Study on supply-chain demand disruption caused by rumor spreading

Haifeng Zhao and Bin Lin (ln315lb122@163.com)
School of Economic and Management, Tongji University, Shanghai, 20092, China

Abstract

Rumor spreading is an important factor resulting in supply chain demand disruption. A supply-chain demand change prediction model is developed based on a new rumor spreading model, Susceptible-Infective-Isolated-Immune (SI2I) model. In this model, the impact of rumors on demand can be quantitatively reflected by the proportion of ignorants and immunes in the population.

Keywords: Supply chain, Demand disruption, Rumor spreading

Introduction

Supply chain risks, vulnerabilities and uncertainties have become topical issues of interest amongst academics and practitioners in the last few years. Supply chains are vulnerable to disruption risks or high-impact, low-likelihood risks, affect organizations in a major way (Chopra and Sodhi 2004, Kleindorfer and Saad 2005). MIT research group on “Supply Chain Response to Global Terrorism” (2003) has distinguished 6 different types of failure modes, i.e. the limited ways in which the disruption affects the supply-chain, those are: “Disruption in supply, Disruption in Transportation, Disruption at facilities, Freight breaches, Disruption in communications and Disruption in Demand”. Although demand disruptions happen infrequently, they have significant impacts on the whole supply chain (Tang 2006). Delay and disruption downstream can lead to the loss of demand, temporarily or permanently, thus affecting all the firms upstream. Many factors result in the demand disruption, such as the global financial crisis, nature disasters and wars. Besides, rumors against products and services also play important roles and should not be ignored. Many well-known companies (e.g., Procter and Gamble, P&G; McDonald's) have been the targets of rumors, sometimes with serious and adverse consequences. Traditionally rumors usually spread by word of mouth, but with the emergence of the Internet and its possibilities new ways of rumor propagation are available, such as writing email, using instant messengers or publishing their thoughts in a blog (Kostka et al. 2008). People create, modify, and share rumors astoundingly fast, easily and unscrupulously on the Internet, due to its anonymity, diversity, instantaneity, and extended capacity to spread. The impact of rumors on consumers' consumption related beliefs and attitudes is bigger than ever before and therefore firms have best reason to study and manage the demand disruption caused by rumor spreading to make loss as little as possible.

From the perspectives of firms, disruption in demand is difficult to manage, because the demand variation is usually nonlinear and hard to predict accurately. In this paper, according to the features of rumors' influence on consumers' attitudes and purchase intention and the mechanism of rumor dissemination, we attempt to build a mathematics model to analyze the variation trend of demand quantitatively under rumor spreading circumstances. The results provide the basis for adopting the supply chain coordination strategies and help to handle the demand uncertainty in an efficient and effective way.

Literature review

It has shown that an important influence on consumer's choice of products is the word-of-mouth (WOM) spread by other consumers (Brown and Reingen 1987, Katz and Lazarsfeld 1955, Reingen and Kernan 1986). WOM communication about products has been shown to influence product evaluation to an even greater extent than information from a well-known objective source—Consumer Reports (Herr et al. 1991). Unlike advertising and other forms of communication; neither the timing nor the content of WOM is under the control of the manufacturer. Compounding this is the fact that WOM communication often includes negative accounts of products or services because consumers often use WOM to express dissatisfaction (Folkes et al. 1987, Richins 1983, Swan et al. 1989). Hence, firms are often particularly concerned about negative WOM, particularly when there is no evidence of its being true—that is, when it is a rumor. Empirical studies have found that negative information (like rumors) is capable of significantly affecting consumers' consumption related beliefs and attitudes. In fact, it has found that negative product information is generally perceived as more diagnostic or informative and weighted more heavily in consumer judgments (Herr et al. 1991). Other research has found negative information results in more strongly held attributions regarding product beliefs than does positive information (Mizerski 1982) and the effect of negative information is more enduring than positive information (Cusumano and Richey 1970, Richins 1983). Researchers have also shown that negative information more strongly influences attitudes and purchase intention than does positive information, particularly in the service sector (Weinberger and Dillon 1980). Kamins et al. (2002) studied the consumer responses to rumors particularly and focused on rumor transmission and beliefs about marketplace rumors held by the public. Consumers reported that they were exposed to and spread more negative than positive rumors.

