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Full Length Research Paper

Triplex-network design for research of supply chain reliability

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The purpose of this paper was to explore a research design, which can integrate knowledge in multi-discipline into triplex-network architecture, for the development of systematic Supply Chain Reliability (SCR) theory. Through analysis of the emergence of triplex-network in supply chains, triplex-network-based evaluation model of SCR was proposed and a numerical example was provided. The dynamic interactions of various entities involved in a supply chain lead to their relation emerging as interactive triplex-network in higher level and further lead to the supply chain emerging as a complex societal-techno interactive system in even higher level. Therefore, hierarchical conceptual architecture and triplex-network analysis are significant for the development of SCR theory. SCR was considered as a unification of fuzzy and random meaning in dynamic environment in this paper. Furthermore, intrinsic relationship between the theoretical foundation of SCR evaluation and the cloud theory was discovered and accordingly, cloud theory is applied to study the evaluation of SCR. Multi-disciplinary meta-synthesis research method presented in this paper will bring inspiration to multi-disciplinary reliability-related researches. This work contributed to the understanding and evaluation of SCR and has important implication as for the need to incorporate various entities and networks into the collaborative management process of supply chains to reduce disruption risks. This work will provide valuable insight to academicians and business professionals.

Key words: Supply chain management, reliability, triplex-network, emergence, societal-techno interactive system, meta-synthesis.

INTRODUCTION

Supply Chain Management (SCM) is increasingly seen as a set of practices aimed at managing and coordinating the entire chain from raw material suppliers to end customers (Selen and Soliman, 2002). Although there are various definitions about SCM, it may be appropriate to apply the definition as the “network of organizations that are involved, through upstream and downstream linkages, in the different processes and activities that produce value in the form of products and services in the hands of the ultimate consumers” (Christopher, 1992) to the description of SCM. SCM may also be regarded as the process of strategic management of information flow, linkages (upstream and downstream) involved in the activities, tasks and processes, with various networks and delivery of quality products and services through the firms and to the customer, in an efficient manner (Akintoye et al., 2000).

Supply chains today tend to be global in nature, comprising complex interactions and flows between tens, even hundreds and thousands of companies and facilities geographically distributed across regions and countries (Gaonkar and Viswanadham, 2007). This makes them increasingly vulnerable to disruption (Adhitya et al, 2007; Wu et al, 2007).

Generally speaking, disruption risks of a supply chain may be classified into two types: risks arising from within the supply chain and risks external to it. For the former, the cause is the interaction between firms across the entire supply chain. This set of internal risks includes supply risk (Mahnam et al., 2009), demand risk, credit risk, etc. External risks, on the other hand, arise from the interactions between the supply chain and its environment, such as terrorist attacks, wars, earthquakes,

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economic crises, devaluation of currencies, SARS, tsunamis, computer virus attacks, etc. (Kleindorfer and Saad, 2005).

Supply chain managers and researchers continue to aspire to integrated supply chain management across functions (Stevens, 1989). The challenges involved in managing supply chain disruption risks arise from the fact that: (1) Entities in supply chain are dynamic, heterogeneous and distributed; and (2) They are tightly linked at intra- and inter-enterprise levels and critically affect the performance of one another. These make the detection of disruption and its root causes difficult (Adhitya et al., 2007). Supply chain design models have traditionally treated the world as if we knew everything about it with certainty. In reality, however, parameter estimates may be inaccurate and even if all of the parameters of the supply chain are known with certainty, the system may face disruptions from time to time (Snyder, 2003). Uncertainties in supply, demand, transportation, inventory, marketing, etc., can interrupt supply chain operations and cause significant adverse effects. So how do we design a supply chain to make it reliable (that is, performing well when parts of the chain fail)? This question leads to researches on a significant topic, that is, Supply Chain Reliability (SCR) (Jüttner et al., 2003).

Up to now, there is no general acknowledged definition of SCR. Thomas (2002) was the first who explicitly presented the concept of SCR and SCR was defined as "the probability of the chain meeting mission requirements to provide the required supplies to the critical transfer points within the system". Some literatures presented the concept of SCR from techno-system perspective, for example, arrival time (Van Nieuwenhuyse and Vandaele, 2006), potential failure (Quigley and Walls, 2007). Generally speaking, a supply chain is reliable if it performs well when parts of the chain fail (Snyder, 2003).

