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An Innovative Matrix to Mitigate Supply Chain Risk: Insights for Industry

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Abstract: The purpose of this study is twofold: firstly, to define a supply chain matrix situation level (Normal, Near-Miss and Subject to Disruption) and secondly, to use PAL2v to refine and improve the limitations of FMEA technique. We use the Paraconsistent Annotated Logic with an annotation of two values (PAL2v) to generate an innovative matrix to mitigate risks. There are two significant contributions on implementing the proposed Matrix: to create more favorable conditions for organizations to evaluate the supply chain risk events and to provide score leverage for sustainable development of businesses. The proposed matrix has limitation of usage; we have limited our study for one organization. Future research may consider multi-organizations. This innovative matrix generated a guideline to be used in the organizations. The practical implication is the promotion of a more preparedness to mitigate the risks in a supply chain. The proposed matrix used a different approach to improve the limitations of FMEA technique and to solve the problem of inconsistency through PAL2v.
Key words: Supply Chain Matrix, Risk Management, SCM performance, Paraconsistent Annotated Logic with annotation of two values (PAL2v).

Uma Inovativa Matriz para Mitigar os Riscos de uma Cadeia de Suprimentos: Uma Visão Industrial

Resumo: O propósito deste estudo é duplo: primeiramente, definir a matriz da cadeia de suprimentos pela situação de nivel (normal, quase anormal e sujeita a rompimento) e segundamente, usar da PAL2v para refinar e melhorar a limitação da técncia FMEA. È usada a PAL2v para gerar a matriz inovadora que irá mitigar os riscos. Existem duas significantes contribuições em implementat a matriz proposta: Criar uma condição mais favorável para as organizações em avaliar os eventos de risco da uma cadeia de suprimentos e de prover uma pontuação para alavancagem do desenvolvimento sustentável de seus negócios. A matriz proposta tem limitações de uso; este estudo foi focado apenas em uma empresa. Para pesquisia future, tal estudo sera feito em várias empresas. Tal inovativa matriz gera guias de uso para as empresas. Portanto, a implicação na prática vem do fato de promover mais praparação para mitigar os riscos da uma cadeia de suprimentos. Por fim, a matriz proposta usa diferente técnica para melhorar a limitação de uma FMEA em resolver o problema de inconsistencia propondo o uso da LPA2v.
Palavras Chave: Matriz de Suprimentos, Gerenciamento de Riscos, LPA2v, FMEA.

1. Introduction

With the increasing globalization, environmental change and new technologies (internet of things, cyber physical systems and artificial intelligence), escalating risks have affected global businesses and supply chains. Therefore, mitigating supply chain risks becomes an issue. Before one can mitigate risks, an evaluation of the risks is necessary. The traditional evaluation of risks in a supply chain is based on statistical methods. These methods are related to the likelihood of occurrence of risk (based on a historical data or a subjective likelihood). The risk occurrence is compared with business impact to create a risk evaluation matrix. However, these methods potentially have some limitations in measuring the risk level because it is based on the opinions of experts (human knowledge).

The quantification of these limitations is used in this paper. The structured analysis is based on Paraconsistent Logic (PL) [1]. Para consistent logic belongs to the Group of so-called non-classical logics and has the property to accept contradictions in its fundamentals without trivialization. Therefore, this study uses a special type of PL denominated Paraconsistent Annotated Logic with annotation of two values (PAL2v) to evaluate the risks in a supply chain. Moreover, we also considered a system for evaluating uncertainty measures with a number of criteria; they are classified based on the following factors: a) The system must be capable of generating results to present satisfactory interpretation: the uncertainty measures must be meaningful, clear and accurate enough to justify conclusions. b) The system must be capable of tackling non-exact information: The uncertainty measure must be capable of modeling partial or limited information, as well as inaccurate displays of uncertainty. c) The system must be capable of calculating non-exact values. For uncertainty values, there must be rules to combine uncertainty measures, and update them when there is new evidence of information; it can then derive other uncertainties that are helpful for decision making. d) The system must be capable of presenting consistent results: For the treatment of uncertainties, the system supplies methods to permit the verification of uncertainties to be displayed in all the default suppositions. e) The system must be able to provide good computation for the involved data: In uncertainty treatment, the values are computationally factual so it enables the system to set interface rules and obtain conclusions. In the treatment of data with non-exact values the system must allow for the combination of qualitative evaluations with quantitative non-exact values.

