Logist. Res. (2013) 6:3–15
DOI 10.1007/s12159-012-0083-z

ORIGINAL PAPER

Understanding demand volatility in supply chains through the vibrations analogy—the onion supply case

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Received: 3 October 2011 / Accepted: 25 June 2012 / Published online: 8 July 2012

Abstract Fluctuating demand for goods in many situations is not caused by genuine discontinuities in the consumption or usage of those goods. Basic food products, for example, are consumed at relatively stable rates. But disruptions in their supply—real or imputed—may cause demand volatility with consequences of unwanted price fluctuations. In this paper, the vibrations analogy is proposed to better understand this phenomenon. Various alternative scenarios of damping vibrations are discussed in this paper, viz., underdamped, overdamped, and critically damped system. An interpretation of those scenarios is offered with respect to their meaning to supply chain management and illustrated through the case of the onion supply. The proposed analogy is found to be useful in explaining and taking appropriate steps for improvement in such cases.

Keywords Supply chain · Vibrations analogy · Supply disruption · Volatility · Damping · Onion supply

1 Agricultural supply chains and the promise of an alternative analytical approach

In recent years, supply chain management has emerged as one of the most important functions in business. From oil rigs to onion farms, supply chains are now being considered as most critical for the successful integration of business functions across the globe. Arshinder et al. [1], De Treville et al. [7] and Vonderembse et al. [40] have emphasized supply network designs, strategies and practices as essential elements of business strategy in the rapidly changing world of sourcing, production and distribution.

A supply chain links a network of companies, forming multiple tiers. In normal course, the customers are getting their desired product on time, at appropriate price and in sought quantities. But disruptions and delays occur at times. Disruptions and delays have been discussed by Chopra and Sodhi [4] among different categories of risk. Dependence on fewer sources of supply [36] is considered as one of the several drivers of disruption risk. Poor quality or yield at supply source is mentioned as another potential driver of risk. To support the process of value creation to customers in complex supply chains, information needs to be utilized and exchanged in buyer–supplier relationship [12, 25, 26]. The more tightly coupled the business processes are, the more the information sharing is required, as studies in a manufacturing context have shown [31, 35, 37, 38, 41].

Flexibility of demand has been considered [29]. Phenomena of unwanted supply chain fluctuations have also been incorporated in a different line of research, that is, the bullwhip effect and supply chain issues among others [5, 8, 13–15, 17, 22]. The objective of the present paper was not to review the bullwhip effect and related research in detail. This is because of certain significant differences of the present analogy approach from the discussed stream. Particularly in the traditional bullwhip effect literature, demand or order amplification is discussed as movement is made toward upstream in the chain. Analysis may pertain to the managerial discussion in a highly organized industrial chain or modeling approach limited by the assumptions. The setting may also be limited by one firm in each tier with two or more number of levels in the chain.

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The present paper focuses on a real onion supply case and tries to explain the happenings with the help of vibrations analogy, although it has a reasonable scope for generalization. To the best of our knowledge, this kind of analogy has not been discussed precisely following the vibration theory in the supply case scenarios including the bullwhip effect literature. Additionally, we also incorporate the supply chain structural issues. The proposed approach, however, is also expected to contribute toward adding new insights, particularly in terms of an interaction of supply chain structure and bullwhip effect handling.

Most of the supply-chain-related work has been done in an industrial context so far. But agricultural supply chains have received less focus in the literature. This might be because agricultural supply chains should be analyzed depending on specific product and process characteristics [39]. One illustrative case study has been presented by Rong et al. [23], related to a specific agricultural product, that is, the supply chain for bell peppers. Focus of these authors is on controlling the fresh food quality throughout the supply chain.

Key points associated with the difference between the “bullwhip effect studies” and the present study are as follows:

- In traditional “bullwhip,” the stimulation comes from changes in demand at the downstream end of the supply chain; in the present case, the stimulation comes from the upstream supply.
- In “bullwhip,” one-to-one single supplier links along the supply chain are considered; in our case, situations of smaller and larger numbers of potential suppliers at a tier are also incorporated.
- In general, the discussions usually consider supply chains in industrial contexts, that is, for “industrialized” wholesaling and retailing; we look at agricultural context considering a relevant case.

This paper suggests an analysis of the case of onion supplies in India, applying a non-traditional approach. In this case, focus on information sharing and the structure of the supply chain are critical. It makes use of the analogy of vibrations theory to study supply chain phenomena, following the suggestions by Schleifenbaum et al. [27]. Kachani and Perakis [9] applied fluid dynamics models in transportation and pricing. Romano [21] explained supply chain issues with the help of fluid dynamics in the context of clothing industry.

More specifically, this paper investigates how the upstream disruptions in an agricultural supply chain cause increased order volatility in the downstream sections of the chain. It considers alternative approaches to dampen the order volatility following supply chain disruption based on the proposed vibration–supply chain analogy.

After a brief introduction to the food supply markets in India, in its third section the paper mainly discusses the basics of vibration theory and its relationship with supply chain management. Three cases of “viscous damping” are also explained. In Sect. 4 of the paper, insights from the vibrations analogy are transferred to the case of a recent supply crisis in the market for onions in India, in order to illustrate the usefulness of the vibrations analogy. These sections try to answer the following questions:

i. What are the differences between various supply chain situations?
ii. What are the critical parameters in a supply chain scenario affecting its fluctuations/damping behavior?
iii. Which consequences for supply chain design and management may be drawn from the vibrations analogy analysis to better control fluctuations?