We argue that SCR researches should pay attention to dynamics, complexity and uncertainty of the holistic supply chain system and the research perspective can surpass traditional techno-system perspective of reliability engineering by adopting multi-disciplinary meta-synthesis method (Gu and Tang, 2005). The proposed research perspective is illustrated as Figure 1.

A supply chain can be treated as a societal-techno interactive system constituted by interactive triplex-network (that is, physical network, participant network and information network) with entities involved in moving products or services from suppliers to customers.

Emergence of triplex-network in supply chains

"With the advent of information technology, supply chains have acquired complexity almost equivalent to that of biological systems" (Surana et al., 2005). Complex Adaptive System (CAS) (Holland, 1995) has been a research effort attempting to find common characters and formal distinctions among complex systems arising in diverse domains that might lead to a better understanding of how complexity occurs, whether it follows certain general laws of nature, and how it might be related to simplicity (Surana et al., 2005). The core idea of the CAS theory is that "adaptation builds complexity" (Holland, 1998), that is to say, the complexity of CAS originates from the adaptability of individuals. Considering the characteristics of CAS and supply chain system, the latter can be seen as a kind of CAS, and with this recognition, various concepts and methods in CAS theory can be applied in triplex-network analysis of supply chain system.

There are many uncertain factors in supply chains and the environment and some uncertain factors will lead to various kinds of nonlinear phenomena in the operation process of supply chains, promoting the occurrence of ceaseless change. Changes constitute the dynamic foundation of system evolution. A supply chain is characterized by multi-entity, which embedded the whole process from supply to demand. The entities in a supply chain distribute in different districts or trades, but they are not isolated from each other. Resources can flow and redistribute optionally, leading to the forming of new groups so as to continuously adapt to the environment at a higher level for survival and development. Through sustaining learning and accumulating experience, the whole system will continuously perfect itself and evolve and form a collaborative symbiotic network. Enterprise operation (Kleczyk, 2008), environment change and interactive behaviours of entities will bring complexity to a supply chain. Additionally, owing to the independence, adaptability and intelligence of entities, interactive behaviours of entities will lead to the system ceaselessly evolving in an adaptive and self-organized manner under the influence of information feedback. The behavioural law of entities organically relates to the evolved law of the system, the subtle change in entities often leads to the change in nature of the whole system; this phenomenon is the so-called emergence of CAS.

The emergence of triplex-network in supply chain system are depicted as Figure 2. Entities in a supply chain spread around in different areas and industries, but they are not isolated. The flow and redistribution of resource lead to the reform of groups to adapt to changeable environment continuously at a higher level. The subtle change in entity level often leads to great change in higher level and reveals character that the entity level does not have. This phenomenon is the emergence in supply chain system (Choi et al., 2001). Disruption risks will bring uncertainty to various levels of a supply chain. The adaptability and interaction of entities will lead to the system ceaselessly evolving by adaptive and self-organized manner under the influence of information flow. A supply chain that has flexibility, adaptability and agility will be more reliable for survival and development.

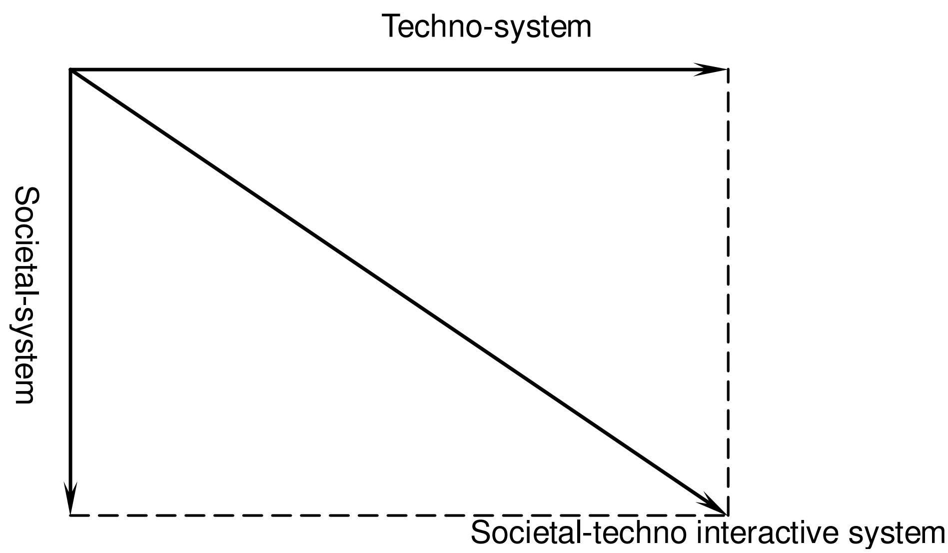

Figure 1. Research perspective of meta-synthesis method.

