Proceedings of the 2015 International Conference on Industrial Engineering and Operations Management
Dubai, United Arab Emirates (UAE), March 3 – 5, 2015

A Novel Application of System Survival Signature in Supply Chain Risk Management

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***Abstract*—Supply chains have become complex because of the globalization and outsourcing, and the lack of visibility across the entire network makes it difficult to manage the risks. The concept of 'System survival signature' has recently been developed for capturing the network configuration of a system comprising different types of components. Its utilization in the evaluation of system reliability is unique in terms of its capability of segregating the network signature from the probability distribution of failure time of components. We introduce this concept in the realm of supply chain risk management. This novel application can be helpful in evaluating supply network reliability through gauging two distinct features of network configuration and risk profiles of the suppliers. The application is illustrated with the help of two simple examples. The technique can be of significant value to the supply chain managers in taking strategic decisions concerning suppliers and network configuration. We have also adapted the existing risk importance measures in the field of reliability engineering for their application in the domain of supply network reliability.**

Keywords—Supply chain risk management; system survival signature; supply network reliability; network configuration

I. INTRODUCTION

Supply chain risk management is an active area of research that has been receiving a great deal of interest from academics and practitioners [1].The uncertainties in supply and demand, global outsourcing and short product life cycles have made the management of supply chain risks quite challenging [2]. The today's leaner and just-in-time gloabalized supply chains are more vulnerable to operational and external (natural and man-made) disruptions than ever before [3].

There are a number of key debates in the literature of risk focusing on the qualitative and quantitative aspects of risk assessment and therefore, choice of methodology must be given due consideration before its application in the field of supply chain risk management [4]. The application of risk theory to supply chain management is still in its early stages of research and there is requirement of conducting empirical studies of already established models. There is also a major research gap of exploring established risk practices in other fields for application in the domain of supply chain risk management [4].

Supply chain disruptions arising from natural disasters, plant fires, terrorism and supplier bankruptcy, have been the source of major damages in various industries. In order to mitigate the risks, supply chain managers adopt various strategies including addition of inventories, multi-sourcing and designing standardized parts. Supply chains have become too complex because of globalization and off-shoring of manufacturing operations that expose the entire chain to various types of disasters [5]. The individual risks are interconnected and risk mitigation strategy at one end may result in exacerbating another risk [6].

Reliability of a supply network can be expressed in terms of connectivity across the two ends of the network in case of any disruption taking place within the entire chain. Connectivity reliability is the probability that guarantees functioning of links between given pairs of nodes in a network. The existing literature on supply network disruptions considers various approaches ranging from the social network perspective to the stochastic modeling. However, the concept of engineering systems reliability has not been explored much within the domain of supply chain risk management. The existing studies focus on the conventional computation of supply network reliability through decomposition of the network into series and parallel structures [7-9]. However, complex networks may not be feasible to model through this approach. Furthermore, the effect of uncertainties of the risk profiles of suppliers is not considered in relation to the network configuration of the entire supply chain. We present a novel application of the recently developed concept of system survival signature within the domain of supply chain risk management and demonstrate the concept with the help of simple examples. Future research in this area can help supply chain managers take effective strategic decisions in managing complex supply chains. The concept of system signature is presented in Section II followed by the description of risk importance measures in Section III. Section IV explicates the application of system survival signature within the realm of supply network. Future research agenda is presented in Section V.

II. SYSTEM SIGNATURE

System signature captures the configuration of different components in the system. The concept was developed for evaluating the survival distribution of a system that is the function of network configuration and the probability distribution of the failure of components. Following definitions and notations are useful for comprehension of the concept.

For a system with n components, state vector $X = (x_1, x_2, \dots, x_n) \in \{0,1\}^n$, where for each i, $x_i = 1$ if the ith component is working and $x_i = 0$ if it is not working.

Definition. Consider the space $\{0,1\}^n$ of all possible state vectors for an n-component system. The structure function $\varphi : \{0,1\}^n \rightarrow \{0,1\}$ is a mapping that associates those state vectors X for which the system works with the value 1 and those state vectors X for which the system fails with the value 0 [10].

Definition. Let τ represent a coherent system of order n. Assume that the lifetimes of the system's n components are independent and identically distributed (i.i.d.) according to the (continuous) distribution F. The signature of the system τ, denoted by s_τ , or simply by s when the corresponding system is clear from the context, is an n-dimensional probability vector whose ith element s_i is equal to the probability that the ith component failure causes the system to fail. In brief, $s_i = P(T = X_{i:n})$, where T is the failure time of the system and $X_{i:n}$ is the ith order statistic of the n component failure times, that is, the time of the ith component failure [10].

The concept of system signature was introduced for evaluating the reliability of a system consisting of m components having iid failure times [11]. System signature possesses the unique feature of segregating the system structure from the random failure times of the components.