2 The market for onions in India

Agriculture is the source of livelihood to more than two-thirds of India’s population and contributing approximately 20 % to the gross domestic product (GDP) of India. Thus, agriculture holds a prominent position as an occupation for the common Indians. Agricultural commodity exports contribute nearly 20 % of the total export earnings of the country. Onion, tomato and mushroom are highly export competitive among fresh vegetables. India ranks first in the world accounting for around 21 percent of the world area, in which onion is planted. Globally, the country occupies the second position, after China, in onion production, with a production share of around 14 percent. Besides India and China, the other major onion-producing countries are Turkey, Pakistan, Iran, Japan, Brazil, United States of America and Spain. Onion is produced for both domestic consumption and exports. India produces all varieties of onion—pink, red, yellow and white, big or small [19].

Onion is an elementary part of the diet in India. A common man in India spends more than 43 % of his disposable income on food items (PHDCCI 2011) [18]. Thus, any substantial increase in food prices may lead to certain effect on monthly budget. This case discusses the onion crisis faced during the last quarter of the year 2010 and in the beginning of 2011.

In India, onion is extensively cultivated in all seasons over a large area spread almost throughout the country. However, Karnataka, Maharashtra and Gujarat are the major onion-producing states accounting for about 60 % of the area and production of onion in the country. According to the National Horticulture Board (India), Maharashtra is the largest onion-producing state accounting almost one-fourth of total production of the country.

Figure 1 clearly depicts that Maharashtra leads in production (21 %) of onion in the country. Thus, we have chosen Maharashtra as one of the states for our study on onion crisis to understand more clearly how the supply shortage may lead to order variation and subsequent inefficient damping.

According to the National Horticulture Research and Development Foundation (India), diseases caused by unseasonal rains ruined almost 70 percent of the "Kharif" (corresponding to the period under consideration) onion crop in Maharashtra in the year 2010, which was responsible for the nationwide shortage of the commodity. This led to a sharp fall in output in the state—the largest producer of the commodity in the country—which in turn resulted in sky-high prices across the country. Existing market players virtually block the entry of new players, which led to practices such as cartelization and hoarding. Apart from this, the inadequacy of supply chain infrastructure added woes to the common man. In this way, the major causes for increase in prices can be identified as follows:

(i) Unseasonal rains
(ii) Practices such as cartelization and hoarding
(iii) Inadequate supply chain infrastructure

In this paper, the inadequacy of supply chain infrastructure to dampen the price and demand volatility is being discussed in detail using the supply chain–vibrations analogy.

3 Introducing the vibrations analogy

Efficiency of supply chains mostly depends on management decisions, which are often based on intuition and experience. Different stages in supply chains are often supervised by different groups of people with different managing philosophies, which sometimes create problems. Sarimveis et al. [24] also laid emphasis on rigorous framework for analyzing the dynamics of supply chains