The rest of this paper is organized as follows. Section 2 presents the relevant literature on Supply Chain Risk Management (SCRM) and Supply Chain Risk (SCR) evaluation, Failure Mode and Effect Analysis (FMEA), the Para consistent Annotated Logic (PAL) and the PAL2v. The developed model is presented in the Section 3. Section 4 presents an example of risk evaluation in a supply chain. The findings and discussions are given in Section 5. Finally, Section 6 is the concluding remarks.

1. Literature Review

2.1 Supply Chain Risk Management (SCRM)

For supply chain networks with several tiers, there are numerous risks. Generally, the risks can be classified into two types: risks arising from within the supply chain network and risks external to the network. The attributes of operational risks are due to the interactions between firms across the supply chain network, such as supply risks, demand risks, and process risk. According to Barve et al. (2009), the human factors are responsible for the agile supply chains. In Faisal et al. (2007) the Risk Mitigation Environment (RME) is quantified and presented in the form of a single numerical index. Supply chain risk management is defined by Norrman and Jansson (2004) as: "collaborating with partners in a supply chain to apply risk management process in order to mitigate risks and uncertainties in a supply chain". He et al. (2015) showed through a case study the importance that the manufacturer may collaborate with component suppliers to enhance quality design. Furthermore, an effective management of risks is the focal concerns for firms to survive and achieve a competitive advantage business environment. Singhal et al. have shown that the supply chain risk management has emerged as a natural extension of supply chain management with the prime objective of identifying the potential sources of risks and suggesting suitable action plans to mitigate them. Recent events demonstrated that when a disruption occur, it would affect the supply chain and the corporation's ability to continue its operations, deliver finished goods or provide critical services to customers.

Due to the complex nature of risks, various tools are used to plan a mitigation strategy to address critical areas. Therefore, the field of SCRM is of increasing interest from industrial and academic standpoints. Currently, there are thousands of research articles and business reports on SCRM. Some of the recent contributions are: Rangel et al. (2014) and Blos et al. (2015) classified as SCRM; Ivanov et al. (2016) reviewed the state-of-the-art on supply chain disruptions and recovery policies; Ge et al. (2016) developed a hybrid optimization-simulation model to mitigate the supply chain risks; Li et al. (2016) considered a pricing strategy and coordination in a dual channel supply chain with a risk-averse retailer. Zepeda et al. (2016) analyzed the supply chain risks by considering inventory problem; Boyson (2014) presented cyber supply chain risk management; Mangla et al. (2014) managed risks in operational networks in green supply chain using Monte Carlo simulation; Rajesh and Ravi (2015) developed an approach model to mitigate the risks in the context of an electronic supply chain; Subulan et al. (2015) developed a model based on fuzzy logic to deal with risk and uncertainty in the context of a lead/acid battery closed-loop supply chain; Blos et al. (2015) developed a general supply chain continuity framework to deal with the risks in supply chain; Marufuzzaman et al. (2014) analyzed the impact of intermodal-related risk to design and manage biofuel supply chain; Oliveira et al. (2013) used a LaGrange an decomposition to deal with risks and uncertainty in oil supply chain investment planning; Le et al. (2013) developed an algorithm to avoid risk for a retailer sharing data in retail supply chain collaboration; Giarola et al. (2013)

developed an approach to deal with the risks of ethanol supply chain in the context of economy and environment strategies. Wang et al. (2015) considered an EOQ model for imperfect quality items with partial backorders and screening constraint and Peng et al. (2012) developed an empirical research on Taiwanese industries considering outsourcing. In order to provide more orientation for the application of the developed model, the concept of near-miss in supply chain is considered as well. In Haksöz (2013), a near-miss is defined as an event or series of events that could have resulted in one or more specified undesirable consequences under different but foreseeable circumstances.