A. System Survival Signature

A closely related concept of system signature has recently been introduced for dealing with different types of components within a system [12]. Let $\Phi(l)$, for $l = 0,1,2,..,m$, denote the probability that the system is working when l of the components are working. The concept is restricted to coherent systems which means that $\Phi(l)$ is an increasing function of l assuming that $\Phi(0) = 0$ and $\Phi(m) = 1$. There are $\binom{m}{l}$ state vectors $\underline{x}$ with precisely l components $x_i = 1$, so with $\sum_{i=1}^{m} x_i = l$; the set of these state vectors are denoted by S_l. Because of iid assumption for the failure times of m components, all the state vectors are equally likely to happen, therefore

$$\Phi(l) = \binom{m}{l}^{-1} \sum_{\underline{x} \in S_l} \Phi(\underline{x}) \qquad (1)$$

Let $C_t \in \{0,1,\dots,m\}$ denote the number of components working in the system at time $t > 0$ and F(t) be the cumulative distribution function of the failure time of the components, then for $l \in \{0,1,..,m\}$

$$P(C_t = l) = \binom{m}{l} [F(t)]^{m-l} [1 - F(t)]^{l} \qquad (2)$$

$$P(T_S > t) = \sum_{l=0}^{m} \Phi(l) P(C_t = l) \qquad (3)$$

B. Systems with Multiple Types of Components

Let $\Phi(l_1, l_2, \dots, l_K)$ for $l_k = 0,1,2,..,m_k$, denote the probability (system survival signature) that the system is working when l_k of the components of type k are working for each $k \in \{1,2,\dots,K\}$. There are $\binom{m_k}{l_k}$ state vectors $\underline{x}^k$ with precisely l_k of its m_k components $x_i{}^k = 1$, so with $\sum_{i=1}^{m_k} x_i{}^k = l_k$; the set of these state vectors of components of type k are denoted by $S_l{}^k$ while $S_{l_1, l_2, \dots, l_k}$ indicates the set of all state vectors of the system for which $\sum_{i=1}^{m_k} x_i{}^k = l_k, k = 1,2,\dots,K$. Because of iid assumption for the failure times of m_k components of type k, all the state vectors $\underline{x}^k \in S_l{}^k$ are equally likely to happen, therefore

$$\Phi(l_1, \dots, l_K) = \left[\prod_{k=1}^{K} \binom{m_k}{l_k}^{-1}\right] \times \sum_{\underline{x} \in S_{l_1, l_2, \dots, l_k}} \Phi(\underline{x}) \qquad (4)$$

Let $C_t{}^k \in \{0,1,\dots,m_k\}$ denote the number of components of type k working in the system at time $t > 0$ and $F_k(t)$ be the cumulative distribution function of the failure time of the components, then for $l_k \in \{0,1,..,m_k\}, k = 1,2,\dots,K$

$$P\Big(\bigcap_{k=1,\dots,K} \{C_t{}^k = l_k\}\Big) = \prod_{k=1}^{K} P(C_t{}^k = l_k)$$

$$= \prod_{k=1}^{K} \binom{m_k}{l_k} [F_k(t)]^{m_k - l_k} [1 - F_k(t)]^{l_k} \qquad (5)$$

$$P(T_S > t) = \sum_{l_1=0}^{m_1} \dots \sum_{l_K=0}^{m_K} \Phi(l_1, \dots, l_K) P\Big(\bigcap_{k=1}^{K} \{C_t{}^k = l_k\}\Big)$$

$$= \sum_{l_1=0}^{m_1} \dots \sum_{l_K=0}^{m_K} \Big[\Phi(l_1, \dots, l_K) \prod_{k=1}^{K} P(C_t{}^k = l_k)\Big]$$

$$= \sum_{l_1=0}^{m_1} \dots \sum_{l_K=0}^{m_K} \Big[\Phi(l_1, \dots, l_K) \prod_{k=1}^{K} \Big\{\binom{m_k}{l_k} [F_k(t)]^{m_k - l_k} [1 - F_k(t)]^{l_k}\Big\}\Big] \qquad (6)$$

Equation (6) represents the survival function of the system segregating the survival signature of the system from the probability of the failure times of individual group of components. It is the unique feature of this technique that once the survival signature of the complete network is determined, different probability distributions of the failure time of components can be examined for the analysis of system reliability. Furthermore, the importance of specific group of components can be visualized through simulation of the model.

III. RISK IMPORTANCE MEASURES

There are a few significant importance measures in the field of risk and reliability [13]. The existing importance measures have been adapted for their application in the field of supply network reliability as shown in Table I.

TABLE I. RISK IMPORTANCE MEASURES

Measure	**Abbreviation**	**Principle**	**Adaptation to System Survival**
Risk reduction	RR	$R(base) - R(x_i = 0)$	$S(l_k = m_k) - S(base)$
Fussel-Vesely	FV	$\frac{R(base) - R(x_i = 0)}{R(base)}$	$\frac{S(l_k = m_k) - S(base)}{1 - S(base)}$
Risk achievement worth	RAW	$\frac{R(x_i = 1)}{R(base)}$	$\frac{1 - S(l_k = 0)}{1 - S(base)}$
Birnbaum importance	BI	$R(x_i = 1) - R(x_i = 0)$	$S(l_k = m_k) - S(l_k = 0)$

Following definitions are used in Table I.

- $R(x_i = 1)$: the increased risk level without basic event x_i or with basic event x_i assumed failed,
- $R(x_i = 0)$: the decreased risk level with the basic event x_i optimised or assumed to be perfectly reliable,
- $R(base)$: the present risk level,
- $S(l_k = 0)$: the decreased system survival probability with the disruption of m_k components,
- $S(l_k = m_k)$: the increased system survival probability with all m_k components working,
- $S(base)$: the present system survival probability,

The RAW presents a measure of the 'worth' of the type of components in 'achieving' the current value of risk and represents the importance of maintaining the current level of reliability for the type of components. The risk measures contain important information for the managers in taking appropriate strategic decisions as shown in Table II. The same table has been adapted for application in the realm of supply network as shown in Table III.