Daley and Kendall (1964) first studied the phenomenon of rumor spreading and proposed the basic DK model of rumor spreading. In their model, the population is subdivided into three groups: those who are unaware of the rumor (ignorants), those who spread the rumor (spreaders), and those who are aware of the rumor but choose not to spread it (stiflers). Maki and Thomson (1973) later modified the DK model and developed the MK model, in which rumors propagate through direct contact between spreaders and others. The DK and MK models have been used extensively for quantitative studies of rumor spreading (Csanyi and Szendroi 2004, Gu et al. 2008, Lefevre and Picard 1994, Newman et al. 2002, Pittel 1990, Wang et al. 2006), but major shortcomings of these models were that they either neglected the topological characteristics of social networks or some of these models were not suitable for large-scale spreading process. Zanette (2001, 2002) and Buzna et al. (2006) established a rumor spreading model on small-world networks and provided a threshold of rumor spreading. Moreno (2004) studied the stochastic MK model on scale-free networks and insisted that the uniformity of networks had a significant impact on the dynamic mechanism of rumor spreading. Nekovee et al. (2007) and Isham et al. (2010) built a new model by combining the MK model with the SIR (Susceptible, Infected, and Recovered) epidemic model on complex networks and, furthermore, derived the rumor spreading mean-field equations and investigated the steady state of rumors on general complex networks. Zhao et al. (2011, 2012) analyzed the dynamics of rumor spreading on homogeneous networks considering the forgetting mechanism, and concluded that the final state of stiflers depends greatly on the average degree of networks.

As a result, a large body of research has shown that rumors (negative) have a great impact on consumers' attitudes and purchasing intention. Moreover, consumers do at times believe and are willing to spread rumors. In addition, several models regarding rumor spreading have been built, which provide a basis for building a mathematics model for quantitative analysis of demand disruption caused by rumor spreading.

Model development

The dynamic behavior of rumor spreading assembles the SIR epidemic spreading model. The entire population is divided into three groups that are S, I, R. Here S, I, R stand for the people who are spreading rumor (Spreaders, similar to Infective), those who never heard rumor (Ignorants, similar to Susceptible), and the ones who heard rumor but do not spread it (Stiflers, Similar to Removed), respectively. The tendency of individuals to accept a rumor with a certain probability depends on the importance and credibility of the rumor. On the other hand, individuals no longer spread a rumor when they know the rumor is outdated or wrong. The spreading process starts with one or more individuals being informed of a rumor and terminates when no spreaders are left in the population. Besides, the spreaders may stop spreading a rumor spontaneously at a certain rate in consideration of forgetting mechanism. The rules of SIR rumor spreading with forgetting mechanism (Zhao et al. 2013) are as follows. ①When a spreader contacts with an ignorant, the ignorant becomes a spreader or a stifler with a certain probability respectively. ②When a spreader contacts with another spreader, the initiating spreader becomes a stifler with a certain probability. ③When a spreader contacts with a stifler, the initiating spreader becomes a stifler with a certain probability. ④The spreaders become stiflers spontaneously at a certain rate.

In the SIR model, we consider that stiflers choose not to propagate a rumor because of disbelief or uninterest (Zhao et al. 2013). Here we define the stiflers who believe the rumor but have no interest in spreading it as isolators (O); the stiflers who don't believe the rumor as immunes (M). In reality, the choices of these two groups are different after rumor spreading. The immunes will still purchase products and services, but the isolators will not. Hence, besides ignorants, the immunes are the only individuals who still keep beliefs and purchasing intention, and obviously, the demand of consumers is tightly connected with the number of ignorants and immunes in the population. In addition, generally, the positive influence between spreaders is much bigger than the negative influence in the marketplace. Hence, we suppose that a spreader will continue to spread rumors when he/she contacts another spreader.

As a result, we build a new rumor spreading model called Susceptible-Infective-Isolated-Immune (SI2I) model. In this model, a population is divided into four groups, ignorants, spreaders, isolators and immunes (represented by I, S, O, and M, respectively), according to the perception and reaction of an individual to a rumor. Rumors spread and fade away through contact between different individuals. As shown in Fig.1, The SI2I rumor spreading rules can be summarized as follows. ①When an ignorant contacts a spreader, the ignorant becomes a spreader with probability λ, namely spreading rate. ②When an ignorant contacts a spreader, the ignorant becomes an isolator due to uninterest or an immune due to disbelief, with probability β, φ, respectively; and obviously, $\beta + \varphi = 1-\lambda$, namely refusing rate. ③When a spreader contacts an isolator, the initial spreader becomes an isolator with probability γ. ④When a spreader contacts an immune, the initial spreader becomes an immune with probability θ. ⑤Spreaders spontaneously become isolators at a rate δ because of losing interest or forgetting.

