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Application of Intuitionistic Fuzzy Entropy to Disruption Risk Management in Aerospace Supply Chain

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Abstract: This study proposes a multiple-criteria decision-making (MCDM) model as a hierarchical framework for strategic planning of disruption risk and selection of contiguous solutions. This model is applied to the aerospace industry, which is characterized by low-probability, high-consequence (LP-HC) disruption risk involving flight safety issues, and seeks to provide supply-chain owners a decision framework for minimizing disruption risk in the aerospace supply chain. The study's findings indicate that application of the intuitionistic fuzzy entropy weight (IFEW) method to aerospace supply chain disruption risk management yields excellent results, and can provide enterprises wishing to establish resilient supply chains important guidelines in the selection of an optimal decision-making portfolio (ODMP).

Keywords: Aerospace supply chain, disruption risk, intuitionistic fuzzy entropy weight

1 Introduction

The expansion of spread of global and regional economic integration has been accompanied by the spread of supply chains across geographical boundaries. However, multiple types of catastrophic events [1,2], including natural disasters, man-made destruction, infectious disease outbreaks, economic turmoil, and geopolitical instability, etc., occur frequently around the world, and these events often have direct or indirect impacts on supply chains, with varying degrees of severity. Nevertheless, most enterprises often find it difficult to predict or prevent these incidents, which in severe cases may force enterprises to stop production, close plants, or terminate business. Because of this, how enterprises can adopt active and effective response strategies to minimize losses due to broken supply chains, and how they can effectively maintain supply chain resilience, has become an important topic for both industry and the academic researchers.

A review of the supply chain disruption risk research literature from the past decade or more reveals that the major impacts of unforeseen supply chain disruptions on enterprises are typically classified as the three aspects of supply disruption [3,4,5], operational disruptions [6], and demand disruption [14,7]. However, based on the review of vulnerable links in supply chain processes, by our study, the impacts of catastrophic disruptions on aerospace industry supply chains should be classified as five types of risk include supply disruption, production disruption [7], transportation disruption [8], demand disruption, and logistics support disruption.

In fact, these catastrophic events in supply chains have two main characteristic dimensions, which are the probability and the consequences risk of those events. Different from general operational risks, the risk of unforeseen disruption events is characterized by low probability and high consequence (LP-HC) risk [1,3,9]. Since probability of these events are low and difficult to predict, research on strategies for managing this type of risk has largely been neglected in the past. In light of these circumstances, this paper chooses the LP-HC supply chain disruption risks involving flight safety issues faced by an aerospace industry in Asia as the subject of the study of the management on supply chain disruption risk.

This paper is organized as follows. Section 2 contains a review of previous research on global supply chain and in-depth analysis of best practices in crisis management. Section 3 introduces the empirical research framework and research methodology. In Section 4, an empirical study using the intuitionistic fuzzy entropy weight

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method is conducted. Finally Section 5 presents conclusions and suggestions for future research directions (referred to Bianca and Ferrara [10]).

2 Literature Review

This paper investigates supply chain disruption risk literature, also performs in-depth analysis of best practices in crisis management in industry during the past decade or more, including a review of vulnerable links in aerospace supply chain processes. This study classifies supply chain disruption risk management strategies as the six categories of disruption of supply, disruption of production, disruption of transportation, disruption of demand, disruption of logistics support, and project management.

2.1 Supply disruption strategies (C1)

Catastrophic supply disruptions will directly influence enterprises' level of supply, and may directly impact suppliers by causing suppliers to be unable to make on-time and on-quality deliveries. The severe consequences of this type of incident will inevitably cause the disruption of sources of supply. The chief strategies used to effectively reduce the impact and losses of supply disruption incidents include establishing *sourcing policies* [11], implementation of *performance measurement* [12], and creation of a *substitute parts database*.

Sourcing policies (C11)

The chief purpose of establishing sourcing policies is to disperse supply risk and maintain low inventory levels. Relevant strategies include: purchasing from *multiple suppliers* [1,3,4,13,14] in order to reduce the level of dependence on any one supplier. For instance, as a rule, Walmart employs no more than one-third of the capacity of any one supplier. Employing a *make-and-buy* [15,16] strategy, which allows companies to quickly switch between production sites when necessary, and increases supply flexibility. *Contingent sourcing* [5], such as by purchasing from the aftermarket. Use of a *resilient supply portfolio* [9]; for instance, Li and Fung completely deconstruct supply chain process links in order to facilitate supply from factories in different countries or areas, where the enterprise itself plays the role of an integrator.

Performance measures (C12)

For instance, aerospace manufacturers may grade their suppliers using an ABC system [17]. If supplier resilience is included in evaluation mechanisms, apart from promoting a healthy cooperative/ competitive relationship between suppliers and outsourcers, this can also increase the enterprise's ability to switch between suppliers. For example, because DuPont has consistently striven to make safety a habit, it only cooperates with suppliers that comply with safety and regulatory requirements.

Substitute parts database (C13)

For example, aerospace manufacturers usually establish substitute source databases for parts and components, including alternative suppliers, interchangeable substitute parts, and aftermarket sources, etc. As soon as delivery delays, a production stoppage by the original supplier, or other supply disruption occurs, the firm can promptly respond by using this database to find feasible substitute parts, which will mitigate the impact of sudden shortages and enhance the effect of rapid logistics services.

2.2 Production disruption strategies (C2)

When a disruption in the supply of materials may cause the disruption of subsequent production processes, or a catastrophic production-side incident occurs, either event may directly or indirectly impact the enterprise itself. The severe consequences of this type of disruption will typically cause enterprises major economic losses, and may cause delays or interruptions in an enterprise's production or services. The main strategies used to effectively reduce the impact of production disruptions and the ensuing losses include establishing *inventory policies* [3,17], implementing *demand-pull production*, and use of a *decentralized production base*.

Inventory policy (C21)

The purpose of inventory policies is not to set aside even more seldom-used safe inventory, but rather to maintain a *strategic inventory* [3,15,16] of important goods and materials. For instance, a service provider can replenish items in accordance with the original supplier's list of lifecycle spare parts, or use a *sell-one-store-one* inventory policy [3] for each key part or component. Other strategies include selection of *strategic location* [16] stock and vendor-managed inventory (VMI) [13,18,19].