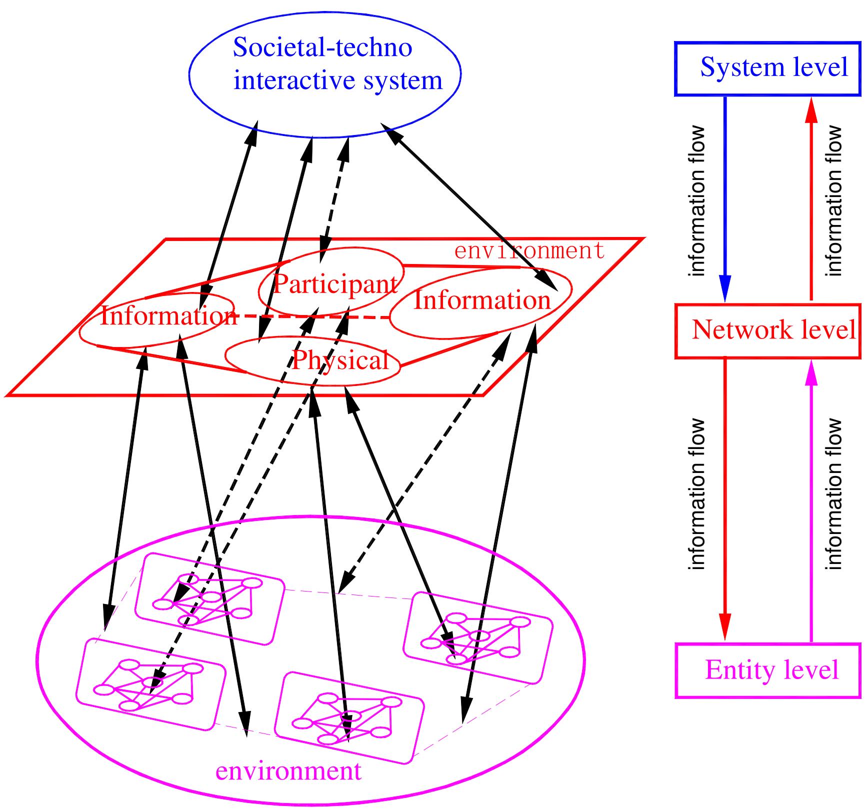

Figure 2. Emergence of triplex-network in supply chain system.

In supply chain system, interactions between the lower and the upper level and within the same level rely on information transmission. "Flow" is an important concept in the CAS theory and information flow has the characteristic of "flow". Interactions between and within physical elements and participants lead to the emergence of triplex-network in higher level through information flow and then, Interactions between and within networks lead