2.2 Supply Chain Risk (SCR) Evaluation

From Braithwaite and Hall (1999), it is shown that supply chain consists of many companies and tiers. Some researchers suggested that the effects of disruptions in supply chains have escalated in the last few years (Christopher and Lee, 2001; McGillivray, 2000; Engardio, 2001; Park et al. 2013; Slack et al. 2009). In this sense, managing the risk impact in a supply chain became an important responsibility. One of the objectives of this paper is to evaluate the risk. SCR evaluation is made up of two measures: likelihood of occurrence (measures the probability that the event will occur) versus business impact (measures the consequences on the organization if the event occurs).

One of the tools to assess SCRs is FMEA technique (Failure Mode and Effect Analysis). However, FMEA technique needs some refinement and improvement (Gilchrist, 1993). In this paper, we propose the use of PAL2v to refine and improve the limitations presented by the FMEA technique.

2.3 Failure Mode and Effect Analysis (FMEA)

Failure Modes and Effects Analysis (FMEA) is a step-by-step approach to identify all possible failures in a product design, manufacturing/assembly process, and/or final product/service. "Failure modes" means the ways in which something might fail. Failures are any errors or defects, especially ones that affect the customers. "Effects analysis" refers to studying the consequences, or effects of those failures (ASQ Quality Press, 2013).

According to Ghadge et al. (2015), FMEA predicts Risk Priority Number (RPN) to measure the level of failure modes for a system. In this research, RPN is used to measure the level of failure modes in a supply chain system. Furthermore, RPN is an index that expresses the risk level priority associated with each failure mode. The RPN index is determined by calculating the product of the three indexes: RPN = Occurrence score (O) * Severity score (S) * Detection score (D)

Stamatis (1995) defines each one of the above three indexes in a 10-point rating scale. The RPN for each one of the three indexes are presented according to Table 1, and can define the supply chain situation as Normal Level, Near-Miss Level and Subject to Disruption Level.

There is one situation for "Normal" level in a supply chain:

1. Risk Occurrence = Low and Risk Severity = Low.

Where the Occurrence value goes from 1 to 5 (zero to low) and the Severity values goes from 1 to 4 (zero to minor).

There are five situations for "Near-Miss" Level in a supply chain:

1. Risk Occurrence = High and Risk Severity = Low.
2. Risk Occurrence = Medium and Risk Severity = Low
3. Risk Occurrence = High and Risk Severity = Medium.
4. Risk Occurrence = Low and Risk Severity = Medium.
5. Risk Occurrence = Medium and Risk Severity = Medium.

Where the Occurrence values goes from 6 to 7 (Occasional to Medium) and the Severity values goes from 5 to 7 (Moderate to Functional).

Table 1. The RPN Classification x Situation Level in a SC.

	Normal	Near-Miss					Subject to Disruption		
O	LOW	HIGH	MEDIUM	MEDIUM	LOW	HIGH	LOW	MEDIUM	HIGH
S	LOW	LOW	LOW	MEDIUM	MEDIUM	MEDIUM	HIGH	HIGH	HIGH
D	LOW/MEDIUM/HIGH								

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There are three situations for "Subject to Disruption" Level in a supply chain:

1. Risk Occurrence = Low and Risk Severity = High.
2. Risk Occurrence= Medium and Risk Severity = High.
3. Risk Occurrence = High and Risk Severity = High.

Where the Occurrence values goes from 8 to 10 (high to almost certain) and the Severity values goes from 8 to 10 (inoperable to hazardous).

* The detectability index used in all the three above supply chain situations was used in its totality (low, medium and high).