Demand-pull production (C22)

The purpose of demand-pull production is to quickly respond to customer demand and enhance logistics service levels, which requires the establishment of order fulfillment processes (OFP) with a high degree of flexibility and responsiveness. When a customer requires production, the manufacturer can initiate *make-to-order*

[13,20] or *assemble-to-order* [21,22]. For instance, after a major earthquake affected Taiwan in 1999, Dell faced possible component shortages as a result of supply disruptions. Because Dell employed an *assemble-to-order* model, it was able to make flexible daily adjustments in response.

Decentralized production base (C23)

Companies can opt to disperse their production facilities in locations with favorable investment conditions. Apart from gaining inexpensive resources, reduced costs, suppliers' technological capabilities, customers in new markets, and improved competitiveness, this approach can also provide supplementary production bases. For instance, based on its Copy Exactly model, Intel has established multiple wafer manufacturing facilities with mutually-interchangeable processes at various locations worldwide. When the SARS outbreak occurred in Asia during 2003, Intel was able to transfer production to different facilities without affecting yield. Furthermore, when a territorial dispute over the Diaoyutai Islands broke out between China and Japan in 2012, rioting in China damaged Japanese-affiliated plants and offices, many Japanese companies adopted a China plus one strategy to decentralize their production base and hedge against their China risk.

2.3 Transportation disruption strategies (C3)

When sudden transportation disruptions occur, such as the interruption or destruction of supply channels causing inability to ship parts or raw materials, this will indirectly cause the interruption or delay of manufacturing. This may also lead to the interruption or destruction of sales channels by making it impossible to ship products to customers, which may indirectly lead to disruption of demand and sales losses. The chief strategies employed in order to effectively reduce the impact of disruption of transportation and the ensuing losses include *flexible transportation* and *economic transportation*.

Flexible transportation (C31)

These strategies include *multi-modal transportation*, *multiple-carrier transportation*, and *multiple routes* [16]. In transportation decision-making, enterprises should entrust their transportation needs to qualified, well-established forwarders, which will ensure that forwarders can quickly and flexibly switch between different transport modes, vehicles, and routes in the event of transportation disruptions. For instance, during the US West Coast port lockout in 2002, some forwarders began shipping manufactured products from Asia via the Panama Canal to ensure that the goods would reach the US East Coast.

Economic transportation (C32)

Enterprises can select the most favorable transportation solution in view of the contractual delivery date and transportation cost effectiveness. For instance, during the US West Coast port lockout in 2002, NUMMI shipped a batch of parts from Japan by air freight, with transportation priority determined on the basis of cost effectiveness; as a result, only car parts were shipped by air freight, ensuring on-time delivery, and delays were allowed in truck parts deliveries.

2.4 Demand disruption strategies (C4)

Demand disruption often occurs when sudden events cause major drops in market demand, and can lead to excess production, accumulation of excessively large stocks, and tying-down of capital, resulting in major losses. The chief response strategies include *dynamic planning*, *shifting demand* [4], and *revenue management* [15,16].

Dynamic planning (C41)

When a supply chain faces severe market demand fluctuations, strategies for reducing the bullwhip effect caused by unpredictable environmental factors include *dynamic assortment planning* [16], *dynamic pricing and promotion* [15,16], and *better planning and coordination of supply and demand* [23]. For example, after the 911 terrorist attacks occurred in the US in 2001, Continental Teves relied on the customer sales records and consumption level information that it had routinely gathered to quickly prioritize filling urgent customer parts shortages.

Shifting demand (C42)

This strategy includes such measures as: *shifting demand across time*, such as when a manufacturer implements a service life extension program (SLEP) for a customer's old aircraft in order to prolong its *service life*; *shifting demand across markets*, such as when a manufacturer converts passenger aircraft to cargo aircraft on behalf of a customer, and thereby increasing demand for cargo transport usage; and *shifting demand across products* [13], such as when a manufacturer upgrades equipment on a customer's an aircraft to new products.

Revenue management (C43)

Enterprises can use the methods of *dynamic forecasting*, *dynamic pricing*, or *discount allocation* methods to ensure that goods in inventory are effectively allocated to sales markets, and thereby achieve the objective of maximizing revenue. For instance, Caleb Technologies helped Continental Airlines to develop the CrewSolver decision-making support system, which generates globally optimal recovery solutions. As a consequence, during the initial period of disruption following the 911 terrorist attacks, the system enabled Continental Airlines to quickly reassign aircraft crew to new flight schedules while complying with government regulations, contractual requirements, and customers' expectations. This system ultimately helped Continental Airlines to save approximately US$40 million in costs [16].

2.5 Logistics support disruption strategies (C5)

The chief strategies enabling manufacturers and logistics service providers (LSPs) to provide customers localized and all-round logistics support services, and effectively reduce the risk of disruption of logistics support involving durable goods (such as aircraft, defense weaponry, rail transport vehicles, important facilities, and other equipment assets), and enhance the availability of durable goods, include *information sharing* [13,24,25], adoption of *logistics support systems*, and implementation of *remote mutual redundancy*.

Information sharing (C51)

To ensure that supply chain participants can correctly and effectively share information in real-time, so that upstream and downstream partners can obtain important information concerning the supply and demand situation, bottlenecks, and vulnerabilities, which will facilitate more accurate forecasting and better coordination and planning, relevant strategies include *increasing visibility* [13,22], increase *warning capabilities* [26], and *promoting open communication*.

Logistics support systems (C52)

For instance, aircraft maintenance providers can establish logistics information management systems (LIMS) providing links to the information of important supply chain partners and customers, and facilitating the execution of logistics acquisition processes (such as technical data, spare parts, equipment, tools and consumables) in line with the six major principles of purchasing: right time, right quality, right quantity, right price and right place, which will provide customers with a logistics service mechanism [27] enabling accurate information, proactive monitoring, and real-time early warning. This will avoid or mitigate the impact of logistics support disruptions.

Remote mutual redundancy (C53)

Replacement of the remote backup concept with *remote mutual redundancy* will eliminate the disadvantage of redundant investment in important facilities that are seldom used. Furthermore, the application of this concept to logistics support units decentralized across different sites can facilitate synchronous sharing of tasks, and ensure that remote mutual assistance can be implemented when sudden disruptions occur. For example, when the SARS outbreak continued to spread in March 2003, Taiwan Hewlett-Packard divided its departments into three groups, where each set of groups constituted an integral one-third part of the entire company. When personnel in any one group were suspected of having the symptoms of SARS, the company could thus still maintain at least two-thirds of its operating capabilities.