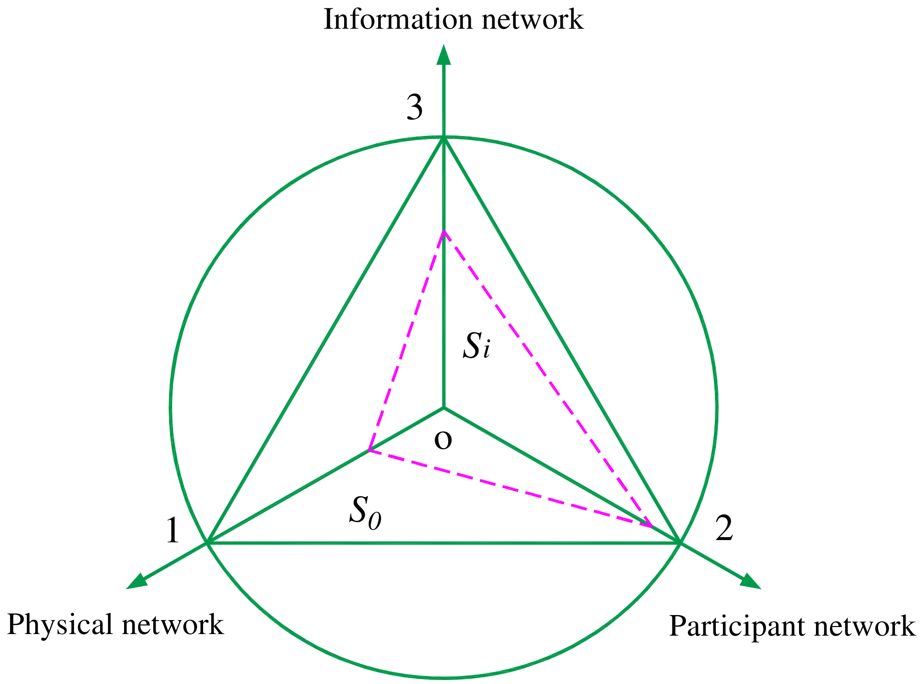

Figure 3. Illustration of the comprehensive performance of triplex-network.

to the emergence of a societal-techno interactive system.

Evaluation of SCR based on triplex-network model

Based on triplex-network architecture, comprehensive performance model of triplex-network for SCR evaluation can be develop. The following method provides an approach for SCR evaluation and is helpful to discover the relation between qualitative fuzzy linguistic terms and quantitative numerical values (Sreekumar and Mahapatra, 2009) about SCR.

When a supply chain is considered as a whole, one cannot describe its reliable state easily. In this paper, six grades were endowed to SCR: (1) Ideality: Highest reliability and perfect operational ability; (2) Superior: High reliability, keeping main operational ability well; (3) Satisfaction: Some drawbacks emerge in the supply chain, while the basic operational ability is unaffected; (4) Inferior: Main operational ability is hampered; (5) Crisis: Major drawbacks emerge in the supply chain; (6) Disruption: Supply chain has lost its operational ability.

Influencing factors of SCR depend on many indexes for expression and these indexes are hard to compare one by one. To tackle this problem, influencing factors of SCR can be classified in network level and normalization for concrete indexes should be done accordingly.

Then, the comprehensive performance model of triplex-network can be developed as follows. Firstly, introduce a circle. Secondly, divide the circle into three equal parts and obtain three points on the circle. Thirdly, draw three radii from the centre of the circle to the three points and let the length of radii represent the ideal value of each influencing aspect when the SCR is in ideality. The area S_0 of the equilateral triangle, which is constituted by the link between every two of the above three points, represents the comprehensive performance of triplex-network when the supply chain is in ideality. The actual value of comprehensive performance of triplex-network in each time form a smaller triangle (the broken line segments represents the sides of the triangle) as is shown in Figure 3 and the triangular area S_i represents the actual comprehensive performance of triplex-network in each time. When the SCR decreases, the triangular area S_i shrinks correspondingly.

The triangular area S_i can be applied to evaluate the comprehensive performance of triplex-network in uncertain environment. The ratio S_i/S_0 can represent the SCR in each time. However, a concrete approach is therefore needed, in order to determine to which grade the SCR will belong. Considering cloud theory (Li et al., 2009) has intrinsic relationship with the character of SCR, the idea of cloud theory can be applied. Fuzzy theory and random theory form the foundation of cloud theory, which is a mathematical tool specialized in dealing with uncertain and fuzzy knowledge and can realizes the transition between concepts and corresponding data. Cloud theory can obtain explanation from classical random theory and fuzzy theory. It reflects the relationship between randomness and fuzziness and forms mapping between qualitative concepts and quantitative data.