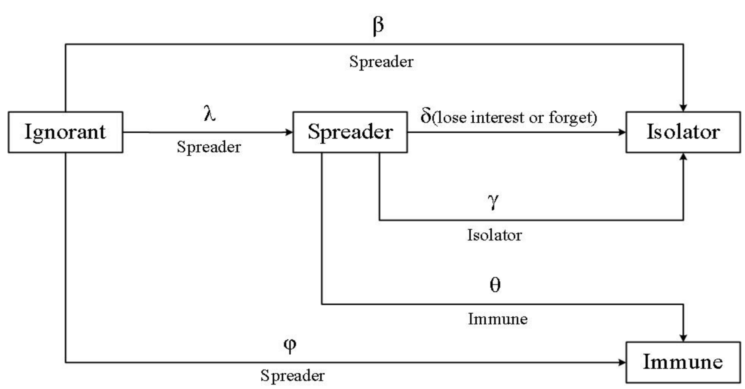

Fig 1 – Structure of the SI2I model for the rumor spreading process.

We consider a closed and homogeneously mixed population consisting of N individuals as a social network where individuals are vertices and contacts between people are edges. Then, an undirected graph G = (V, E) can be obtained, where V is the set of vertices and E is the set of edges. As we all know, a general social network is not a regular network; nevertheless, it should be noted that the number of people that each individual directly contacts in reality is substantially close, and the number approximates a Poisson distribution. Hence, rumor spreading based on the SI2I model will be discussed on a homogenous network in this paper. I(t), S(t), O(t), M(t) denote the density of population that are ignorants, spreaders, isolators, and immunes at time t, respectively. They satisfy the normalization condition: $I(t) + S(t) + O(t) + M(t) = 1$, $I(t), S(t), O(t), M(t) \geq 0$.

In the light of the SI2I rumor spreading process elaborated above, the mean-field equations can be acquired as follows:

$$dI(t)/dt = -\langle k\rangle I(t)S(t) \quad (1)$$
$$dS(t)/dt = \lambda\langle k\rangle I(t)S(t) - \langle k\rangle S(t)(\gamma O(t) + \theta M(t)) - \delta S(t) \quad (2)$$
$$dO(t)/dt = \beta\langle k\rangle I(t)S(t) + \gamma\langle k\rangle S(t)O(t) + \delta S(t) \quad (3)$$
$$dM(t)/dt = \varphi\langle k\rangle I(t)S(t) + \theta\langle k\rangle S(t)M(t) \quad (4)$$

Here $\langle k\rangle$ denotes the average degree of the network.

In the initial period of rumor spreading, there are very few people who know the rumor; thus, they become spreaders, as everyone has the desire to disseminate the rumor. So here is a hypothesis that there is only one spreader at first, and all the other people are ignorants.

Hence, the initial condition for SI2I rumor spreading model is $I(0) = (N-1)/N$, $S(0) = 1/N$, $O(0) = M(0) = 0$.

We assume that each ignorant is a potential consumer, and the unit demand is denoted by q, thus the total demand of the population before rumor spreading is $Q = Nq$.

From the perspectives of enterprises, only ignorants and immunes will still purchase their products and services, so, at time t, the total demand is $Q(t) = Q_0\big(I(t) + M(t)\big)$.

Here Q_0 denotes the total demand in the initial period of rumor spreading, and obviously, $Q_0 = (N-1)q$.

Numerical simulation

The Runge-Kutta method can be used to solve the differential equations (3)-(6) and analyze the effects on demand by the rumor spreading process. According to the above description in Section 3, here a homogeneous network is constructed, which consists of N individuals, and the demand of each individual is q. In the following simulation we assume the size of network $N = 10^6$, the average degree $\langle k\rangle = 10$, the unit demand $q = 1$, and in the initial condition there is only one spreader in the network, thus $S(0) = \frac{1}{10^6}$, $I(0) = \frac{10^6-1}{10^6}$, $O(0) = 0$, $M(0) = 0$, and $Q_0 = 10^6 - 1$.

Fig 2 shows the general variation trends of the four kinds of agents in the SI2I rumor spreading model. From Fig 2 we can find there is a sharp increase in the number of spreaders as spreaders begin to propagate a rumor. With further spreading of the rumor, the number of spreaders reaches a peak and thereafter declines until it becomes zero, which marks the termination of rumor spreading. In this whole process, the number of ignorants always reduces while the number of isolators and immunes always increases until they reach the balance, respectively.