2.4 Paraconsistent Annotated Logic (PAL)

In recent years, Paraconsistent Logic has a fruitful new field of application, mainly due to the exponential growth in technology and Artificial Intelligence (AI). In order to solve theoretical difficulties raised by the inconsistent database, Para consistent tools have been successfully applied. In this sense, Para consistent logic touches various areas like ontology, the philosophy of science, applied science, and technology, for example robotics, expert systems and computing (Abe and Da Silva Filho, 2003; Nakamatsu et al., 2002; Da Silva Filho et al., 2009). Moreover, due to the theoretical and technical evolution, Para consistent model theory (PMT), Paraconsistent set theory (PST), Para consistent geometry (PG) and Paraconsistent annotated logic (PAL) have been developed. Recently, there were several researches in the fields of medicine (Da Silva Fiho et al., 2009) and industry (Da Silva Filho, 1997) using PAL.

The Paraconsistent Annotated Logic (PAL) belongs to a family of Paraconsistent logics and can be represented through a lattice of four vertices, as demonstrated on Figure1. These four vertices represent extreme logical states referring to the proposition that will be analyzed (Jas'kowski, 1969; Subrahmanian, 1987; Da Costa et al., 1991; Da Silva Filho et al., 2010). Da Silva Filho (2012) defined PAL as a class of evidential logic that threated the signals by annotations. In proposition *p*, there exists a finite lattice that attributes a logical value annotation. A PAL can be represented as a finite lattice of "four states"; the Propositional statement precedes an Evidence degree. Therefore, an Annotated sentence associated to the Lattice of the PAL can be read in the following way:

$P_{(T)}$ ==> the annotation or Evidence Degree T assigns a connotation of "inconsistency" to the proposition *P*.

$P_{(t)}$ ==> the annotation or Evidence Degree *t* assigns a connotation of "truth" to the proposition *P*.

$P(_F)$ ==> the annotation or Evidence Degree *F* assigns a connotation of "falsehood" to the proposition *P*.

P($\perp$) ==> the annotation or Evidence Degree $\perp$ assigns a connotation of "indefinite" to the proposition *P*.

The annotation may compose of 1, 2 or *n* values, depending on the Para consistent logic utilized.

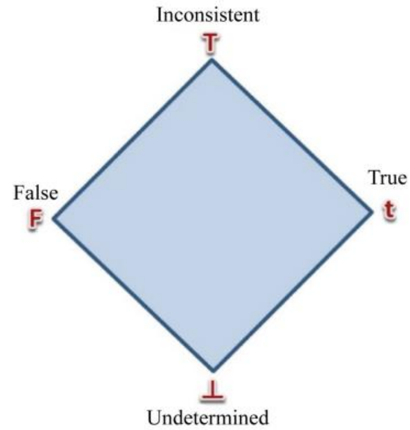

Figure 1. Lattice FOUR with PAL2v logical states (Hassel Diagram).

2.5 Paraconsistent Annotated Logic with annotation of two values (PAL2v)

Inserted into the Group of non-classical Logics, LPA2v is a special type of Paraconsistent Annotated Logic which presents conditions to compute contradictory signals without the conflict of information invalidating the conclusions. According to Abe and Da Silva Filho (2003) and Da Silva Filho et al. (2010), it is possible to obtain a representation on how accurate the annotations (or the evidences) are on a proposition *P* using a lattice formed by the ordained pairs, such as: $\tau = \{(\mu, \lambda)|\mu$, and $\lambda \in [0, 1] \subset \Re\}$. In this case, an operator ~ is introduced: $|\tau| \rightarrow |\tau|$. The operator ~ constitutes the "meaning" of the logical symbol of negation $\neg$ of the system to be considered (Da Silva Filho et al., 2010). In this way, a four-vertex lattice associated with the Annotated Paraconsistent Logic with annotation of two values (PAL2v) is formed. The first element (μ) in the ordained pair (μ, λ) is the degree in which the favorable evidences support the proposition *P*, and the second element (λ) represents the degree in which the unfavorable evidences, or contrary evidences, deny or reject the proposition *P*. Thus, the intuitive idea of the association of an annotation (μ, λ) to a *P* proposition means that the degree of favorable evidence in *P* isμ, and the degree of unfavorable (or contrary) evidence is λ. In an intuitive manner, Da Silva Filho et al.(2010) showed that such Lattice have the following annotations:

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(1, 0) → indicating existence of *total favorable evidence, and unfavorable zero evidence*, attaching a true logical connotation to proposition *P*.
(0, 1) → indicating existence of *zero favorable evidence, and total unfavorable evidence*, attaching a connotation of falsity logical to proposition *P*.
(1, 1) → indicating existence of *total favorable evidence, and total unfavorable evidence*, attaching an inconsistency connotation logical to proposition *P*.
(0, 0) → indicating existence of *zero favorable evidence, and unfavorable zero evidence*, attaching an indeterminate logical connotation to proposition *P*.
The formula (¬ *A*) is read "the negation or weak negation of *A*"; (*A* ∧ *B*), "the conjunction of *A* and *B*"; (*A* ∨ *B*), "disjunction of *A* and *B*"; (*A* → *B*), "the implication of *B* by *A*". Based on Figure 1, the annotations above are represented as follow:
P(μ, λ): T = **Inconsistent** ➔ *P*(1, 1),
F = **False** ➔ *P*(0, 1),
t = True ➔ *P*(1, 0),
⊥ = **Indeterminate** ➔ *P*(0, 0).

According to Da Costa (1974), Subrahmanian (1987) and Da Costa and Marconi (1989), the PAL language, the semantics of a complete set of connectives and axioms are described with details.
With the values considered in a *unitary quadrant of the Cartesian plane* (UQCP), it is possible to find the linear transformations to a Lattice *k* of analog values to the Lattice associated to the PAL2v (Da Costa et al., 1991; Da Silva Filho et al., 2006; Da Silva Filho, 1999). Therefore, the linear transformation is represented by the equation:

$$T(X, Y) = (x - y, x + y - 1) \quad (1)$$

In UQCP, the values of Favorable Evidence Degree μ are exposed in the axis *x*, and the values of Unfavorable Evidence Degree *λ* in the axis *y*.

From the first term (*X*) from the equation of the final transformation, we have:
$X = x–y=\mu–\lambda$, which is denominated of Certainty Degree (D_C). Therefore, the Certainty Degree of the PAL2v analysis is obtained:

$$D_C = \mu-\lambda \quad (2)$$

Its values, which belong to the set ℜ, vary in the closed interval +1 and –1, and are in the horizontal axis of the Lattice, called "degrees of certainty axis".

From the second term (*Y*) of the final transformation, there is: $Y=x+y-1=\mu+\lambda-1$, which is denominated Contradiction Degree (*Dct*). Therefore, the Contradiction Degree of the PAL2v analysis is obtained by

$$Dct = (\mu+ \lambda) -1 \quad (3)$$

Its values, which belong to the set ℜ, vary in the closed interval +1 and –1, and are in the vertical axis of the diagram, called "degrees of contradiction axis" (Da Silva Filho and Rocco, 2008).

The results of the linear transformation in Eq. (1) indicate that, in the notation of LPA2v (Abe and Da Silva Filho, 2003), Eqs. (2) and (3) are functions of μ and λ that may represent a Para consistent logical state ετ. Therefore:

$$\varepsilon_{\tau(\mu,\lambda)} = (\mu - \lambda, \mu + \lambda - 1) \quad (4)$$