Let X be the set $X = \{x\}$, which is the universe of

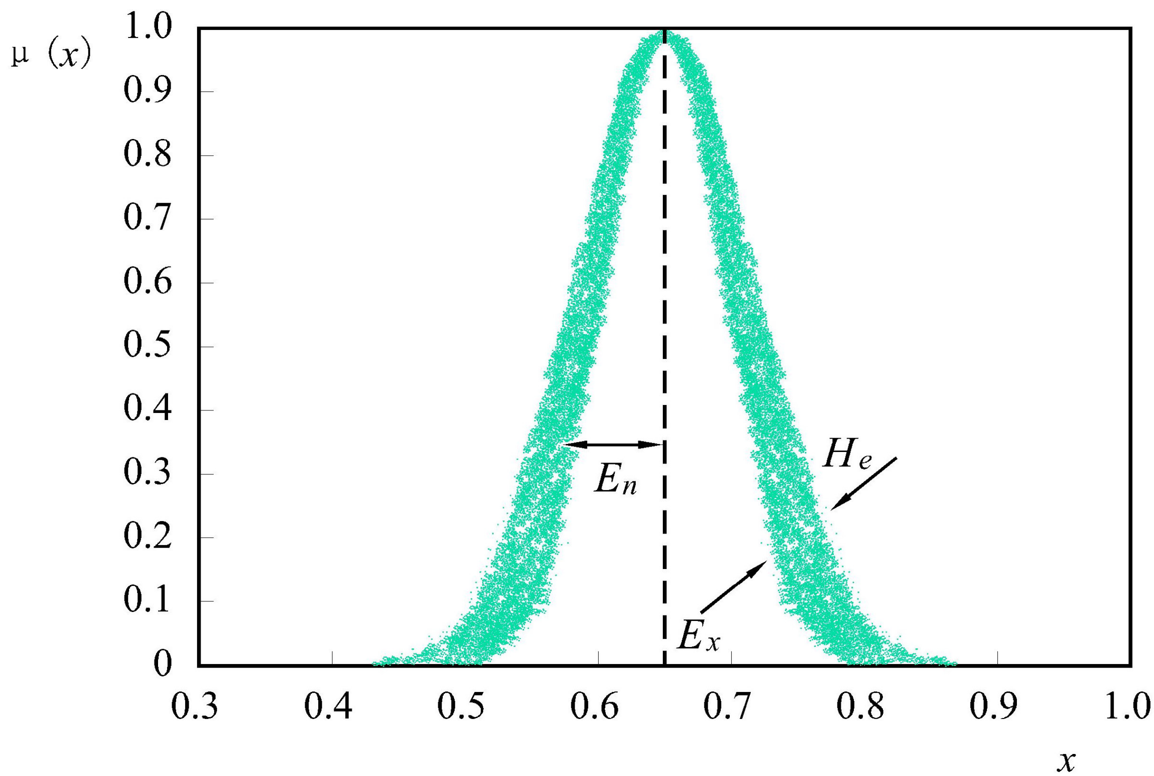

Figure 4. Membership cloud and its eigenvalues.

discourse and L is a linguistic term (fuzzy subset), which has relation with *X*. For any $x \in X$, let $\mu_L(x) = [0,\ 1]$, which is a membership of *x* to *L*. The distribution of membership in the universe of discourse is called membership cloud (cloud for short) (Li, 1996). Cloud is the mapping from the universe of discourse *X* to the interval [0, 1]. That is, $\mu_L(x): X \to [0,\ 1]$, $\forall x \in X$, $x \to \mu_L(x)$.

Membership of a certain point in the universe of discourse varies subtly and brings little effect to the holistic character of the cloud. For a fuzzy set, of what important is the holistic character of the cloud, that is, the shape and variation law of the cloud. The following two laws have been proved as truth (Li, 1996): (1) For substantive fuzzy concepts in natural and social science, the expectation curves of cloud approximately obey normal or half-normal distribution. (2) Membership distribution of certain points in the universe of discourse has the shape of normal distribution.

It is meaningless to discuss membership of a certain single point if no consideration is given to the holistic shape and agglomeration character of the cloud.

The normal cloud has universal applicability and reveals basic laws of vast fuzzy concepts in natural and social science. A normal cloud can be depicted by three eigenvalues, that is, expectation (*Ex*), entropy (*En*) and hyperentropy (*He*) (Li et al., 2000):

1) The expectation (*Ex*) in the *x*-axis corresponds to the center of gravity of the cloud. In other words, the element *Ex* in the quantitative domain is fully compatible with the linguistic term. In Figure 4, the area center under the cover of the membership cloud can be denoted as *G* (*Ex*, $\sqrt{2}/4$), which reflect the central information value of corresponding fuzzy concepts.

2) The entropy (*En*) is a measure of the coverage of the concept within the quantitative domain. It can be also considered as a measure of fuzziness of the concept. The *En* is defined by the bandwidth of the Mathematical Expected Curve (*MEC*) of the normal cloud and show how many elements in the quantitative domain can be included in the linguistic term. The *MEC* of the normal cloud corresponding to a linguistic term can be seen as its membership function.

3) The hyperentropy (*He*) is the entropy of the *En*. It is a measure of dispersion of the cloud drops. In Figure 1, the *He* denotes the stochastic distribution variance of the membership degree corresponding to the point *M* (*Ex*+ $\sqrt{\ln 8}$ *En*, $\sqrt{2}/4$) in expectation curve of the membership cloud. The *He* indirectly reflects the thickness of cloud, the lager of the *He*, the more dispersive of cloud drops and accordingly, the thicker of cloud. The variances of two points *A* (*Ex*, 1) and *B*

Table 1. Numerical eigenvalues of SCR.