2.6 Project management strategies (C6)

When enterprises initially purchase durable goods, they often focus on the excellent performance of new equipment types, but neglect the importance of after-sales logistics services. We therefore recommend that logistics services providers handling durable goods perform whole-life-cycle project management, and offer customers even more dependable whole-life-cycle logistics services while maintaining project accountability. The chief relevant strategies include *risk management*, *effective communication*, *integration*, and *collaboration*.

Risk management (C61)

In addition to playing the role of supply-chain integrators, enterprises must also enhance the risk consciousness of all participants if they wish to establish a robust supply chain risk management environment and instill an effective risk management culture. Relevant strategies include *creating vulnerability maps* [3,23], *improving visibility on supply chain vulnerabilities* [6], establishing *risk management procedures*, establishing *risk management knowledge bases*, performing *strategic risk planning* [24], *risk pooling*, and *continuous risk assessment and analysis*.

Effective communication (C62)

During the initial stage of a supply chain disruption, it is recommended that manufacturers and logistics service providers carefully select an external spokesperson to play the role of firefighter. For instance, companies can adopt a strategy of *active and continued communication*, and thereby attempt to secure control over their message, and engage in a *crisis communication* strategy aimed at heading off even worse disaster. Effective communication can ease the market's qualms, create a win-win situation, end lingering negative effects, and minimize the impact of customers' possible cancellation or reduction of orders, reneging on their pledges, or even refusal to do business with the company. For example, when a strong earthquake struck Taiwan in 1999, TSMC established a *24-hours telephone hotline* providing customers *the latest and most accurate information*; this successfully allayed doubts and ensured that the market realized that TSMC was implementing a recovery plan [3].

Integration (C63)

The chief motivations for supply chain integration include simplification of operating procedures, reduction in lifecycle costs, shortening of response time, acquisition of key technologies, and the enhancement of the liquidity of market supply and demand. Relevant strategies include establishment of a *contractual system* able to consolidate the collaborative relationship between partners, such as through the use of *flexible quantity contracts* and *risk sharing contracts* [20,24]; organization of *strategic alliances* making partners members in a tight-knit community and creating long-term strategic benefit. For instance, when a fire occurred at the Aisin Seiki plant of the Japanese firm Kariya in 1997, an emergency response alliance consisting of over 60 companies sprang into action, and provided horizontal support; by filling Toyota's orders for Aisin Seiki's control valves, they minimized losses throughout the entire supply chain.

Collaboration (C64)

The purpose of collaboration is to establish long-term partnerships through coordination and cooperation among supply chain partners and expand the scope of mutual benefit and sharing, in order to enhance supply chain efficiency and resilience. Relevant strategies include the establishment of *collaborative partnerships and relationships*, development of *trust among supply-chain partners* [24], and enhancement of *coordination among supply chain partners*. For example, after a fire occurred at Philips' wafer fabrication facility in Albuquerque, New Mexico in 2000, Nokia actively assisted Philips in restoring production; this not only helped meet Nokia's customers' demands, but also forced rival Ericsson to exit the cell phone market, giving Nokia a dominant position in the market [16]. Other strategies include collaborative planning, forecasting and replenishment (CPFR) [13,23].

The foregoing accounts of supply chain disruption risk management strategies from the literature mostly consist of the description of individual disruption management strategy issues, and the literature contains little research on contiguous solutions. Thus, after reviewing the foregoing literature and best practices in crisis management, this paper attempted establish a hierarchical framework for selection of strategic planning strategies from best practices in crisis management. Referring to the *Comprehensive Emergency Management* [28] published by U.S. Federal Emergency Management Agency in 1979, this paper will divide disaster management into the four solution phases of *Mitigation* (S1), *Readiness* (S2), *Contingency* (S3) and *Recovery* (S4), in order to evaluate the importance of strategic criteria and effects of the combination of solutions in all four phases.

3 Research Framework and Methodology

This study's framework includes 6 primary strategic criteria Cp (C1 - C6), 18 secondary criteria Cpq (C11 - C64), and 4 phase solutions Sr (S1 - S4). Figure 1 consists of a hierarchical framework showing the establishment of strategic criteria and selection of solutions. The following sections explain the research subjects, design of the expert questionnaire, and research methodology.

3.1 Expert in-depth questionnaire

This paper selects a small number of representative aerospace technology companies in the Asia-Pacific region possessing aircraft R&D, manufacturing, assembly, systems integration, testing and validation, logistics support, and flight service capabilities, etc., as the research subjects. The selected companies all have more than 3,000 employees. Most of the respondents at these companies are have actually participated in supply-chain management work, and include managers, operations staff, industry consultants, and relevant industry experts.

With regard to questionnaire design, this paper employed a 9-point assessment scale; in comparison with the most commonly used 5-point scales, the use of a 9-point scale enabled respondents to make more precise distinctions, and facilitated the selection of compromise attributes between two adjacent attributes, which helped the respondents to fully express their expert views.

Table 1 shows the conversion of linguistic variables into intuitionistic fuzzy numbers (IFNs). This paper employed SPSS software to perform reliability analysis, and Cronbach's alpha was employed to assess the reliability of the results of the experts' questionnaires.