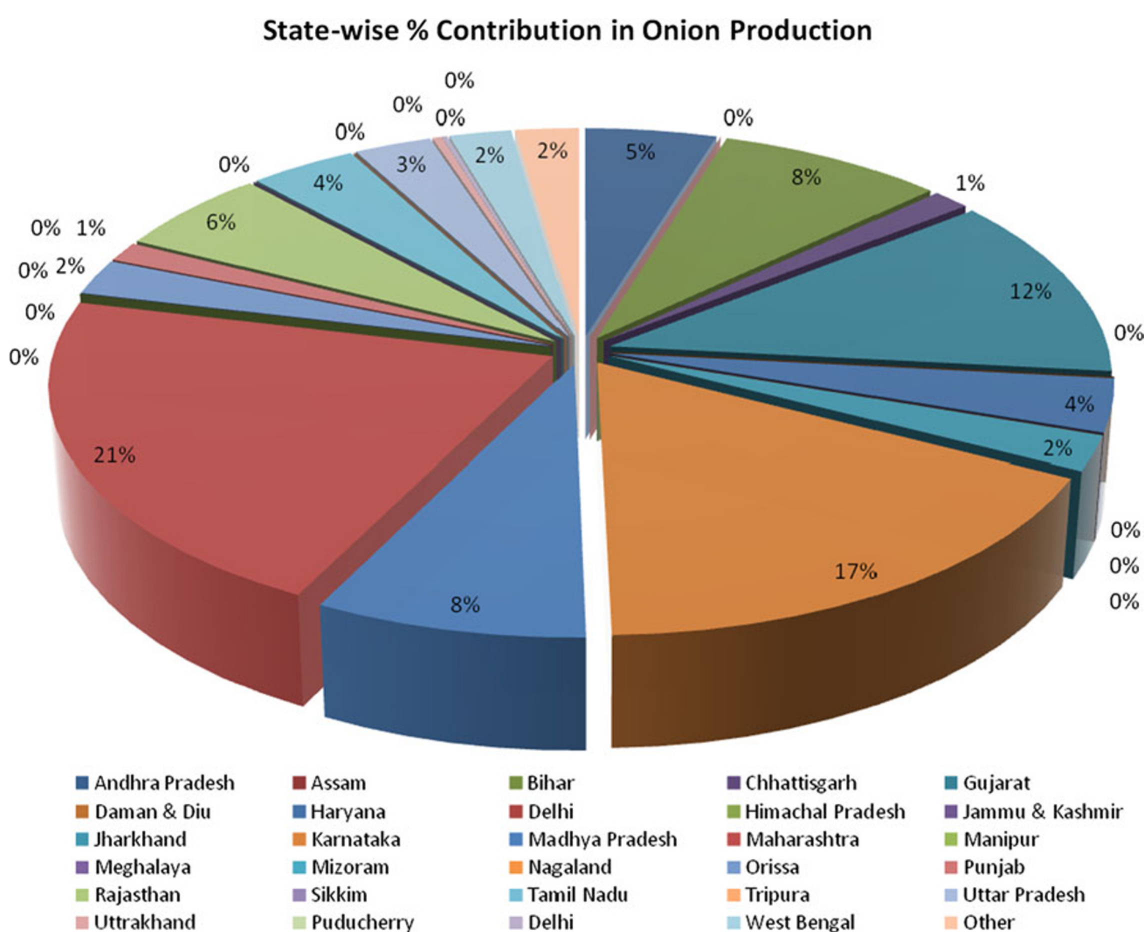

Fig. 1 Onion production in Indian states

Table 1 Some of the research work done in supply chain situation

Topic	Author	Area of study
How can fluid dynamics help supply chain management?	Romano [21]	Configuration of supply networks and business processes to achieve time performance using fluid dynamics–supply chain analogy
Dynamic modeling and control of supply chain systems: A review	Sarimveis et al. [24]	Use of control theory approach in supply chain management
Application of control theoretic principles to manage inventory replenishment in a supply chain	Sourirajan et al. [28]	Use of control theoretic principles to manage the inventory replenishment process in a supply chain under different forecast situations
Measuring endogenous supply chain volatility: Beyond the bullwhip effect	Kim & Springer [11]	Exploring the causes of supply chain volatility

and taking proper decisions to significantly improve the performance of the systems. In order to better understand supply chain phenomena, several analogies have been proposed for their analysis, such as fluid mechanics and supply chain analogy by Romano [21] and control theory analogy by Dejonckheere et al. [6]. Table 1 shows some of the work done related to the analogy among others used in supply chain context. These analogies help in investigating the supply chain from a different perspective. However, as mentioned before, we examine the supply process using a fresh and interesting approach, that is, the vibrations analogy.

3.1 Basic terminology

Any motion that repeats itself after an interval of time is called vibration. Examples from common life include swinging of a pendulum and plucked string of a guitar. The theory of vibrations deals with the study of oscillatory motion of bodies and the forces associated with them [20].

As shown in Fig. 2, a vibratory system in general comprises:

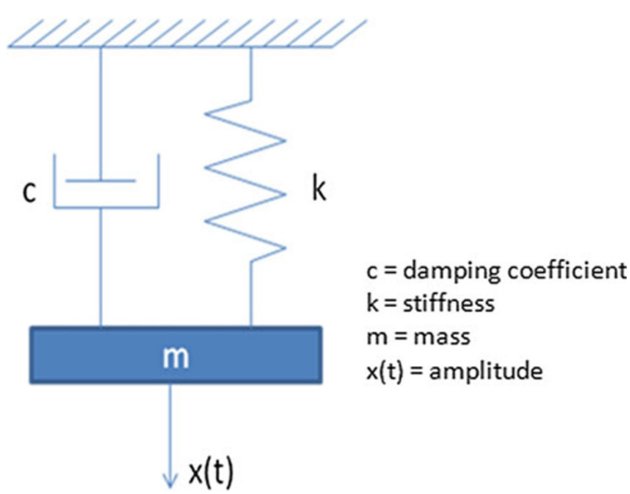

Fig. 2 Fundamental elements of a vibratory system

(i) A means for storing potential energy, which may be provided in the form of a spring or any other elastic member.
(ii) A means for storing kinetic energy, which may be in the form of mass or any other inertial member.
(iii) A means by which energy is gradually lost, which may be provided in the form of a damper.

Presently, we are considering damped vibration system with single degree of freedom. Further damping can be classified in different ways such as:

(i) Coulomb or dry friction damping
(ii) Viscous damping
(iii) Hysteretic damping

Coulomb or dry friction as well as hysteretic damping relate to the friction and therefore may not have direct relevance for the present case. Further, viscous damping is commonly considered in the vibration analysis. Also because of its relevance, the viscous damping has been used in the present paper after providing a brief overview of the vibration.

The description as given in Table 2 forms the basis of vibrations in the "vibration–supply chain analogy." Before moving on to the analogy, it is imperative to have a basic idea of supply chain management/processes.

3.2 The supply chain management–vibrations analogy

According to APICS (APICS Dictionary [2], supply chain management can be defined as "The design, planning, execution, control, and monitoring of supply chain activities with the objective of creating net value, building a competitive infrastructure, leveraging worldwide logistics, synchronizing supply with demand, and measuring performance globally." According to the Council of Supply Chain Management Professionals (CSCMP), "Supply Chain Management encompasses the planning and management of all activities involved in sourcing and procurement, conversion, and all logistics management

Table 2 Typical characteristics of spring damper system

S. No	Spring (refer Fig. 2)	Viscous damper
1.	It is connected at both ends with mass on one side and rigid surface on the other	Viscous damping occurs in a mechanical system because of viscous friction that results from the contact of a system component and a viscous liquid
2.	Its one end is fixed and the other moves with movement of mass triggered by initial displacement from mean position	The damping force is produced when a rigid body is in contact with a viscous liquid and is usually proportional to the velocity of the body
3.	Stiffness (k) is the basic mechanical property of a spring	Damping coefficient (c) is the specific characteristic of a viscous damper as shown in Fig. 2

