRI value. It can be used as a safety indicator to measure the varying level of risk attached to raw materials from different suppliers and production batches from different processes. With this safety indicator, an optimal production plan becomes possible, both avoiding the uneconomic mixing of raw materials and reducing the risk of cross-contamination at the same time. Apart from its importance in the QA process for food production, the proposed method can also be used as a new decision-making tool for recipe testing of new products or for supporting the supplier selection process in order to improve product quality and safety management while maintaining operational efficiency.

In situations where knowledge about origins of risk generation is limited, point estimate approaches (Huss et al. 2000; Tuominen et al. 2003) have often been employed to evaluate the risk simply due to their simplicity of application. Although there is a reasonable justification for their use in the early stages of risk assessment, such approaches convey a false sense of certainty when risk is estimated as a numerical value. The fuzzy enabled risk assessment method proposed in this chapter estimates the uncertainty inherent in input values and allows users to conveniently describe uncertainty. Furthermore, this fuzzy method can be easily transformed into traditional probabilistic methods when sufficient information and knowledge about the food production system are available. In addition, the proposed methodology offers a new way of assessing, tracking and tracing risks at a supply chain level and so provides quantitative evaluation for all production stages. It also provides insight into potential risk mitigation options and identifies the weak links in food supply chain activities.

Despite these tangible benefits, there are some limitations and weaknesses in the model. Some are general problems associated with all forms of risk assessment modelling, while others are specific to the model. The main challenge of this research is to demonstrate a model which can provide a single value risk indicator (AFSRI) to represent the overall risk rating of the production process/batch. All hazards need to be identified, risk attributes have to be accounted for and both of these aggregated in the assessment. The complexity of the model lies in establishing the degrees of risk [$g(s, l, e)$] of all identified hazards, which itself requires complex fuzzy calculations. In addition, using fuzzy AHP and synthetic extent analysis to obtain comparative hazard weightings requires a certain amount of computational effort. Referring to Chang (1996), for an $n \times n$ fuzzy pairwise comparison, the time complexity value under synthetic extent analysis is $n(n + 6)$. The complexity of calculations often inhibits organisations from implementing those sophisticated methods in their daily operations. In order to make the proposed methodology more practical and easy-to-use, the fuzzy method is only introduced when there is a difficulty in accurately representing uncertainty or a lack of knowledge about associated values, so as to reduce the additional complexity brought in by fuzzy operations. In addition, while the model is developed as a potential early-stage approach to risk assessment, sufficient information is still required to adequately characterise the food production system and a long list of values (grades of risk factors for all identified hazards) must be provided, before the risk quantification is possible.

6.7 Conclusion

This chapter proposes a new risk assessment methodology that enables manufacturers to perform a structured analysis of aggregative food safety risk for all processes throughout the different stages of the food supply chain. The qualitative scales were converted into values by using TFNs to capture the vagueness in the linguistic subjectivity of food risk definitions. A hierarchical structure model was developed for various categories of hazards identified, in order to determine the AFSRI for a given process or product. An example of its application was presented via a case study, wherein the method's approach was illustrated with a medium-sized cooked meat producer. Numerical examples of the aggregative risk assessment were presented together with the application of AFSRI in the production planning process.

One key purpose of this study is to develop a methodology for determining a quantified food safety risk indicator to support operational decisions. The aggregative risk assessment approach provides an opportunity for innovation in operations planning through incorporating safety factors within operational decisions in a quantitative form. However, the model presented here may also function as a more limited but supportive part of practical food safety management tools in the food sector. It gives insight into potential risk mitigation between supply chain processes, which can help managers to understand how risks change and transfer across the supply chain. The approach has the ability to capture the vagueness of human judgment and effectively solve multi-attribute decision problems. This consequently provides support when making decisions on which interventions and actions might be applied to enhance food safety. With these advantages, and the fact that AFSRI focuses on products and their production processes, it can be a valuable component of a HACCP system. In this role, it can be used proactively to support decisions on the optimisation of production processes according to the aggregated risk level.

Additional to the various advantages of the proposed approach for food risk management, this research work can be extended further by modelling the process effects (such as growth, inactivation, removal, partitioning and cross-contamination) on risk transmission along the food supply chain. This will provide a more systemic view of how risks are developed and migrated along the food chain and thereby support risk management decisions. This can further increase the computational complexities involved, but constitutes a further piece of research work we would like to carry out in the future.

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