3.2 Intuitionistic fuzzy multiple-criteria decision-making (MCDM) analysis

Atanassov [30] proposed the concept of intuitionistic fuzzy sets (IFS) in order to express using conventional fuzzy theory differences in degree of membership

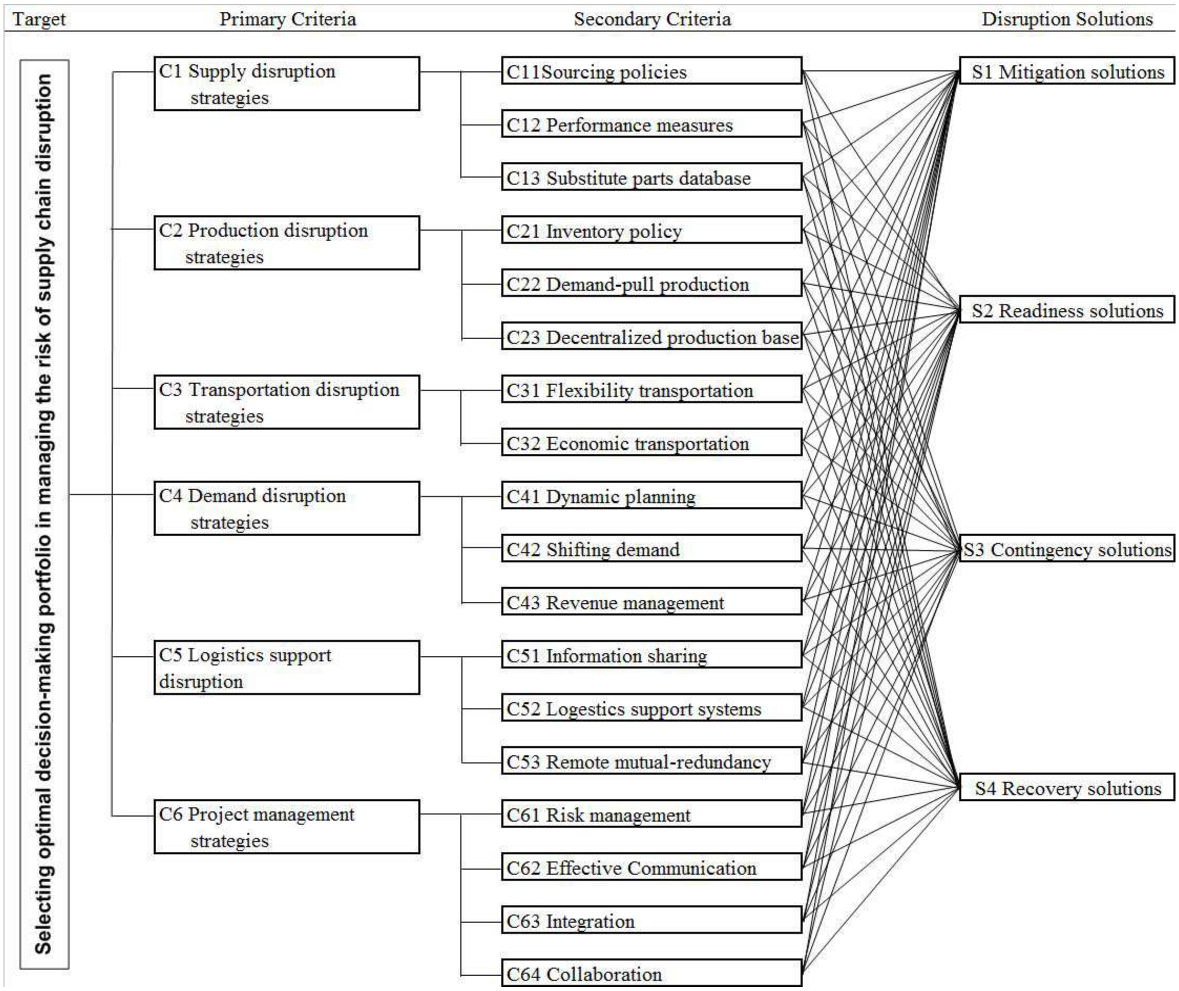

Fig. 1: Selection hierarchical framework of strategic criteria for solutions

Table 1: Conversion between linguistic variables and IFNs

Point scale	Linguistic variables	IFNs(μ, ν, π)
9	Extreme important	(0.95, 0.05, 0.00)
8	Pretty important	(0.85, 0.10, 0.05)
7	Very important	(0.75, 0.15, 0.10)
6	Important	(0.65, 0.25, 0.10)
5	Medium	(0.50, 0.40, 0.10)
4	Unimportant	(0.35, 0.55, 0.10)
3	Very unimportant	(0.25, 0.65, 0.10)
2	Pretty unimportant	(0.15, 0.80, 0.05)
1	Extreme unimportant	(0.05, 0.95, 0.00)

The IFNs is referred to Zhang and Liu [29]

between the fuzzy linguistic concepts of ”approve” and ”disapprove” using numerical values. In this approach, the magnitudes of linguistic variables in the form of ratios are used to express the degree of ”approval”, ”disapproval” and ”neutrality” toward an event. Because this approach can objectively express individuals’ actual thinking, it possesses powerful expressive ability in dealing with uncertain information and is better able to solve multiple attribute decision making (MADM) problems; the IFS method has therefore gradually come into widespread use in recent years. This study consequently uses an intuitionistic fuzzy function to analyze decision-makers’ preferences, and believes that this approach is consistent with a decision-making model in which multiple individuals objectively express approval, disapproval and neutrality.

According to the concepts of Atanassov [30] and Gau and Buehrer [31], an IFS function can be defined as follows:

Definition 3.1. Assuming that $X = \{x_1, x_2, \ldots, x_n\}$ is a fixed and non-empty set, A is termed an IFS in X, which implies that $A = \{\langle x, \mu_A(x), \nu_A(x)\rangle | x \in X\}$ where the number $\mu_A(x) : X \to [0,1], x \in X$ denotes the *degree of* *membership*, $\nu_A(x) : X \to [0,1], x \in X$ denotes *degree of non-membership*, and the condition $0 \le \mu_A(x) + \nu_A(x) \le 1$ is satisfied. Furthermore, for all $x \in X$, and for each IFS A in X, we call the intuitionistic index of an element $x \in X$ in A, $\pi_A(x) = 1 - \mu_A(x) - \nu_A(x)$ is the intuitionistic fuzzy index of the element $x \in X$ in A, $\pi_A(x)$ representing the *degree of hesitancy* of x to A, where $0 \le \pi_A(x) \le 1$ clearly holds for all $x \in X$.