Qualitative linguistic term	C_{min}	C_{max}	*Ex*	*En*	*He*
Ideality	0.93	0.99	0.96	0.010	0.002
Superior	0.72	0.98	0.85	0.043	0.004
Satisfaction	0.45	0.85	0.65	0.067	0.004
Inferior	0.26	0.64	0.45	0.063	0.004
Crisis	0.07	0.43	0.25	0.060	0.004
Disruption	0.01	0.19	0.10	0.030	0.003

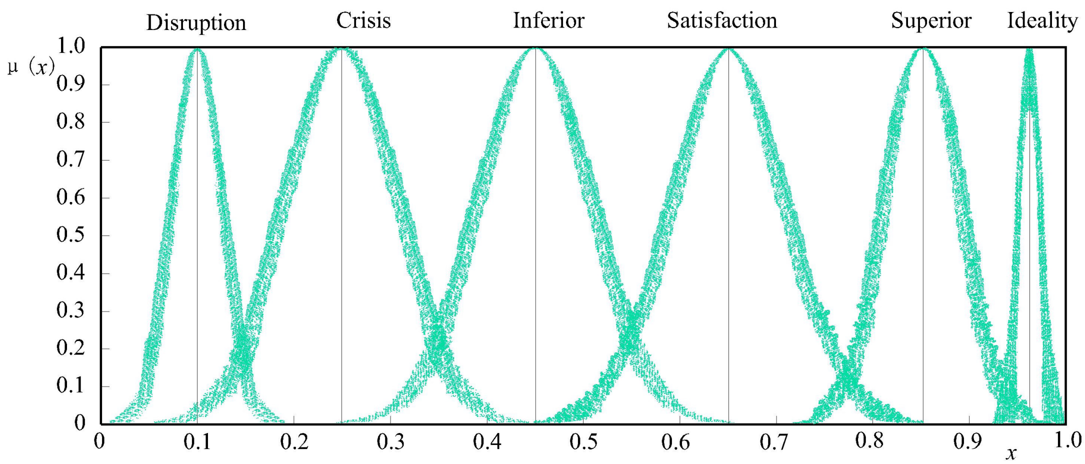

Figure 5. Membership cloud of SCR.

($Ex+3En$, 0.0111) in the membership cloud curve can be taken as zero. Variances of other points in the curve present half-normal distribution along the degressive direction, from the *He* to zero.

From Figure 4, the three eigenvalues of cloud model unify fuzziness and randomness into a whole and form the mapping from qualitative concepts to quantitative data, reflecting the quantitative character of qualitative knowledge.

For index with bilateral constraint [C_{min}, C_{max}], the following formula can be used to approximate the three eigenvalues (Li, 1997).

$$Ex=(C_{min}+C_{max})/2 \quad (1)$$
$$En=(C_{max}-C_{min})/6 \quad (2)$$
$$He = k \quad (3)$$

Where k is a constant and can be adjusted according to concrete indexes.

The generation algorithm of cloud is shown as follows (Li et al., 2000):

(1) $x_i = G(Ex, En)$. Generate random values that satisfy the normal distribution, which has the expectation *Ex* and standard deviation *En*;

(2) $En_i = G(En, He)$. Generate random values that satisfy the normal distribution, which has the expectation *En* and standard deviation *He*;

(3) Calculate $\mu_i = \exp[-(x - Ex)^2]/2En_i^{\,2}]$ and let (x_i, L_i) be the cloud drops. Assign numerical values to *Ex*, *En* and *He*, respectively.

The above algorithm can generate normal cloud with arbitrary number of cloud drops. The three eigenvalues are enough to depict the configuration of the whole cloud.

Numerical example

For a supply chain, considering the comprehensive performance of triplex-network described above, the equilateral triangle area S_0 and the smaller triangle area S_i should be calculated. Let the radii of the circle equal to number 1 and assume the above influencing aspects of triplex-network respectively equal to 0.70, 0.80 and 0.90, which are relative values obtained by unitary processing. In this way, the result of S_i/S_0 can be calculated and a value of 0.637 is obtained.