Fig 3 shows the general variation trend of total demand change with the rumor spreading process. From Fig 3 we can find there are two kinds of shape of total demand change curve depending on propagation parameters $(\lambda, \beta, \varphi, \delta, \gamma, \theta)$. The red solid line represents the scenario with $\lambda = 0.6, \beta = \varphi = 0.2, \delta = 0.3, \gamma = 0.7, \theta = 0.3$. In this scenario, the total demand always reduces in the whole process. The variation trend of total demand is similar to that of the ignorants (Fig 3). The blue solid line represents another scenario with $\lambda = 0.8, \beta = \varphi = 0.1, \delta = 0.5, \gamma = 0.3, \theta = 0.7$. In this scenario, the total demand sharply decreases at first and then bottoms out to a higher value. The minimum value of total demand $\min\{Q(t)\}$ can be used to measure the maximum rumor influence and the steady-state value of it can be used to measure the final influence. It is determined by spreading parameters whether the lowest point of total demand appears in the valley or in the steady-state.

Fig 4 shows the total demand along with δ when $\lambda, \beta, \varphi, \gamma,$ and θ are fixed to 0.8, 0.1, 0.1, 0.3 and 0.3. Clearly, the bigger the value of δ, when other parameters are fixed, the smaller the rumor’s influence on demand. In reality, along with the increase of δ, the probability that spreaders lose interest in or forget about the rumor increases if the rumor itself is not absorbing, for example. As a result, the number of spreaders reduces, which leads to the decrease of the rumor influence on demand. At the same time, the number of isolators increases as same as that of spreaders decreases. When a spreader contacts an isolator, he/she becomes an isolator with probability 30%. Along with the increase of the number of isolators, the rumor influence on demand is further weakened.

In Fig 5, given the other parameters are fixed, the bigger the value of γ, the bigger the rumor’s influence on demand. In reality, with a higher γ, isolators can make more spreaders into isolators, which leads to smaller number of the spreaders and makes the rumor spreading process reach steady faster. However, once a spreader becomes an isolator, he/she will never have a chance to contact an immune, which means that the spreader will never know the truth and wake up. From the perspective of companies, though isolators don’t propagate a rumor again, they still believe it and don’t purchase any product or service. If isolators have stronger influence on spreaders, the rumor termination time comes earlier but the final demand becomes smaller.

Fig 6 illustrates how the total demand changes with the parameter θ over time, when the other parameters are fixed. Clearly, the bigger the value of θ, the smaller the rumor influence on demand, but the longer time it takes for the rumor to terminate. In reality, when the immunes contact the spreaders, they will not be affected by the rumor, due to their full internal information, strong expertise or high social responsibility (such as insiders, experts and government officers).

A larger θ means that immunes have higher credibility; they can make more spreaders change into immunes, and therefore, decrease the influence of the rumor on demand.

Fig 7 describes how the total demand changes over time for different spreading rate λ. Distinctly, compared with other parameters, the change of total demand along with the spreading rate is more dramatic. From Fig 7, we can see that the bigger the value of λ, the smaller the value of total demand as the rumor spreading reaches the equilibrium. Furthermore, a higher λ means that the value of total demand begins to decline earlier and reaches the lowest point faster. In reality, with a high spreading rate and low refusing rates, when the ignorants contact the spreaders, they are easily deceived and incited by the spreaders, and, then they will propagate the rumor as well. With more ignorants turning into spreaders, the rumor takes off widely and rapidly, which leads to the significant decline of demand.

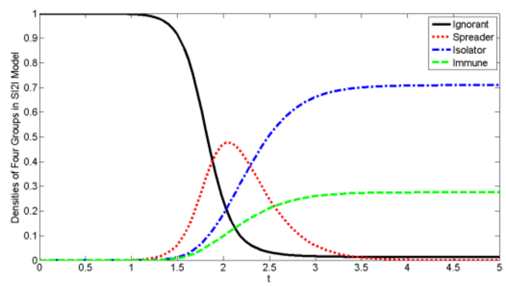

Fig 2 – Plot of the densities of ignorants I(t), spreaders S(t), isolators O(t), and immunes M(t) versus system time t with $\lambda = 0.8, \beta = \varphi = 0.1, \delta = 0.5, \gamma = \theta = 0.3$.