TABLE II. INFORMATION IN RISK MEASURES [13]

Risk significance FV	**Safety significance BI**	**Potential for safety improvement**	**Potential for relaxation**
High	High	Component, defence in depth	No
High	Low	Component	No
Low	High	Do not degrade component	No
Low	Low	No	Component, defence in depth

TABLE III. INFORMATION IN RISK MEASURES FOR SUPPLY NETWORK STRATEGIES

Risk significance FV	**Safety significance BI**	**Potential for improvement**	**Potential for relaxation**
High	High	Supplier, network structure	No
High	Low	Supplier	No
Low	High	Maintain risk profile of supplier	No
Low	Low	No	Supplier, Network structure

IV. APPLICATION OF SYSTEM SURVIVAL SIGNATURE IN SUPPLY NETWORK

A. *Example No. 1*

We apply the concepts of system survival signature and risk importance measures in the realm of supply network. In order to facilitate clear understanding of the concepts, we present two example models. The first example illustrating a supply network is shown in Fig. 1. The suppliers have been segregated into three groups on the basis of their risk profiles. In order to calculate the survival signature, the network was modeled in R software using the 'ReliabilityTheory' package [14]. The resulting network obtained through running of the code is shown in Fig. 2.

The survival function (non-zero values) calculated in R software is shown in Table IV (Appendix). A code was developed in Matlab R2009a for the detailed analysis of the network reliability. The probability distributions representing the risk profiles of different types of suppliers were assumed as exponential. Firstly, in order to calculate the impact of the reliability of each type of suppliers on the overall reliability of the network, the specific supplier was assumed to be perfectly reliable with the survival distributions of other two types fixed at their current level. The results of the simulation are depicted in Fig. 3. Type 3 suppliers were assumed to be most reliable. The improvement in the network reliability can be observed through the displacement of system reliability curve towards the right. It is evident that Type 2 suppliers have the major impact on the system reliability.

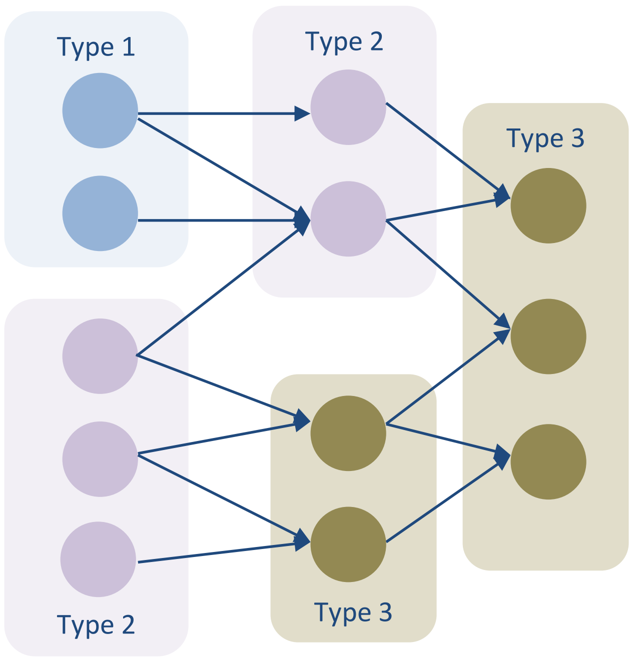

Fig. 1. Supply network representing groups of risk profiles.

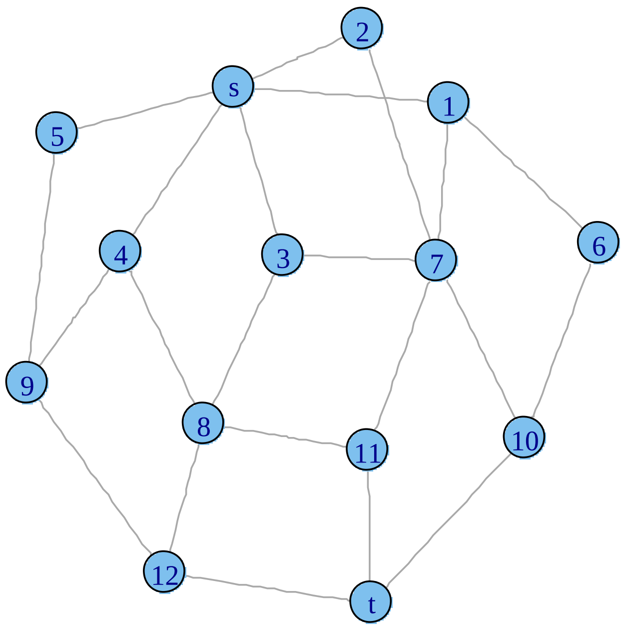

Fig. 2. Network schematic in R software.

In order to compare the different types of suppliers on the basis of network configuration, we assign same probability distribution to each type of suppliers. The impact of the reliability of each type of suppliers on the overall reliability of the network is determined through the same procedure as described earlier. The results depicted in Fig. 4 clearly reveal that the Type 3 suppliers have the major impact on the overall reliability of the system.

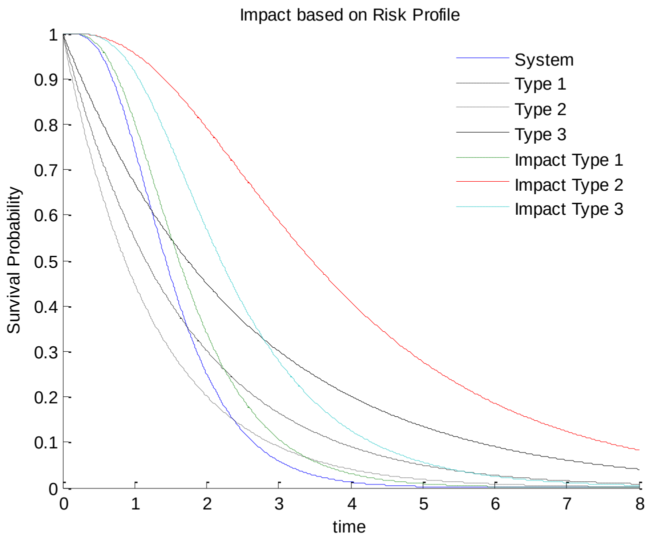

Fig. 3. Impact of supplier type on the basis of risk profile.