Definition 3.2. In order to resolve intuitionistic fuzzy multiple criteria group decision-making problems, assuming a group of experts Ei performing MCDM assessment of a set of Cj evaluation terms, this paper sets the dimensions of the intuitionistic fuzzy decision-making matrix R as $m \times n : R = (r_{ij})$, where $1 \le i \le m, 1 \le j \le n$, and $m, n \in Z^+$; and the matrix R is defined as shown in (1) :

$$R = (r_{ij})_{m\times n} = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{bmatrix} \tag{1}$$

Where $r_{ij} = (\mu_{ij}, \nu_{ij}, \pi_{ij}), i, j \in Z^+$

Definition 3.3. Referring to the intuitionistic fuzzy entropy formula of Vlachos and Sergiadis [32], we define the formula for the entropy H_j of the j^{th} evaluation item as follows:

$$H_j = H_j^{fuzzy} + H_j^{intuit} \tag{2}$$

Where the terms H_j^{fuzzy} and H_j^{intuit} are described by

$$H_j^{fuzzy} = -\frac{1}{m\ln 2}\sum_{i=1}^{m}[\mu_{ij}\ln\mu_{ij} + \nu_{ij}\ln\nu_{ij} - (1-\pi_{ij})\ln(1-\pi_{ij})] \tag{3}$$

and

$$H_j^{intruit} = \frac{1}{m}\sum_{i=1}^{m}\pi_{ij} \tag{4}$$

Let us rewrite (2) as

$$H_j = -\frac{1}{m\ln 2}\sum_{i=1}^{m}[\mu_{ij}\ln\mu_{ij} + \nu_{ij}\ln\nu_{ij} - (1-\pi_{ij})\ln(1-\pi_{ij}) - \pi_{ij}\ln 2] \tag{5}$$

Here, if $\mu_{ij} = 0, \nu_{ij} = 0, \pi_{ij} = 1$, then $\mu_{ij}\ln\mu_{ij} = 0, \nu_{ij}\ln\nu_{ij} = 0, (1-\pi_{ij})\ln(1-\pi_{ij}) = 0$, respectively. Next, we employ the IFEW formula of Zhang and Liu [29], and normalize the entropy H_j of the j^{th} evaluation item to obtain the entropy weight ω_j; this formula is defined as (6):

$$\omega_j = \frac{k - H_j}{n - \sum_{j=1}^{n} H_j} \tag{6}$$

Where k is the ω_j number of the j^{th} evaluation item for which ω_j is to be obtained, and where $k \in Z^+$ and $\sum_j \omega_j = 1$.

After ranking the entropy weight ω_j of n evaluation items from large to small, we determine the ranking scales of high, medium, and low levels. The judgment principles are as follows:

Let ω_j be the weight of the j^{th} ranked Cj terms, so that $\omega_1 \ge \omega_2 \cdots \ge \omega_n$. Let k_1 be the smallest n such that $\sum_{j=1}^{k_1} \omega_j \ge 0.5$ and k_2 be the smallest n such that $\sum_{j=1}^{k_2} \omega_j \ge 0.8$, where $k_1, k_2 \in n \in Z^+$. We first to classify the k_1 of Cj terms corresponding to $\omega_1, \omega_2, \cdots, \omega_{k_1}$ as high-level items, and we denote high-level item by "H"; next, we classify the k_2 of Cj terms corresponding to $\omega_{k_1+1}, \ldots, \omega_{k_2}$ as medium-level items, and we denote medium-level items by "M"; last, we classify the n of Cj terms corresponding to $\omega_{k_2+1}, \ldots, \omega_n$ as low-level items, and we denote low-level items by " L ".

Similarly, we first apply the same principles used for Cj evaluation terms above to the primary criteria Cp, secondary criteria Cpq, and phase solutions Sr, and then use equation (5) and equation (6) to derive the intuitionistic fuzzy entropy values H_{Cp}, H_{Cpq}, and H_{Sr}, and then calculate the entropy weights $\omega_{Cp}, \omega_{Cpq}$ and ω_{Sr}, which allows us to determine the degree of importance of each criterion and the overall effectiveness grade of each solution.

Definition 3.4. We employ the formula defined below (7) to obtain the relative entropy weight of each primary criterion Cp relative to each solution Sr:

$$\omega_{pr} = \frac{\omega_{Cp} \times \omega_{Sr}}{\sum_{p=1}^{t}\sum_{r=1}^{v} \omega_{Cp} \times \omega_{Sr}} \tag{7}$$

Where $p, r, t, v \in Z^+$ and $\sum_p \sum_r \omega_{Cp} \times \omega_{Sr} = 1$

Similarly, in order to obtain the relative entropy weight of each secondary criterion Cpq relative to each solution Sr, we employ the following equation (8):

$$\omega_{pqr} = \frac{\omega_{Cpq} \times \omega_{Sr}}{\sum_{p=1}^{t}\sum_{q=1}^{u}\sum_{r=1}^{v} \omega_{Cpq} \times \omega_{Sr}} \tag{8}$$

Where $p, q, r, t, u, v \in Z^+$ and $\sum_p \sum_q \sum_r \omega_{Cpq} \times \omega_{Sr} = 1$

We now use the foregoing intuitionistic fuzzy MCDM method in the following section to assess the degree of importance of each criterion and the overall effectiveness grade of each phase solution.

4 Empirical Study of Evaluation and Analysis

A total of 34 expert questionnaires were issued, and the recovery rate was 100%. The respondents consisted of managers (29.4%), operations staff (44.1%), industry consultants (14.7%) and relevant industry experts (11.8%), all of whom had actually participated in supply-chain management work for more than 20 years. The experts had backgrounds in areas including supply (18.1%), production (17%), demand (19.1%), logistics (26.6%) and project management (19.1%), and had at least three years of work experience in these areas of specialization. The following is a reliability analysis of questionnaire evaluation results and IFEW calculations and analysis.

4.1 Reliability analysis of questionnaire evaluation results

We used SPSS software to analyze the reliability of questionnaire survey results consisting of the importance of the 18 secondary criteria Cpq and the effectiveness of synthesis of the four solutions Sr as assessed by the 34 experts Ei. The calculated Cronbach's alpha coefficients for reliability are as shown in Table 2.

Table 2: Reliability analysis of Cpq and Sr evaluation results

Evaluation items	Reliability coefficient	Reliability
C11 $\sim$ C64	0.907	Extreme credible
S1 $\sim$ S4	0.830	Very credible
Overall	0.920	Extreme credible

The results of the survey revealed that the Cpq importance evaluation results had an α = 0.907, the Sr effectiveness evaluation results had an α = 0.83, and overall evaluation of both items had an α = 0.92. This indicates that the results of the questionnaire survey as a whole ranged from very reliable to extremely reliable.