or

$$\varepsilon_{\tau(\mu,\lambda)} = (D_C, Dct) \quad (5)$$

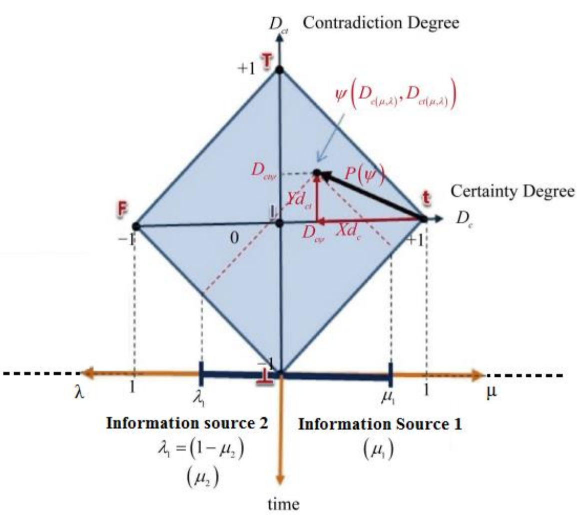

Figure 2. Determine the real certainty degree (*D*CR) and the resulting lattice of PAL2v value where ετ is a Paraconsistent logical state.

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D_C = degree of certainty, computed as a function of two degrees of evidence; μ and λ.
Dct = degree of contradiction, computed as a function of two degrees of evidence; μ and λ (Da Costa and Marconi, 1989; Da Silva Filho et al., 2010).

From previous detailed study (Da Costa, 1974; Da Silva Filho et al., 2010; Da Silva Filho et al., 2011), we can define a *real certainty degree* (D_{CR}) as a D_C value without the effects of contradiction. As seen in Figure 2, the D_{CR} value is on the axis of the degree of certainty on the PAL lattice and is calculated as follows:

If $D_C > 0$.

$$D_{CR} = 1 - \sqrt{(1-|Dc|)^2 + D_{ct}^2} \quad (6)$$

If $D_C < 0$

$$D_{CR} = \sqrt{(1-|Dc|)^2 + D_{ct}^2} - 1 \quad (7)$$

where $D_C = f(\mu, \lambda)$ and $Dct = f(\mu, \lambda)$ are from Eqs. (2) and (3).

From D_{CR}, its normalized value, called the resulting evidence degree (μER) can be found (Da Costa and Marconi, 1989; Da Silva Filho et al., 2010; Da Silva Filho et al., 2016). Therefore:

$$\mu_{ER} = \frac{DCR+1}{2} \quad (8)$$

Based on the fundamentals of PAL2v equations [40], Da Costa and Marconi (1989) and Da Silva Filho (2012) obtained the algorithms that can be used in data analysis and the treatment of information. In this study, we applied a method for analysis, comparison, and decision making using the PAL2v-algorithms (Da Silva Filho, 2012; Da Silva Filho et al., 2010) to the supply chain disruption with historical database of physical risk process and the virtual risk process, respectively.

3.The Developed Model

In order to understand the issue behind the SCRs, the developed model initially considers the problematic assumption. Then the developed framework is described.

3.1 The Problematic Assumptions

In this section, we described the uncertainties that contribute to the generation of a supply chain disruption:

a) Physical risk process: transportation by ship, truck, airplane around the world. Due to the globalization and environmental changes, the disruption risks during cargo transportation between geographically dispersed countries have increased.

b) Virtual risk process: virtual information transmitted by the web to the supply chain partners. This virtual risk process is related to the *important information* from the purchaser and the supplier.

This inaccurate and inconsistent information can disrupt a supply chain.

Both the risk processes described above can result-ed in financial vulnerability, strategic vulnerability, hazard vulnerability and operations vulnerability (Blos et al., 2009).

3.2 The Analysis Framework for SCRs

From Da Silva Filho (2009), we create the analysis framework for SCRs by combining PAL2v with FMEA (see Figure 3). The input μ and λ is based on the FMEA database of RPN-SC situation. Then, based on Da Silva Filho et al. (2011), the PAL2v algorithm is replicated together with the PANnet composing four types of algorithms: 1. Extractor of evidence degrees; 2. PAN; 3. Extractor of contradiction effects; and 4. Extractor of evidence of degrees of frequency. Referring to the proceedings, the supply chain risk manager has enough information to take the correct decision and appropriate action.