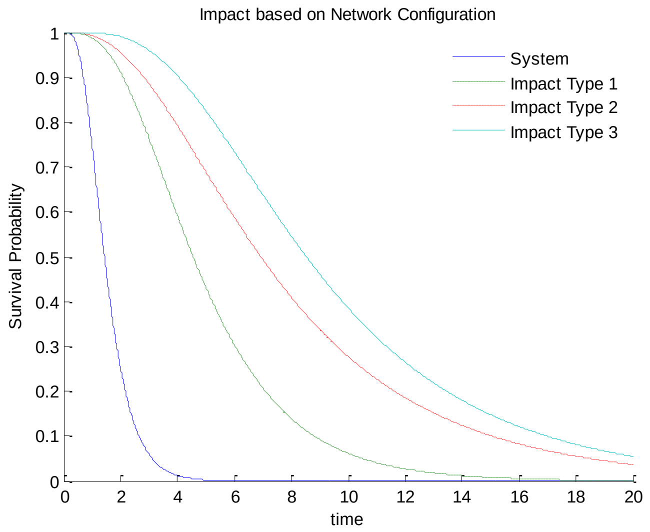

Fig. 4. Impact of supplier type on the basis of network configuration.

Now, we consider discrete reliability values for each type of suppliers. The reliability values of the three types of suppliers are assumed as 0.6, 0.3 and 0.9 respectively. The reliability of the network is calculated as 0.75. The impact of the reliability of each type of suppliers on the overall reliability of the supply network is shown in Fig. 5. It is evident that Type 2 suppliers have the major impact while the Type 1 suppliers control the overall reliability within a limited range.

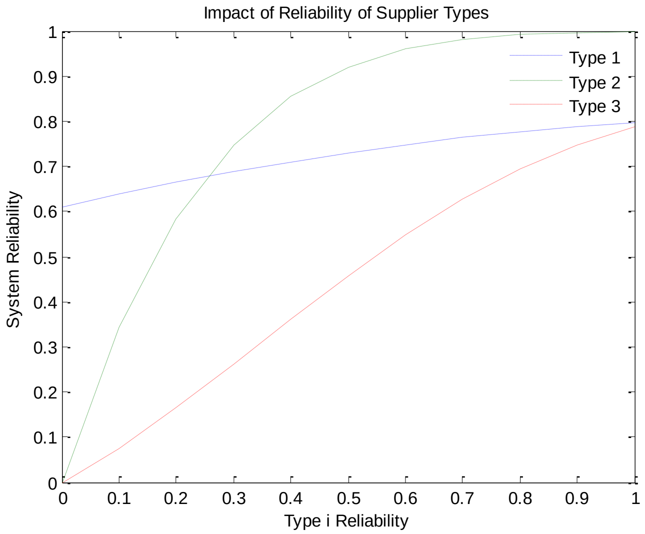

Fig. 5. Impact of supplier type reliability on the network reliability.

The risk importance measures are calculated for each type of suppliers as shown in Fig. 6. Type 2 suppliers have high values for all the three measures of Fussel-Vesely (FV), Risk achievement worth (RAW) and Birnbaum importance (BI). Type 1 suppliers have got low values in all the three measures.

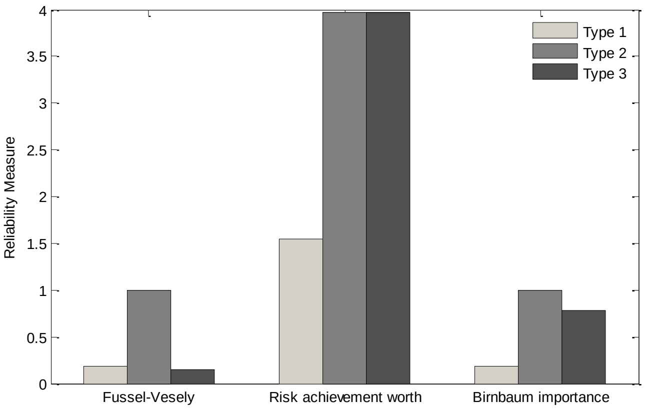

Fig. 6. Risk importance measures.

The risk measures have been explained with the help of system reliability graph as shown in Fig. 7. The FV value of each type of suppliers is directly proportional to the relative difference between the current system reliability value and the one corresponding to the perfect reliability of the specific type of supplier. The BI value corresponds to the difference between the system reliability values relative to the two extreme reliability states of each type of suppliers. RAW value is proportional to the deviation of the current system reliability from the one corresponding to the absolute unreliable state of each type of suppliers.