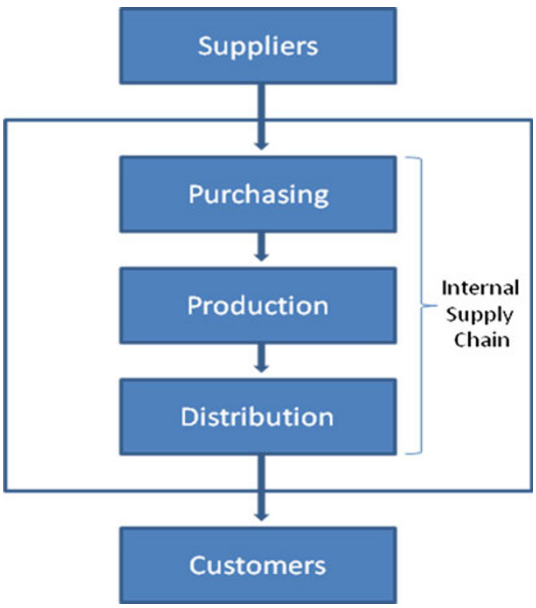

Fig. 3 A general supply chain

activities." It is the flow of material, money and information starting from raw material supplier to the end consumer.

As shown in the Fig. 3 [3], in any organization or any business environment, purchasing, production and distribution combine to form internal supply chain, whereas maintaining cordial and mutually profitable relations with suppliers is known as supplier relationship management. While maintaining such relations at the customer end is known as customer relationship management.

The basic objective of the supply chain is to make available the right product, at the right time, in right quantity, of right quality, at right place and more importantly at right price. But there are always some supply and demand constraints that hinder achieving the aforesaid objective. This paper focuses on analyzing the relationship between the "design and critical design parameters" of supply networks and its ability to dampen unwanted and avoidable demand volatilities. A supply chain–vibrations analogy as discussed in Table 3 has been developed to understand the above relationship more clearly. As mentioned in Sect. 1, specific reasoning might be required for agricultural products as compared to industrial products and situations. Presently in the onion case, stock volume is of less relevance in the context of shortages. This is because of certain difference from the "industrialized" settings as discussed before. Due to shortages at the extreme upstream, possibility of timely keeping more generous stocks by the agencies becomes less relevant. Further, because of the very nature of product and process characteristics, information sharing appears to contribute to the damping in a significant manner. Therefore, the damping ability of this kind of supply chain is an essential parameter in the present case.

From the above discussion, it is clear that the basic properties of a vibratory system (stiffness and damping) resemble the supply chain parameters. Moreover, viscous damping deserves more elaboration here as it resembles the supply chain environment to a large extent.

3.3 The concept of viscous damping

Viscous damping is the most commonly used damping mechanism in vibration analysis. When mechanical systems vibrate in fluid medium such as air, gas, water, and oil, the resistance offered by the fluid to the moving body causes energy to be dissipated. Viscous damping is often added to the mechanical system as a means of vibration control. In the same way, the structural framework of a supply chain acts as a means of vibration and fluctuation control of demand. This aspect will be more clearly explained through the case later.

Viscous damping is also characterized by damping factor (ξ), which can be represented mathematically as:.$\xi = \frac{c}{c_c}$.Here, "c" is the damping coefficient and "c_c"' is the critical damping coefficient, which ensures achieving the approximately equilibrium position of a vibratory system (1 degree of freedom) in minimum time [10].

This results in three cases of viscous damping:

Table 3 Vibrations analogy

S. No	Vibrations	Supply chain
Spring		
1.	It is connected at both ends with mass on one side and rigid surface on the other	Supply chain also has two ends, that is, supply and demand, with supply side mostly acting as rigid surface due to capacity constraint (supply disruption may still occur at an intermediate stage despite the capacity constraint at an extreme end)
2.	The non-fixed end moves with movement of mass triggered by initial displacement from mean position	Demand gets fluctuated from mean position or orders get volatile due to disruption in supply side
3.	Stiffness (load required to produce unit deflection) is the basic mechanical property of a spring	Stiffness in a supply chain can be viewed as the ability of supply chain to bear the supply shock without posing the stock out situation to the customers
Viscous damper		
1.	Damping occurs between parts due to interaction or friction of system component and viscous liquid	Damping of volatile demand may be achieved, if there is necessary and enough interaction or information sharing within and between channel partners
2.	Damping coefficient (c) is the specific characteristic of any viscous damper	Damping ability of supply chain may soon become a quintessential parameter while describing a supply chain

3.3.1 Underdamped system with $\xi < 1$

In a viscously damped system, once free oscillations commence, the non-conservative viscous damping force continually dissipates energy. The system oscillates about an equilibrium position, but each time it crosses equilibrium position, the system's total energy level is less than that in the previous time. The system oscillates with frequency lower than natural frequency of the system, and it is called "frequency of damped vibration." Also, the amplitude of vibration decreases exponentially with time, and thus the system will take infinitely long time to be stable at its mean position as depicted in Fig. 4a.

3.3.2 Overdamped system with $\xi > 1$

The free vibration response of an overdamped system of one degree of freedom is aperiodic, and the response decays after reaching a maximum [refer Fig. 4b]. In this case also, the system will take long time to attain equilibrium position.