4.2 IFEW calculation and analysis

The results of evaluation of the importance of the 18 secondary criteria Cpq by the 34 experts were converted into the intuitionistic fuzzy linguistic variables shown in Table 1, and were expressed as the decision-making matrix R_{Cpq} employing (9):

$$R_{Cpq} = (r_{ij})_{34\times 18} = \begin{bmatrix} (0.95,0.05,0.00) & (0.85,0.10,0.05) & \cdots & (0.95,0.05,0.00) \\ (0.95,0.05,0.00) & (0.65,0.25,0.05) & \cdots & (0.95,0.05,0.00) \\ \vdots & \vdots & \ddots & \vdots \\ (0.95,0.05,0.00) & (0.85,0.10,0.05) & \cdots & (0.85,0.10,0.05) \end{bmatrix}. \quad (9)$$

The results of evaluation of the effectiveness of synthesis of the four solutions Sr by the 34 experts were converted into intuitionistic fuzzy linguistic variables shown in Table 1, and expressed as the decision-making matrix R_{Sr} employing (10):

$$R_{Sr} = (r_{ij})_{34\times 4} = \begin{bmatrix} (0.75,0.15,0.00) & (0.85,0.10,0.05) & \cdots & (0.95,0.05,0.00) \\ (0.95,0.05,0.00) & (0.95,0.25,0.05) & \cdots & (0.35,0.55,0.10) \\ \vdots & \vdots & \ddots & \vdots \\ (0.95,0.05,0.00) & (0.85,0.10,0.05) & \cdots & (0.75,0.15,0.10) \end{bmatrix}. \quad (10)$$

We used equation (5) to calculate the intuitionistic fuzzy entropy H_{Cpq} of intuitionistic fuzzy matrix R_{Cpq}, and then used equation (6) to calculate the IFEW ω_{Cpq}. The IFEW ω_{Cpq} values were finally ranked in descending order to judge their importance, yielding the results shown in Table 3.

Table 3: Order of IFEW values for secondary criteria Cpq

Secondary Criteria	H_{Cpq}	ω_{Cpq}	Rank
C11	0.400	0.075	1
C13	0.432	0.071	2
C51	0.471	0.066	3
C61	0.488	0.064	4
C21	0.491	0.064	5
C62	0.498	0.063	6
C64	0.508	0.062	7
C52	0.527	0.059	8
C63	0.536	0.058	9
C12	0.566	0.055	10
C53	0.593	0.051	11
C22	0.611	0.049	12
C32	0.616	0.048	13
C41	0.623	0.047	14
C31	0.647	0.044	15
C43	0.654	0.043	16
C23	0.670	0.041	17
C42	0.697	0.038	18
Total	10.03	1.000	

It can be seen from the evaluation results in Table 3 that the top eight strategies had cumulative entropy weights accounting for 52.5% of the total and could be classified as highly important strategies, the strategies with the 9^{th} through 14^{th} cumulative entropy weights accounting for 30.8% could be classified as moderately important, and the strategies with the 15^{th} through 18^{th} cumulative entropy weights accounting for 16.7% could be classified as less important strategies. The following reasons were inferred to account for low evaluation results: Because the aerospace manufacturing industry has the characteristics of high investment costs, long payback periods, a high technological threshold, strict flight safety certification requirements, and volume production of multiple types of products, a decentralized production-base (C23) strategy is relatively unimportant. And because aircraft have high unit prices, high degrees of customization, high market concentration, and large demand fluctuations, both shifting demand (C42) and revenue management (C43) strategies are also unimportant.

Relying on the entropy H_{Cpq} of secondary criteria results in Table 3, we first calculated the entropy values $H_{Cp} = \sum_{q=1}^{u} H_{Cpq}$ of the primary criteria, and used equation (6) to obtain the entropy weight ω_{Cp}. The IFEW ω_{Cp} values resulting from these calculations were ranked in order and importance of the corresponding strategies judged, yielding the results shown in Table 4.

Table 4: Order of IFEW values for primary criteria Cp

Primary Criteria	H_{Cp}	ω_{Cp}	Rank
C6	2.030	0.247	1
C1	1.397	0.201	2
C5	1.591	0.177	3
C2	1.772	0.154	4
C4	1.974	0.129	5
C3	1.264	0.092	6
Total	10.03	1.000	

It can be seen from the evaluation results in Table 4 that the top three strategies had cumulative entropy weights accounting for 62.5% of the total, and could be classified as highly important strategies, the strategies with the 4^{th} through 5^{th} cumulative entropy weights accounting for 28.3% could be classified as moderately important strategies, and the final strategy accounting for 9.2% could be classified as less important strategy. The following reasons were inferred to account for low evaluation results: Because aircraft are characterized by large size and the need for special transportation vehicles, customers place great emphasis on timely delivery, and high breach of contract penalties, apart from purchasing high-value transportation insurance, firms must contract transportation responsibilities to reliable, qualified forwarders; since this approach already entails mechanisms for the dispersal and transfer of risk, transportation disruption strategies (C3) and flexible transportation strategies (C31) will be relatively unimportant.

After utilizing equation (5) to calculate the entropy values H_{Sr} of matrix R_{Sr} and then using equation (6) to calculate the entropy weights ω_{Sr}, the IFEW ω_{Sr} values resulting from these calculations were ranked in order and importance of the corresponding strategies judged, yielding the results shown in Table 5.

It can be seen from the evaluation results in Table 5 that the top two solutions had cumulative entropy weights accounting for 52.8% of the total, and can be classified as highly-effective solutions, while the solutions with the 3^{rd} and 4^{th} cumulative entropy weights accounting for 47.2% could be classified as moderately-effective solutions. The fact that all of these solutions had entropy weight contributions of over 22.8% indicates that the selected

Table 5: Order of IFEW values for solutions Sr

Solution	H_{Sr}	ω_{Sr}	Rank
S3	0.531	0.271	1
S2	0.556	0.257	2
S1	0.578	0.244	3
S4	0.606	0.228	4
Total	2.271	1.000	

strategic criteria yielded a contiguous solution as ODMP with excellent overall effectiveness.

In order to provide readers with a better understanding of the relative entropy weights and rank of the importance of the primary criteria Cp and the effectiveness of the solutions Sr, we perform calculation using equation (7) and present the results in Table 6.