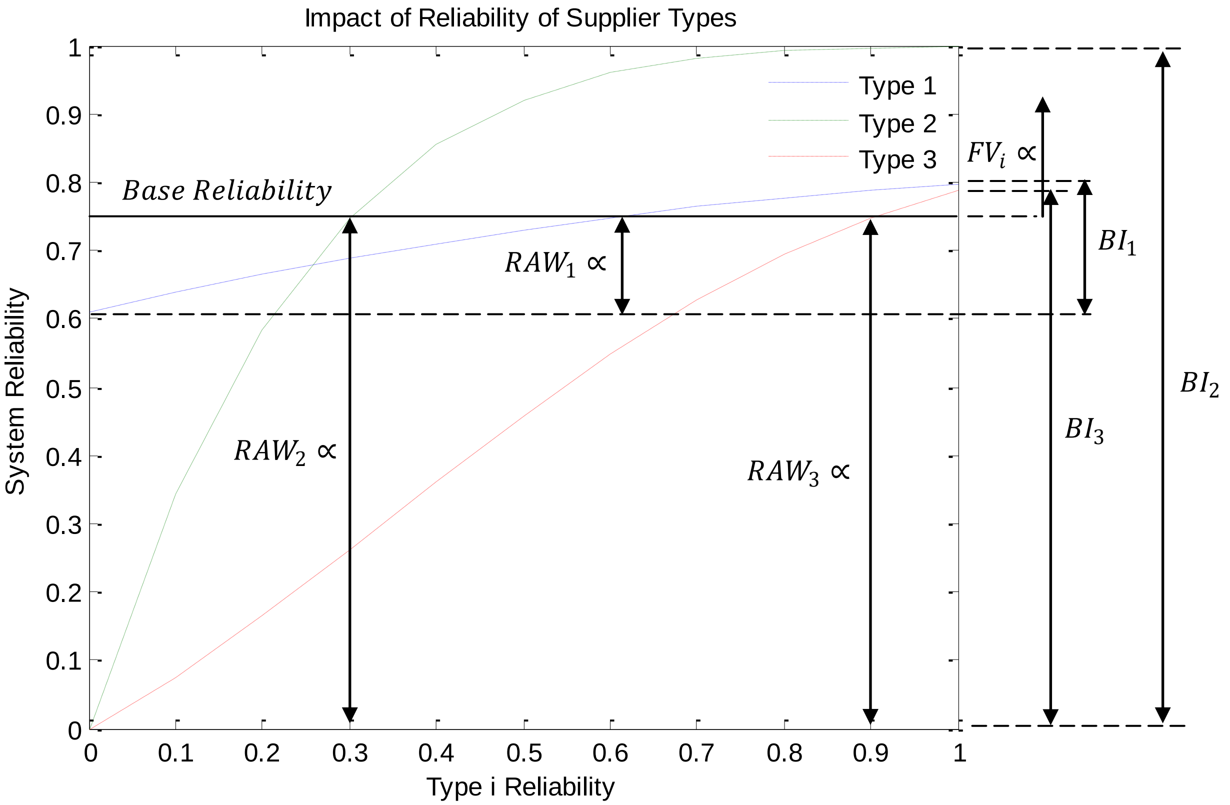

Fig. 7. Representation of risk importance measures.

The reliability targets can be allocated between the supplier types based on the desired system reliability. The contour plots of the reliability allocation between two types of suppliers keeping the constant reliability values of Types 3, 2 and 1 suppliers are shown in Fig. 8, 9 and 10 respectively. Type 2 and 3 suppliers have dominant impact on the overall system reliability.

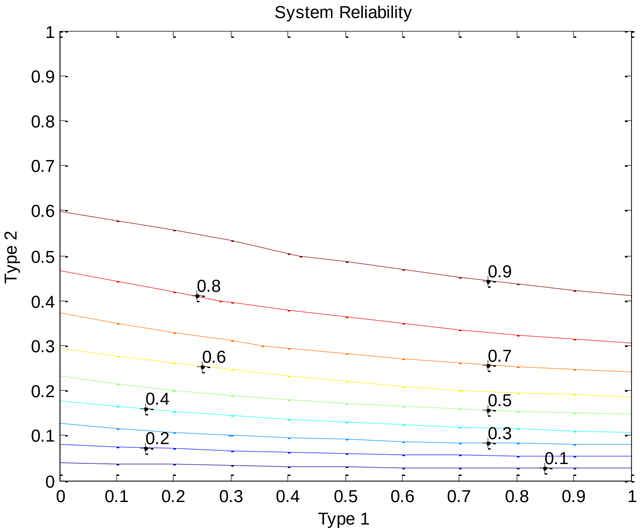

Fig. 8. Reliability allocation between types 1 and 2 suppliers.

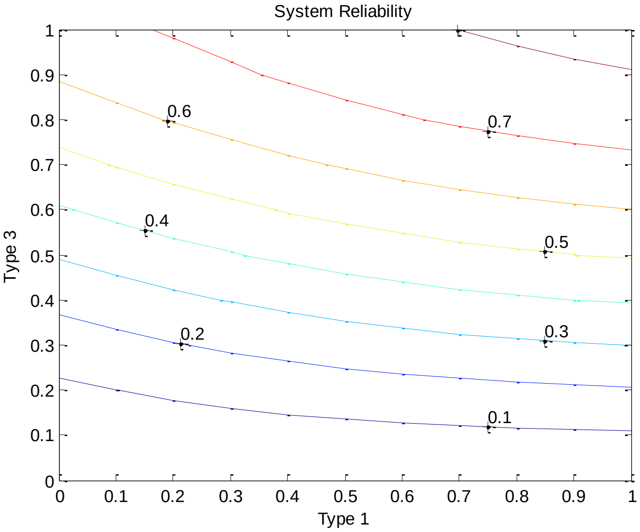

Fig. 9. Reliability allocation between types 1 and 3 suppliers.