4. A Practical Example

To illustrate the application, we use a data related to a risk matrix of a company after interviewing one hundred employees in a period of one year. We use the method of assessment based on Failure Mode Effect Analysis (FMEA) guidelines; it gives a score for the probability of the risk occurrence, the impact of the risk, and the identification method that the firm has to reduce the impact. The expert opinion was fed to the MATLAB software program, by assigning a risk degree for various combinations to define the RPN according to each supply chain levels (as presented on Section 2.2).

Following the framework presented on Section 3.2, the NPR-SC Situation data is inputted on the system with three values (Normal value, Near-Miss value, and Subject to Disruption value). Disruption value is represented by the Minimum and Maximum (described on Figure 4). Then, using the software developed by the Laboratory of Applied Para consistent Logic (LAPL), we generated the PANnet composed of three types of algorithms:

1. Extractor of evidence degrees;
2. PAN;
3. Extractor of contradiction effects.

Finally, the output (Evidence Degree) is obtained.

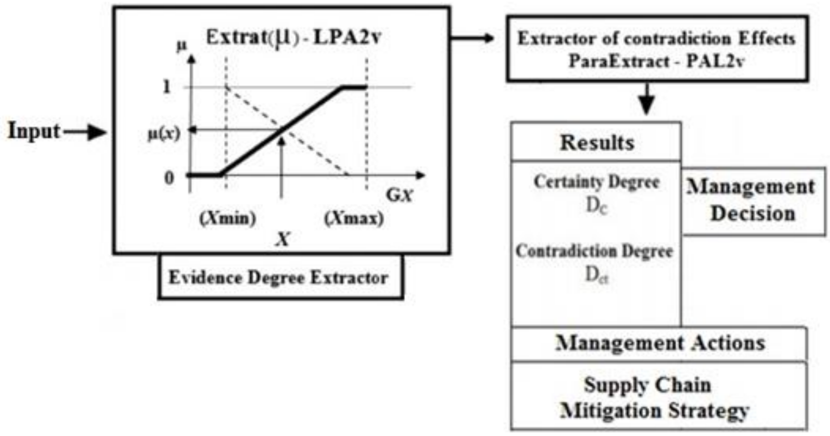

Figure 3. Analysis Frameworks for SCRs.