Similarly, in order to provide readers with a better understanding of the relative entropy weights and rank of the importance of the secondary criteria Cpq and the effectiveness of the solutions Sr, we perform calculation using equation (8) and present the results in Table 7.

The entropy weights of the 14 highly-important and moderately-important secondary criteria in Table 7 have a cumulative total of 83.3%, are classified under the four strategy constructs of systems, management, execution, and technology, and form an ODMP consisting of the contiguous solution shown in Table 8.

This result can serve as an important reference for aerospace operators in the planning strategic criteria and contiguous solutions for management of supply chain disruption risk. This is explained as follows:

Construct of systems: It is recommended that *sourcing policies* and *inventory policies* form the main strategies, and are accompanied by implementation of *performance measures* and *demand-pull production* as auxiliary strategies.

Construct of management: It is recommended that firms rely on enhancement of supply chain *risk management* capabilities as their main strategy, and then adopt *remote mutual-redundancy* and *economic transportation* as auxiliary strategies.

Construct of execution: It is recommended that firms adopt *effective communication* and *collaboration* as their chief strategies, and assess take *integration* and *dynamic planning* as auxiliary strategies.

Construct of technology: It is recommended that use of *substitute parts databases*, *information sharing*, and *logistics support systems* serve as main strategies.

5 Conclusions and Suggestions for Future Research

This paper investigates supply chain disruption risk literature from the past decade or more, performs in-depth analysis of best practices in crisis management from industry, and attempts to derive a MCDM model to serve

Table 6: Ranking of the relative entropy weights of primary criteria and solutions

Primary Criteria & Solutions	ω_{S1}	ω_{S2}	ω_{S3}	ω_{S4}	Total	Rank	Degree of Importance
ω_{C6}	0.0603	0.0635	0.0670	0.0563	0.2471	1	H
ω_{C1}	0.0490	0.0517	0.0545	0.0458	0.2011	2	H
ω_{C5}	0.0431	0.0454	0.0479	0.0403	0.1767	3	H
ω_{C2}	0.0376	0.0396	0.0417	0.0351	0.1540	4	M
ω_{C4}	0.0314	0.0331	0.0349	0.0294	0.1287	5	M
ω_{C3}	0.0225	0.0237	0.0250	0.0211	0.0924	6	L
Total	0.244	0.257	0.271	0.228	1.0000		
Rank	3	2	1	4			
Degree of Effect	M	H	H	M			

Table 7: Ranking the relative entropy weights of secondary criteria and solutions

Secondary Criteria &Solutions	ω_{S1}	ω_{S2}	ω_{S3}	ω_{S4}	Total	Rank	Degree of Importance
ω_{C11}	0.0184	0.0194	0.0204	0.0172	0.0753	1	H
ω_{C13}	0.0174	0.0183	0.0193	0.0162	0.0712	2	H
ω_{C51}	0.0162	0.0170	0.0180	0.0151	0.0663	3	H
ω_{C61}	0.0157	0.0165	0.0174	0.0146	0.0642	4	H
ω_{C21}	0.0156	0.0164	0.0173	0.0146	0.0639	5	H
ω_{C62}	0.0154	0.0162	0.0171	0.0144	0.0630	6	H
ω_{C64}	0.0150	0.0159	0.0167	0.0141	0.0617	7	H
ω_{C52}	0.0145	0.0153	0.0161	0.0135	0.0593	8	H
ω_{C63}	0.0142	0.0150	0.0158	0.0133	0.0582	9	M
ω_{C12}	0.0133	0.0140	0.0148	0.0124	0.0545	10	M
ω_{C54}	0.0125	0.0131	0.0138	0.0116	0.0511	11	M
ω_{C22}	0.0119	0.0125	0.0132	0.0111	0.0488	12	M
ω_{C33}	0.0117	0.0124	0.0130	0.0110	0.0481	13	M
ω_{C41}	0.0115	0.0122	0.0128	0.0108	0.0473	14	M
ω_{C31}	0.0108	0.0114	0.0120	0.0101	0.0442	15	L
ω_{C44}	0.0106	0.0112	0.0118	0.0099	0.0435	16	L
ω_{C23}	0.0101	0.0106	0.0112	0.0094	0.0414	17	L
ω_{C42}	0.0093	0.0098	0.0103	0.0087	0.0380	18	L
Total	0.243	0.2571	0.2711	0.2280	1.0000		
Rank	3	2	1	4			
Degree of Effect	M	H	H	M			

Table 8: Optimal decision making portfolio of the contiguous solution

Construct	Main Strategies	Auxiliary Strategies	$\sum\omega\%$
Systems	Sourcing policies (C11) Inventory policy (C21)	Performance measures (C12) Demand-pull production (C22)	24.2%
Management	Risk management (C61)	Remote mutual-redundancy (C54) Economic Transportation (C33)	16.3%
Execution	Effective Communication (C62) Collaboration (C64)	Integration (C63) Dynamic planning (C41)	23.0%
Technology	Substitute parts database (C13) Information sharing (C51) Logistics support systems (C52)		19.7%
	Total entropy weight		83.3%

as a hierarchical framework for selection of contiguous solutions in strategic planning. We further selected an aerospace industry operator in Asia, in an industry characterized by LP-HC disruption risk involving flight safety issues, as the subject of empirical study. Next, we applied the IFEW method to the results of an expert questionnaire survey to judge the importance of primary and secondary criteria, and calculate the overall combined effectiveness of solutions resulting from the survey. Following ranking and comparative analysis, the following empirical results were obtained:

After confirming the research results with the expert respondents, it was universally felt that these findings were consistent with the expected results. The research results indicate that experts recommend that *project management*, *supply disruption*, and *logistics support disruption* serve as the main strategies when selecting main criteria, and *production disruption* and *demand disruption* be adopted as auxiliary strategies. When selecting secondary criteria, we recommend that strategies can be based on the four strategic constructs of systems, management, execution and technology listed in Table 8, where the eight high importance criteria should serve as the main strategies, and the six moderately important criteria should serve as auxiliary strategies. The fact that the entropy weights of the overall combined effectiveness of the four phase solutions were all over 22.8% indicates that these solutions possess excellent effectiveness. Furthermore, the experts felt that application of the IFEW method can objectively express respondents' true thinking, and the results of the study can provide durable goods manufacturers and LSPs with an important reference for the determination of an ODMP providing a contiguous supply chain disruption risk management solution. This represents this study's research contribution and most innovative aspect in comparison with other literature.