3.3.3 Critically damped system with $\xi = 1$

In a critically damped system, the damping force that leads to critical damping dissipates entire energy of the system before one cycle of motion is complete. A critically damped system can thus pass through equilibrium at most once before the motion decays. Hence, critically damped system brings back the system to nearly equilibrium position in the shortest time, which is evident from Fig. 4c.

From the above discussion, we can see that the damping coefficient (c) plays a major role in deciding the type of damping that will occur in viscous damping of a single degree of freedom system. Similarly, the damping ability of a supply chain decides about the type of damping or subsequently the time required to dampen the fluctuated demand or to bring it back to nearly equilibrium level.

The detailed interpretation of damping coefficient (c) or the damping ability of the supply chain can be made possible with the help of a viscous damper or a simple dashpot model.

The damping coefficient (c) of a simple dashpot can be given as:

$$c = \frac{\mu A}{h}$$

In the above equation, "μ" represents the dynamic viscosity of fluid in the reservoir or dashpot. "A" represents the area of plate in contact with fluid. The plate slides over the fluid in the dashpot, which in turn provides resistance or damping to the motion of plate. "h" represents the depth of reservoir or dashpot.

3.4 Viscous damping applied to supply chains

In terms of supply chain, the interpretation of the above parameters is as follows:

3.4.1 Critical damping coefficient (C_c)

In terms of supply chain, it can be interpreted as the critical damping ability of a supply chain which can bring back the fluctuated demand to nearly equilibrium state in minimum possible time.

3.4.2 Dynamic viscosity (μ)

In fluid dynamics, μ depends on the degree of interaction or strength of interaction between the fluid particles. In terms of supply chain, it can be easily viewed as the degree of

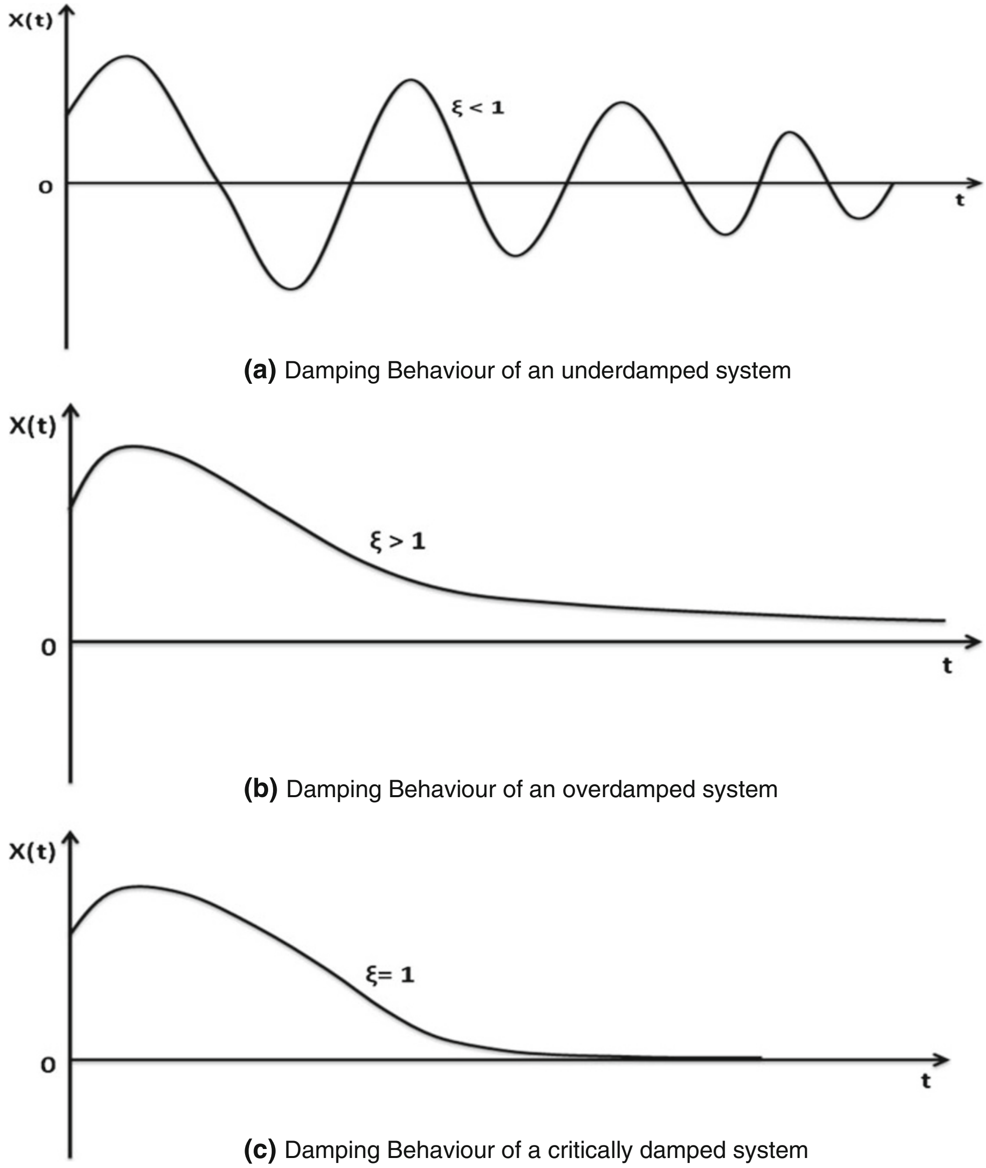

Fig. 4 Damping behavior

interaction or information sharing within and across the different tiers of a supply chain. In practice, it might be difficult to quantify the degree of interaction or the level of information sharing. But a qualitative judgment is possible concerning an appropriate or optimum level of information sharing after experiencing the disadvantages of low and high level of this parameter. If the different links of a supply chain do not interact among and across different tiers of a supply chain or if the information sharing is very low among them, then the orders may get inflated at each stage. Thus, it may take very long time to dampen order volatility, and a state of underdamped vibration may arise. On the other hand, if information sharing is too strong between two members of a supply chain, then the reaction of one member may be so fast to even a small supply disruption at its upstream member that it may lead to inflated orders or increase in order volatility within a supply chain. Thus, we need an optimum μ or the strength of interaction and information sharing among the members of a supply chain.