B. *Example No. 2*

In the second example, the suppliers have been segregated into four groups on the basis of their risk profiles as shown in Fig. 11. The resulting network obtained through the R software is shown in Fig. 12.

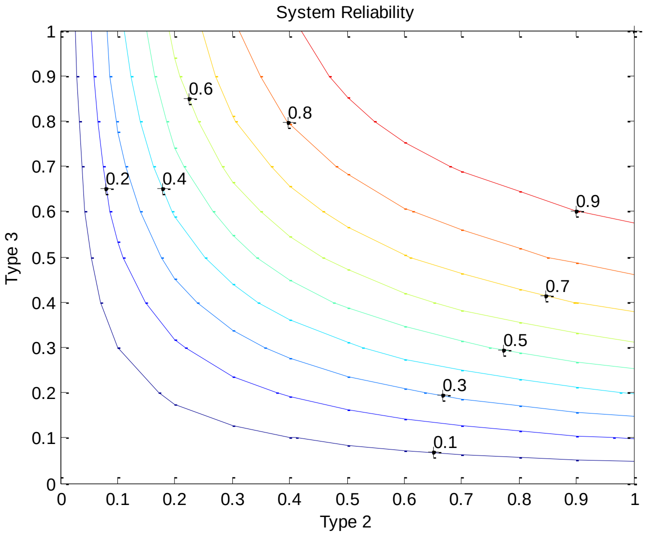

Fig. 10. Reliability allocation between types 2 and 3 suppliers.

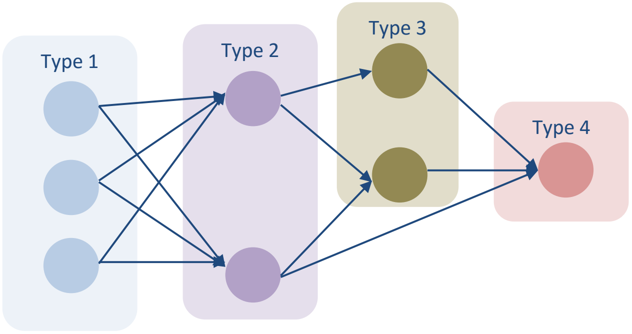

Fig. 11. Supply network representing groups of risk profiles.

The survival function (non-zero values) calculated in R software is shown in Table V (Appendix). The probability distributions representing the risk profiles of different types of suppliers were assumed as exponential. The survival probability of each type of suppliers and that of the system are shown in Fig. 13. The relative impact of the reliability of each type of suppliers on the network reliability is depicted in Fig. 14. It is evident that Type 2 suppliers have the major impact on the system reliability.

The network configuration based impact of the reliability of each type of suppliers on the overall reliability of the network is shown in Fig. 15. The results reveal that the Type 4 suppliers have the major impact on the overall reliability of the system.

Now, we consider discrete reliability values for each type of suppliers. The reliability values of the four types of suppliers are assumed as 0.7, 0.5, 0.8 and 0.6 respectively. The reliability of the network is calculated as 0.432. The impact of the reliability of each type of suppliers on the overall reliability of the supply network is shown in Fig. 16. It is evident that Type 4 suppliers have the major impact while the Type 3 suppliers control the overall reliability within a limited range.

The risk importance measures are calculated for each type of the suppliers as shown in Fig. 17. Type 4 suppliers have highest values for all the three measures of Fussel-Vesely (FV), Risk achievement worth (RAW) and Birnbaum importance (BI). Type 3 suppliers have the lowest values in all the three measures.

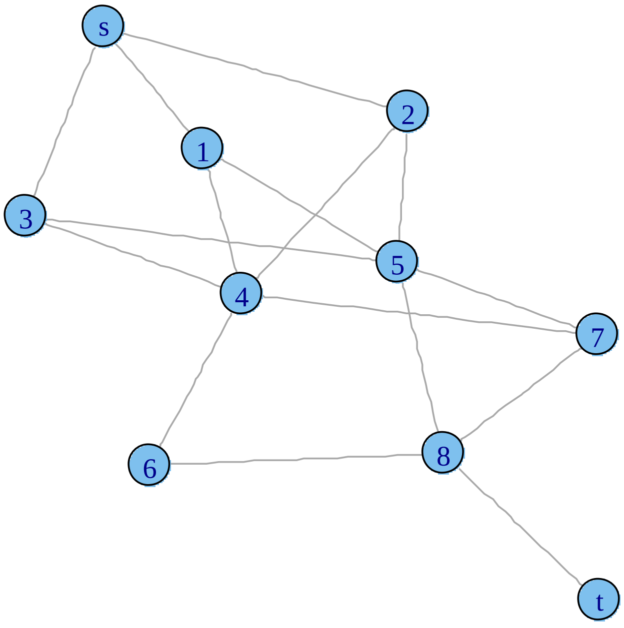

Fig. 12. Network schematic in R software.

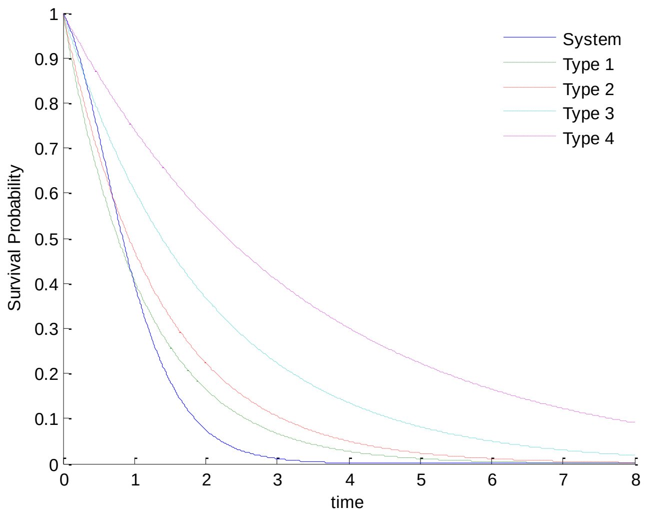

Fig. 13. Survival probabilities based on exponential distribution.