With regard to future research directions, we hope to perform empirical research on related supply chain disruption risk issues in cooperation with public transit operators, which must also place special emphasis on human safety. We look forward to helping these firms enhance their crisis response and disaster resilience capabilities even further, and seek to take more innovative, effective, and useful strategic solutions as our future research directions and objectives.

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References

[1] A.M. Knemeyer, W. Zinn and C. Eroglu, Proactive Planning for Catastrophic Events in Supply Chains, Journal of Operations Management, **27**, 141-153 (2009).

[2] P.L. Meena, S.P. Sarmah and A. Sarkar, Sourcing decisions under risks of catastrophic event disruptions, Transportation Research Part E: Logistics and Transportation Review, **47**, 1058-1074 (2011).

[3] Y. Sheffi and J.B. Rice, A Supply Chain View of the Resilient Enterprise, MIT Sloan Management Review, **47**, 41-48 (2005).

[4] B. Tomlin, On the value of mitigation and contingency strategies for managing supply chain disruption risks, Management Science, **52**, 639-657 (2006).

[5] M. Huang, M. Yang, Y. Zhang and B. Liu, System dynamics modeling -based study of contingent sourcing under supply disruptions, Systems Engineering Procedia, **4**, 290-297 (2012).

[6] P.R. Kleindorfer and G.H. Saad, Managing Disruption Risks in Supply Chains, Production and Operations Management, **14**, 53-68 (2005).

[7] T. Shu, S. Chen, S. Wang and K.K. Lai, GBOM-oriented management of production disruption risk and optimization of supply chain construction, Expert Systems with Applications, **41**, 59-68 (2014).

[8] M.C. Wilson, The impact of transportation disruptions on supply chain performance, Transportation Research Part E, **43**, 295-320 (2007).

[9] T. Sawik, Selection of resilient supply portfolio under disruption risks, OMEGA, **41**, 259-269 (2013).

[10] M. T. Yassen, M. M. El-Dessoky, E. Saleh, E. S. Aly, On hopf bifurcation of Liu chaotic system, Demonstratio Mathematica, **XLVI**, 2013.

[11] H. Shin, W.C. Benton and M. Jun, Quantifying suppliers product quality and delivery performance: A sourcing policy decision model, Computers & Operations Research, **36**, 2462- 2471 (2009).

[12] P. Suwignjo, U.S Bititci, and A.S Carrie, Quantitative models for performance measurement system, International Journal of Production Economics, **64**, 231-241 (2000).

[13] C.S. Tang, Perspectives in Supply Chain Risk Management, International Journal of Production Economics, **103**, 451-488 (2006).

[14] Y. Sheffi, Building a Resilient Supply Chain, Harvard Business Review, **1**, 2-11 (2005).

[15] R.de Souza, M. Goh, M. Kumar and J. Chong, Combating Supply Chain Disruptions: Lessons Learned from Japan 2011, The Logistics Institute Asia Pacific, 1-31 (2011)

[16] C.S. Tang, Robust strategies for mitigating supply chain disruptions, International Journal of Logistics: Research and Applications, **9**, 33-45 (2006).

[17] D. Mohammaditabar, S.H. Ghodsypour, and C. O'Brien, Inventory control system design by integrating inventory classification and policy selection, International Journal of Production Economics, **140**, 655-659 (2012).

[18] D.D. Achabala, S.H. McIntyrea, S.A. Smitha and K. Kalyanama, A decision support system for vendor managed inventory, Journal of Retailing, **76**, 430-454 (2000).

[19] S.M. Disney and D.R. Towill, The effect of vendor managed inventory (VMI) dynamics on the Bullwhip Effect in supply

chains, International journal of production economics, **85**, 199-215 (2003).
[20] T. Wakolbinger and J.M. Cruz, Supply chain disruption risk management through strategic information acquisition and sharing and risk-sharing contracts, International Journal of Production Research, **49**, 4063-4084 (2011).
[21] U. Wemmerlov, Assemble-to-order manufacturing: Implications for materials management, Journal of Operations Management, **4**, 347-368 (1984).
[22] X.F. Shao and M. Dong, Supply Disruption and Reactive Strategies in an Assemble- to- Order Supply Chain With Time-Sensitive Demand, IEEE Transactions on Engineering Management, **59**, 201-212 (2012).
[23] A. Oke and M. Gopalakrishnan, Managing Disruptions in Supply Chains: A Case Study of a Retail Supply Chain, International Journal of Production Economics, **118**, 168-174 (2009).
[24] M.N. Faisal, D.K. Banwet, and R. Shankar, Supply chain risk mitigation: Modeling the enablers, Business Process Management Journal, **12**, 535-552 (2006).
[25] Z. Yu, H. Yan and T.C.E. Cheng, Benefits of information sharing with supply chain partnerships, Industrial Management & Data Systems, **101**, 114-121 (2001).
[26] C.W. Craighead, J. Blackhurst, M.J. Rungtusanatham, and R.B. Handfield, The severity of supply chain disruptions: design characteristics and mitigation capabilities, Decision Sciences, **38**, 131-156 (2007).
[27] W. Liu, D. Xie, Y. Liu and X. Liu, Service capability procurement decision in logistics service supply chain: a research under demand updating and quality guarantee, International Journal of Production Research, **53**, 488-510 (2015).
[28] H. Whittaker, Comprehensive Emergency Management- A Governors Guide, National Governors Association Center for Policy Research, Defense Civil Preparedness Agency, Washington, D.C., U.S.A., 7-38 (1979).
[29] S.F. Zhang and S.Y. Liu, A GRA-based intuitionistic fuzzy multi-criteria group decision making method for personnel selection, Expert Systems with Applications, **38**, 11401-11405 (2011).
[30] K.T. Atanassov, Intuitionistic fuzzy sets, Fuzzy Sets and Systems, **20**, 87-96 (1986).
[31] W.L. Gau and D.J. Buehrer, Vague sets, IEEE Transactions on Systems, Man and Cybernetics, **23**, 610-614 (1993).
[32] I.K. Vlachos and G.D. Sergiadis, Intuitionistic fuzzy information – Applications to pattern recognition, Pattern Recognition Letters, **28**, 197-206 (2007).

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