3.4.3 Area (A)

“A” represents the area of plate in contact with fluid in a simple dashpot model. In terms of supply chain, “A” can be represented as the number of suppliers or members of supply chain in a tier. If the number of suppliers at each stage is low, then it increases the dependency of complete supply chain on one or few members, which may result in inflated orders due to fear of rationing. This particular aspect is also supported by the literature, as many researchers have found existence of inflated demand in fear of rationing by suppliers. On the other side, if the number of suppliers at each stage or tier is very high, then it may lead to an increase in complexity of supply chain, which further reduces the damping ability of the supply chain. Thus, we need an appropriate or optimum number of suppliers at each stage or in a tier to attain the state of critical damping, which dampens the order volatility to equilibrium in minimum possible time.

3.4.4 Depth (h)

In a simple dashpot model, "h" represents the depth of liquid to which the fluid is filled. In the supply chain analogy "h" can be viewed as the mean distance between suppliers in any tier or stage of a supply chain. The term A (Area) ensures that there should be optimum number of suppliers in a tier whereas "h" further puts a check that the mean distance between any two suppliers should also be appropriate or optimum. When h is optimum, that is, the mean distance between suppliers is optimum, then the dependency on few suppliers gets reduced, and thus, volatile and fluctuated demand can be easily dampened, which comes as aftershock of supply disruption. However, if "h" is too small, then it may lead to an unnecessary increase in complexity of supply chain, which may lead to over-damped condition. Similarly, if "h" is very large (an indication of comparatively lower number of suppliers), then it may increase the dependency on one or few suppliers, which may take long time for dampening fluctuated demand, thus resulting in underdamped state of vibration.

From the above discussion, it can be easily concluded that the three parameters of a supply chain structure (μ, A, h) decide the type of damping that may occur in a supply chain and the time that a supply chain takes to dampen the fluctuated and volatile demand after a supply shock or disruption. An interaction among these parameters is possible. For example, a very large "h" might indicate a lower number of suppliers comparatively. However, a relationship of substitutability between number of suppliers and mean distance between suppliers cannot be established precisely in general. For instance, a large number of suppliers do not necessarily reveal smaller mean distance concerning each end consumer. Such consumer may not switch to more distant supplier after getting relevant information. There is a need to critically examine the parameters separately, and a combination of qualitative and quantitative aspects varies from case to case. This can be understood more clearly with the help of an analysis of the case of onion supply, that is, the crisis during 2010–2011.

4 Case analysis

Like a general supply process of food chain, onion is also reaching to the consumers through several channels. This section describes the following:

(i) Various tiers in the supply process of onion
(ii) Supply chain–vibrations analogy in the present case

4.1 Tiers in the supply process of onion

As shown in the Fig. 5, the onion supply chain mostly comprises five tiers:

(i) Tier I: This forms the basis of the onion supply chain and sometimes also called the primary source. This mainly includes the production of onion in farms. Other source of supply in this tier includes importing the onion. However, as India is one of the largest producers of onion in the world, it generally exports.
(ii) Tier II: This includes channel partners that perform the activities like processing, grading and packing and thereby add value to the supply chain as a whole. These are generally located near the farms where onion crop is cultivated. The channel partners of this tier are also involved in the export of onion as per norms laid by the government.
(iii) Tier III: Agrimandis are agrimarkets constituting a significant constituent of tier III of the onion supply case. This includes the channel partners that store the supply received from the tier II partners and fulfill the demand of downstream members. This is the most critical link in the entire supply chain as aggregation and disaggregation of demand in the form of order takes place here. Their location, distance among them, storage capacity and their interaction within and among the tier is of prime importance, which decide the overall stiffness and damping capacity of the supply chain. This is more clearly elaborated later.
(iv) Tier IV: This includes channel partners that deal directly with customers, that is, retailers. These act as the source of information located at the customer end for its demand, preferences, traits, etc.
(v) Tier V: This comprises end customers finally. The customers vary demographically, geographically, economically and socially which get reflected in their buying or ordering behavior.