Then, the scope of each grade of SCR needs to be determined. However, there is therefore the need to generate a bilateral constraint [C_{min}, C_{max}] for each of the above six grades of SCR according to experts' experience. Based on the above formula (1), (2) and (3), the numerical eigenvalue (*Ex*, *En* and *He*) for each

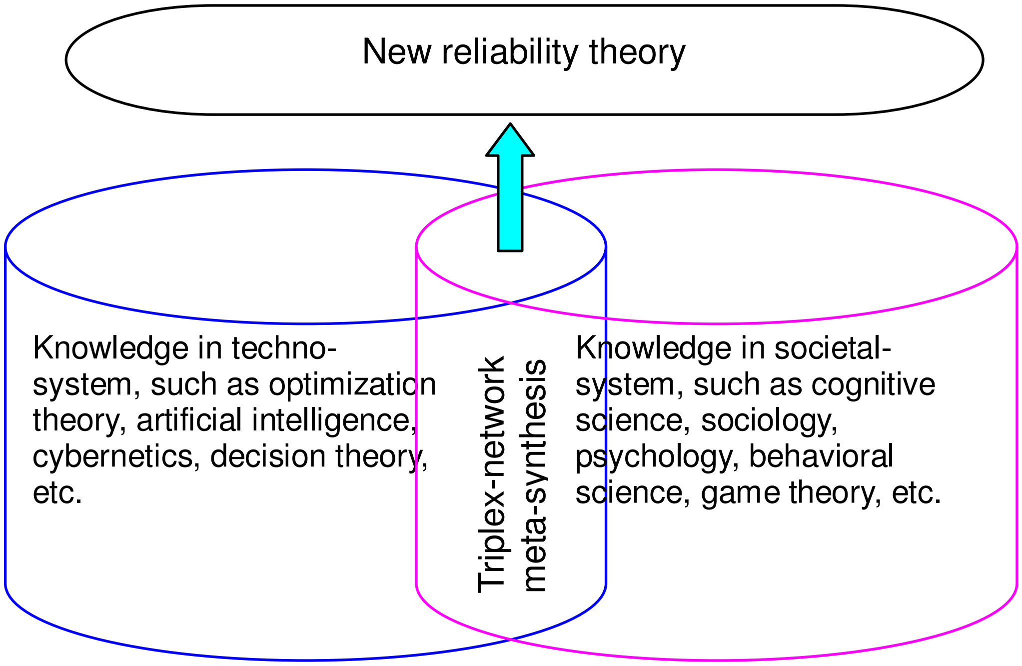

Figure 6. Theoretical source of this research design.

linguistic term can be obtained as shown in Table 1.

Based on the above generation algorithm of cloud, the SCR cloud can be obtained as shown in Figure 4, which represents the clustering and distribution of memberships of SCR values to corresponding linguistic terms of SCR grades. In Figure 5, the *x*-axis represents the definition domain, that is, the different numerical values of S_i/S_0, and the $\mu(x)$-axis represents membership corresponding to each linguistic term of SCR grades.

Locating the result 0.637 of S_i/S_0 in the *x*-axis in Figure 5, It can be seen from the $\mu(x)$-axis that the linguistic term "Satisfaction" suit for expressing the current SCR when all the assumed values and eigenvalues are given as the above. In addition, the corresponding memberships in the $\mu(x)$-axis approximately fall into the scope of [0.80, 0.90], which can reflect the randomness of SCR value and the fuzziness of SCR evaluation.

In the above analytical process, the randomness and fuzziness of SCR obtain integrated expression and uncertain transformation between qualitative expression and corresponding quantitative values of SCR is realized in the triplex-network-based evaluation process.

Conclusion

There are increasing reliability-related researches in engineering and management fields, but they seldom refer to concepts in the academic supply chain literature. This paper was the first to put forward triplex-network architecture for SCR research. This architecture revealed multi-disciplinary character and provided an upper level perspective to consider a supply chain as a societal-techno interactive system and provided a frame for research on interaction inside and between network levels. The complexity of today's supply chain entails multi-disciplinary meta-synthesis research method and this research contributed to this kind of theory. The conceptual system expanded the boundary of traditional reliability theory. Theoretical source of this research design is shown as Figure 6, which may lead a new trend for the development of systemic reliability theory. This paper focuses on SCR, but the methodology and methods presented in this paper will bring inspiration to multi-disciplinary reliability-related researchers and will provide valuable insight to academicians and business professionals.

However, this work merely provided architecture of this research trend and further researches are needed for exhaustive network analysis and empirical illustrations to develop detailed research results.

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