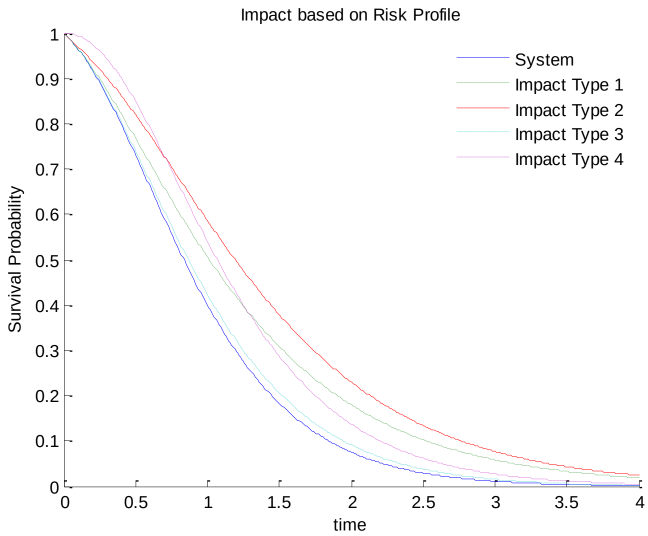

Fig. 14. Impact of supplier type on the basis of risk profile.

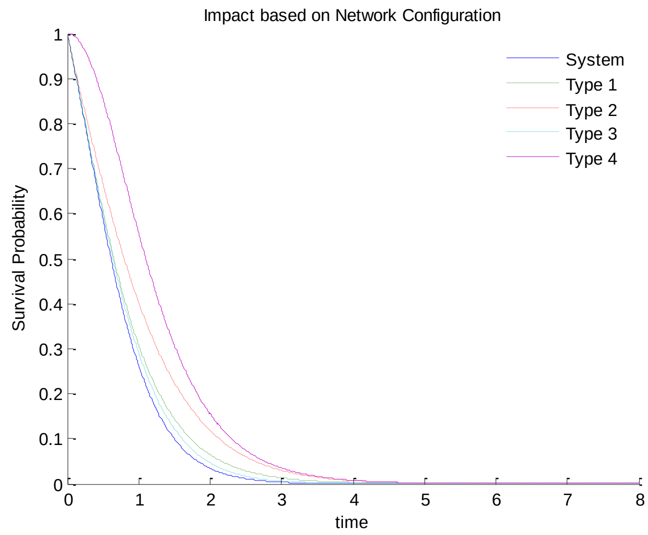

Fig. 15. Impact of supplier type on the basis of network configuration.

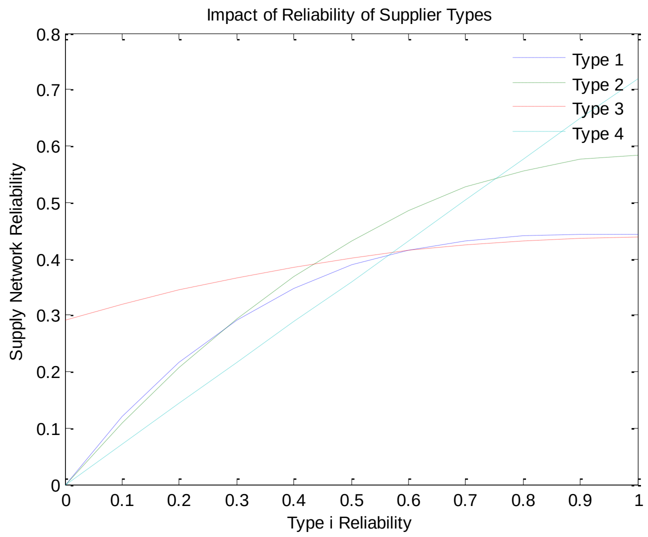

Fig. 16. Impact of supplier type reliability on network reliability.

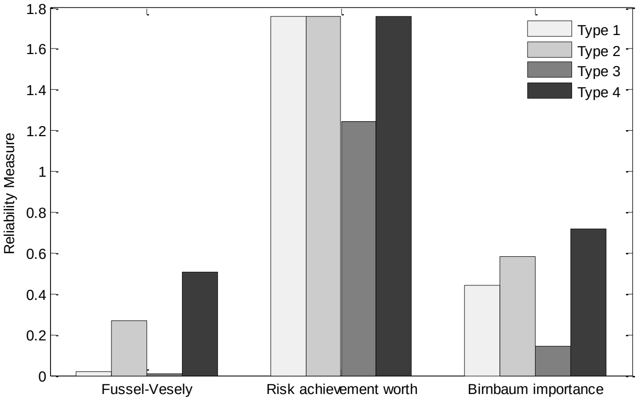

Fig. 17. Risk importance measures.