Although all tiers are important for proper functioning of the complete supply chain, but tier III is the most critical among all, as it performs the function of aggregating as well as disaggregating. It aggregates the supplies from tier

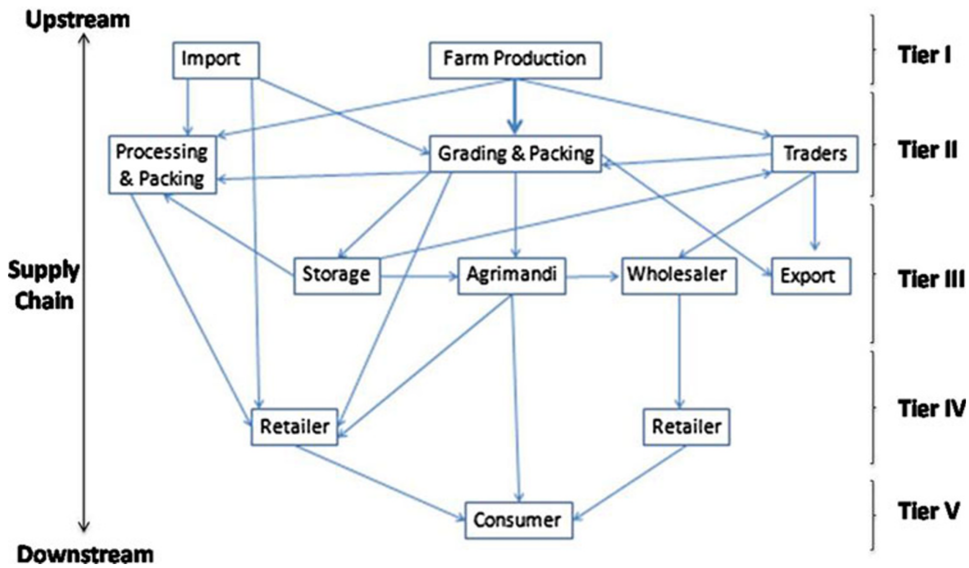

Fig. 5 Channels in the onion supply

II, which constitutes graders, packers and traders, and disaggregates among tier IV and tier V.

4.2 Understanding the onion crisis through supply chain–vibrations analogy

As per data collected from the National Horticulture Board portal, 34 agrimarkets (agrimandis) supply the onion to all the states and union territories of India. These agrimandis constitute tier III of the onion supply chain in India. The location of agrimandis is depicted in the Fig. 6.

As shown in Fig. 6, the number of agrimandis (A) is not enough to cover the entire country, that is, the number of suppliers in tier III are few. This increased the dependency of supply chain on few suppliers and left the tier IV and tier V customers with few options to fulfill their demand. It resulted in inflated demands during crisis due to fear of rationing, which consequently increased the time to bring the prices back to normal. From the vibrations analogy, low value of "A" leads to the situation of underdamped vibration, which means that the system will need indefinitely long time to achieve equilibrium.

Also, the mean distance between the agrimandis (h) is too large, which leads to dependency of tier IV and tier V on few suppliers (agrimandis) in tier III, which again resulted in inflated orders during supply disruption leading to long time for price recovery. From the vibrations analogy, also high value of "h" leads to underdamped vibration and consequently will need a long time to achieve equilibrium.

The degree of interaction or the information sharing among agrimandis (μ) and with its up and downstream is negligible. Wherever present, the communication is not effective enough due to reluctant attitude of traders. This factor again contributed to the onion crisis during December 2010–January 2011.

For getting more insight into the case, we have focused our study on two clusters, which behaved differently during the onion supply crisis. The first cluster comprises two states, namely Maharashtra and Gujarat, which share common border in the Union of India. The second cluster comprises another two states, namely Punjab and Haryana, and one Union Territory, that is, Chandigarh. The study has been done for the same commodity (onion) and for the same time period (December 2010) and the data used are captured from the website of the National Horticulture Board, India (www.nhb.gov.in) [16].

4.2.1 Cluster 1: Maharashtra and Gujarat

In this cluster, there are seven agrimandis, which both serve the states and form tier III of the onion supply chain. In terms of vibrations analogy, it represents "A," which is the number of suppliers in a tier of supply chain. In total, they serve a population of 173 million people living in an area of 504,024 km sq. Thus, the area density of agrimandi in this cluster is 72,003 km sq per agrimandi. The average distance between two agrimandis in cluster 1 is 403 km, which represents "h" in the vibrations analogy. Few agrimandis in the cluster and high average distance between the agrimandis acted as a resistance for information sharing among and across the members of a tier in a supply chain. In terms of vibrations analogy, it (i.e., resistance created due to "h" and "A") has reduced the degree of information sharing (μ) in the supply chain. In this way, all the three factors (μ, A, h) had led the market to the underdamped situation when the supply got disrupted in December 2010–January 2011.