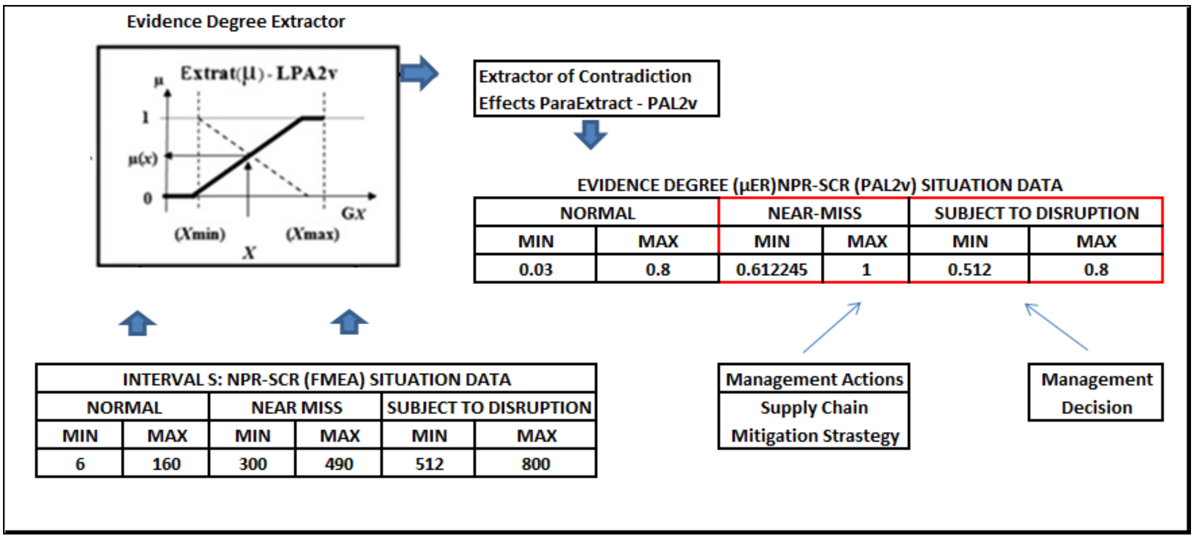

Figure 4. Application of the Analysis Framework for SCRs with PAN2v

4.1 Results

Figure 4 shows the degree of evidence frequency in the PAL2v lattice of paraconsistent logical states for patterns of normal (Min=0.03, Max=0.8), near-miss (Min=0.612245, Max=1) and subject to disruption (Min=0.512, Max=0.8).

For the input, there is the Interval S: NPR-SCR (FMEA) Situation Data. For the results, there is the Evidence Degree (μ_{ER}) NPR-SCR (PAL2v) Situation Data. On Figure 5, there are three situations:

1. Normal Stage (out and far from the red square); 2. Near-Miss Stage (out and up the outer line); 3. Subject to Disruption Stage (inside the red square). Furthermore, Figure 5 describes the degrees of evidence represented by paraconsistent logical states within the PAL2v lattice for the Normal, Near-Miss, and Subject to Disruption on a Supply Chain.

As these values belong to the considered interval and are therefore considered valid, they can be visualized in the PAL2v lattice as a group of paraconsistent logical states. Moreover, the values of the paraconsistent logical states highlights the behavior of each type of NRP-SC Situation, enabling management to define the supply chain impact level and providing the information to the supply chain risk manager to make correct company decision.

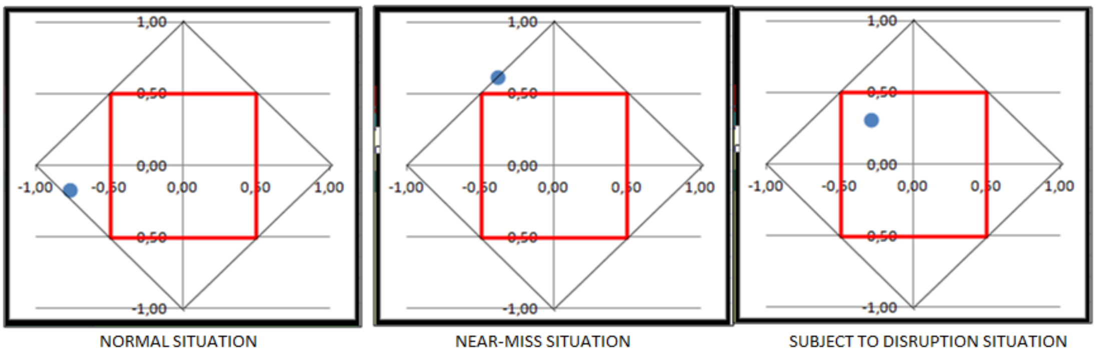

Figure 5. Degrees of Evidence represented by paraconsistent logical states within the PAL2v lattice for Normal, Near-Miss, and Subject to Disruption on a Supply Chain Risk.

5 Conclusion

This study demonstrates how PAL2v is an innovative method to determine the SCR matrix. We define a supply chain matrix situation level (Normal, Near-Miss and Subject to disruption) and apply the PAL2v to refine and improve the limitations presented by the FMEA technique. Thus, the PAL2v algorithms we developed are capable of considering inconsistencies, whereby we generate the most accurate value to analyze the SCRs. These contributions create more favorable conditions for organizations to evaluate the supply chain risk events and provide score leverage for sustainable development of businesses. From Figure 5, the three situations (Normal Stage, Near-Miss Stage and Subject to Disruption Stage) provide the supply chain risk manager a better representation of risks, so that focused attention on the action that will have the best impact on the overall business performance can be achieved.

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