V. CONCLUSION

Supply chain risk management is a promising research field demanding development and application of robust risk quantification techniques. There is a potential of exploring supply chain risk management through the lens of network reliability theory. We have introduced a novel application of system survival signature in the realm of supply network that presents a unique feature of segregating the network signature from the risk profiles of suppliers. Furthermore, we have adapted the risk importance measures existing in the literature of system reliability for analyzing the supply network reliability and helping managers take strategic decisions pertaining to the network re-configuration and risk profile monitoring of suppliers. The application was demonstrated through two simple examples that helped appreciating the potential of conducting further research in this direction. The analysis also revealed the threshold of certain suppliers in relation to their impact on the overall reliability of the network because of the network survival signature. There is requirement of developing robust techniques for modeling the network survival signature as the complexity of existing supply networks makes it difficult to be calculated through existing algorithm used in ReliabilityTheory package of R software. Furthermore, Bayesian belief network (BBN) modeling technique may be explored for evaluating the risk profiles of suppliers keeping in view the merit of BBNs in dealing with uncertainty and limited or incomplete information.

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BIOGRAPHY

Abroon Qazi received the BE degree in Aerospace Engineering from the National University of Sciences and Technology, Pakistan and the MSc. degree in Mechanical Engineering from the University of Engineering and Technology, Peshawar, Pakistan. At present, he is a research student and tutor in Management Science at the University of Strathclyde, UK. He is interested in modeling supply chain risks associated with new product development. In particular, his research project deals with the investigation of interdependency between supply chain risks using Bayesian Belief Networks and formulation of a fair-sharing strategy to align the conflicting incentives of stakeholders within a supply network using Game Theory. Abroon has won sponsored awards to present at conferences organized by the Chartered Institute of Logistics and Transport (CILT) and International Purchasing and Supply Education and Research Association (IPSERA). He has also qualified all the preliminary exams from the Society of Actuaries, USA.

John Quigley received the B.Math. degree in Actuarial Science from the University of Waterloo, Canada, and the Ph.D. degree in Management Science from the University of Strathclyde, UK. At present, he is a Professor and Director of Research in Management Science at the University of Strathclyde, UK. John's main research interests are in elicitation of prior distributions, statistical inference and applied probability modeling with application areas in risk and reliability. In particular, he is interested in decision support methodologies with few data. He has extensive experience with military, aerospace and railway industries. John is a member of the UK. Safety and Reliability Society, a Chartered Statistician, and an Associate of the Society of Actuaries. He has been involved in consultancy with companies such as MoD, DSTL, Railway Safety Standards Board, BAE SYSTEMS, Goodrich and Siemens.

Alex Dickson received the BA degree in Economics and Finance from Keele University, UK and the MSc. degree in Economics from the University of Manchester, UK. He gained the Ph.D. degree in Economics from the Keele University, UK. At present, Alex is a Senior Lecturer in Economics at the University of Strathclyde, UK. Prior to this, he held a lectureship in Economics at Keele University preceded by a postdoctoral research fellowship at the University of Manchester. His primary research interests are in Microeconomics, in particular in: game theoretic approaches to general and partial models of competitive behavior; aggregative games with applications to contests and strategic market games; endogenous timing in games and commitment; and behavioral economics and game theory. Alex has further broad interests in industrial organization, international trade and applied game theory in general.

APPENDIX

TABLE IV. SURVIVAL SIGNATURE (EXAMPLE 1)

Type 1	Type 2	Type 3	Survival Signature
0	1	2	0.12
0	1	3	0.3
0	1	4	0.48
0	1	5	0.6
0	2	1	0.04
0	2	2	0.27
0	2	3	0.56
0	2	4	0.8
0	2	5	0.9
0	3	1	0.12
0	3	2	0.45
0	3	3	0.75
0	3	4	0.96
0	3	5	1
0	4	1	0.24
0	4	2	0.66
0	4	3	0.88
0	4	4	1
0	4	5	1
0	5	1	0.4
0	5	2	0.9
0	5	3	1
0	5	4	1
0	5	5	1
1	1	1	0.1
1	1	2	0.3
1	1	3	0.54
1	1	4	0.76
1	1	5	0.9
1	2	1	0.19
1	2	2	0.53
1	2	3	0.81
1	2	4	0.97
1	2	5	1
1	3	1	0.27
1	3	2	0.7
1	3	3	0.925
1	3	4	1
1	3	5	1
1	4	1	0.34
1	4	2	0.82
1	4	3	0.97
1	4	4	1
1	4	5	1
1	5	1	0.4
1	5	2	0.9
1	5	3	1
1	5	4	1
1	5	5	1
2	1	1	0.12
2	1	2	0.34
2	1	3	0.6
2	1	4	0.84
2	1	5	1
2	2	1	0.22
2	2	2	0.59
2	2	3	0.87
2	2	4	1
2	2	5	1
2	3	1	0.3
2	3	2	0.76

2	3	3	0.97
2	3	4	1
2	3	5	1
2	4	1	0.36
2	4	2	0.86
2	4	3	1
2	4	4	1
2	4	5	1
2	5	1	0.4
2	5	2	0.9
2	5	3	1
2	5	4	1
2	5	5	1

TABLE V. SURVIVAL SIGNATURE (EXAMPLE 2)

Type 1	**Type 2**	**Type 3**	**Type 4**	**Survival Signature**
1	1	0	1	0.5
1	1	1	1	1
1	1	2	1	1
1	2	0	1	1
1	2	1	1	1
1	2	2	1	1
2	1	0	1	0.5
2	1	1	1	1
2	1	2	1	1
2	2	0	1	1
2	2	1	1	1
2	2	2	1	1
3	1	0	1	0.5
3	1	1	1	1
3	1	2	1	1
3	2	0	1	1
3	2	1	1	1
3	2	2	1	1