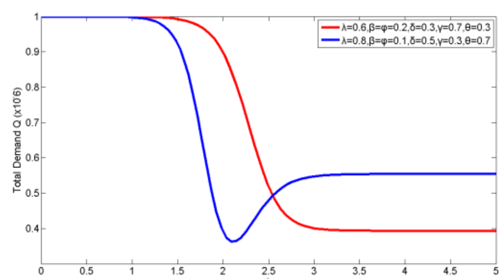

Fig 3 – Plot of the total demand Q(t)(×10^-6) versus system time t with $\lambda = 0.6, \beta = \varphi = 0.2, \delta = 0.3, \gamma = 0.7, \theta = 0.3$ *and* $\lambda = 0.8, \beta = \varphi = 0.1, \delta = 0.5, \gamma = 0.3, \theta = 0.7$

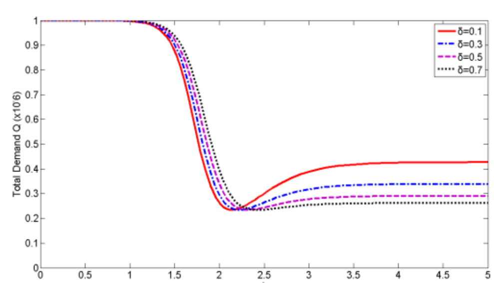

Fig 4 – Plot of the total demand Q(t) (×10^-6) versus system time t along with the forgetting rate δ*, where* $\lambda = 0.8, \beta = \varphi = 0.1, \gamma = \theta = 0.3.$

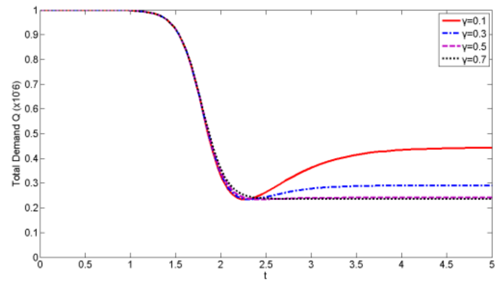

Fig 5 – Plot of the total demand Q(t) (×10^-6) versus system time t along with the probability that a spreader turns into an isolator when he/she contacts an isolator γ*, where* $\lambda = 0.8, \beta = \varphi = 0.1, \delta = 0.5, \theta = 0.3.$

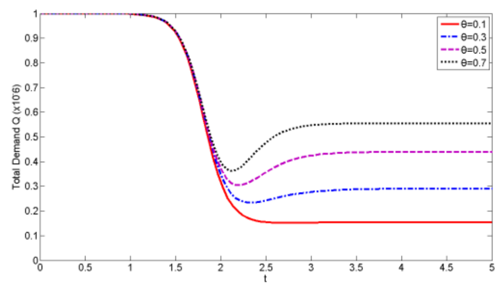

Fig 6 – Plot of the total demand Q(t) (×10^-6) versus system time t along with the probability that a spreader turns into an immune when he/she contacts an immune θ*, where* $\lambda = 0.8, \beta = \varphi = 0.1, \delta = 0.5, \gamma = 0.3.$

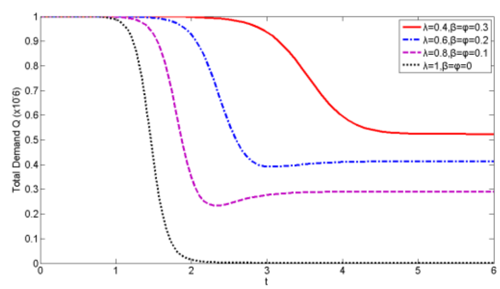

Fig 7 – Plot of the total demand Q(t) (×10^-6) versus system time t along with the spreading rate λ*, where* $\beta = \varphi = (1-\lambda)/2, \delta = 0.5, \gamma = \theta = 0.3.$

Conclusions

In this paper, we have investigated the supply-chain demand disruption problem caused by rumor spreading. Firstly, a mathematics model for quantitative analysis of demand disruption caused by rumor spreading was developed based on the SI2I rumor spreading model. Then, through the numerical simulation, the variation trend of demand along with time was described and the effects of propagation parameters on the variation trend of demand were discussed.

Our research could offer a new method for company managers to predict the variation trend of demand and estimate the final value of demand loss, as the firm is hounded by rumors. Equipped such knowledge, the managers could take measures to manage supply chain more accurately and effectively, which helps to avoid or reduce losses and control the impact on the whole supply chain caused by rumor spreading.

In the present work, we assumed the underlying network to be homogenous. In reality, however, many social and communication networks have different topologies. In addition, faced with a rumor, it is certain that the firm will issue an official statement to clear the air and refute the rumor; in this case, the right information and the rumor both spread in the network at the same time, and the variation trend of demand must be different. We aim to tackle these problems in future work.

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