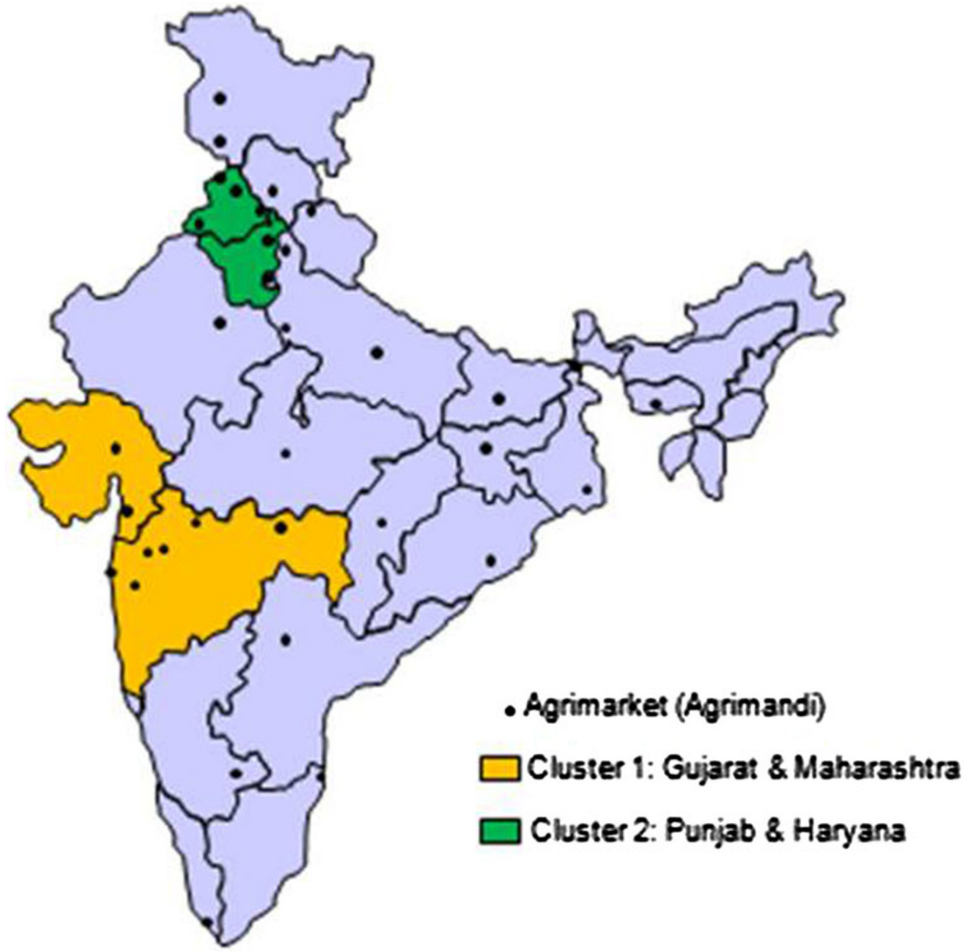

Fig. 6 Spread of agrimandis in India

4.2.2 Cluster 2: Punjab, Haryana and Chandigarh

In this cluster, the five agrimandis serve the two states and a union territory to form tier III of the onion supply chain. Thus, the number of suppliers in a tier (A) is five. These serve people living in an area of 94,574 km sq. The area density of agrimandi in this cluster is calculated to be 18,914 km sq per agrimandi and the average distance between two agrimandis (h) as 226 km. Unlike cluster 1, adequate number of agrimandis and relatively low average distance between two agrimandis help in better information sharing and coordination (μ) in the supply chain.

4.2.3 Comparing Cluster 1 and Cluster 2

Figures 7 and 8 represent the study done for the period during which the onion supply crisis occurred, and thus, the study takes into account only the number of trading days in that particular month, that is, December. Also the start and end of the damping period are decided on the basis of fluctuations in price and arrival quantity. The damping period is considered "start" when price and quantity fluctuate simultaneously and "end" when both attain nearly equilibrium state with low fluctuations. From the above discussion, we find that in case of the supply disruption, all the three parameters of the vibrations analogy enable the cluster 2 to dampen the order volatility in lesser time as compared to the cluster 1. This is evident from Figs. 7 and 8, where price and arrival both have been shown on the basis of available data.

After analyzing all the three factors from the current case perspective, it can be easily concluded that these factors might lead to the situation of underdamped/critically damped vibration in a supply chain, and it took some time to bring the situation back to normal. However, in practice, the cases are analyzed relatively. A comparison is also shown in Table 4 for the cluster 1 and cluster 2. Because of the combination of parameters, cluster 2 seems to handle the situation relatively better.

In practice, a case comparison method has often proved to be useful. The present case helps in understanding the overall system behavior better with the use of vibrations analogy. The approach is suitable for certain generalization also. For instance, if a supply system is found to be underdamped, then the damping coefficient is lower than its critical value. In order

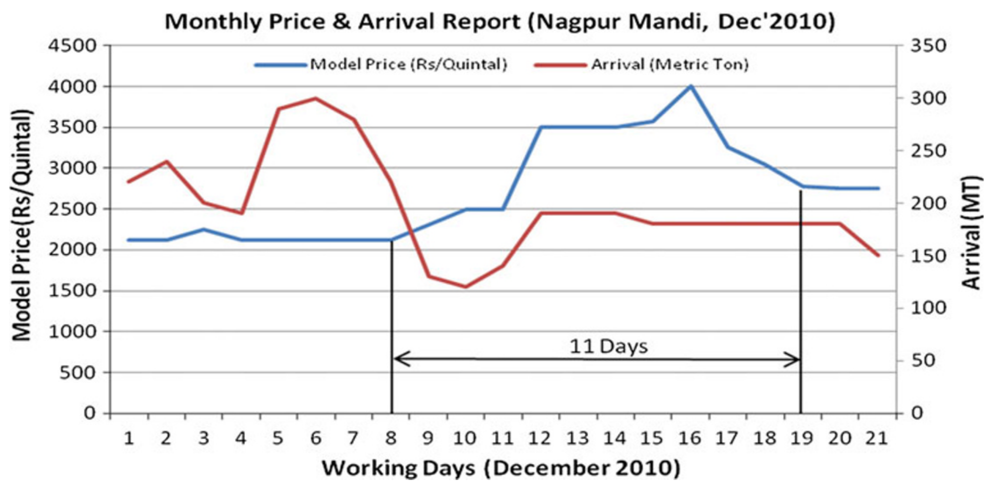

Fig. 7 Cluster 1: monthly price and arrival report (Nagpur Mandi, December 2010)

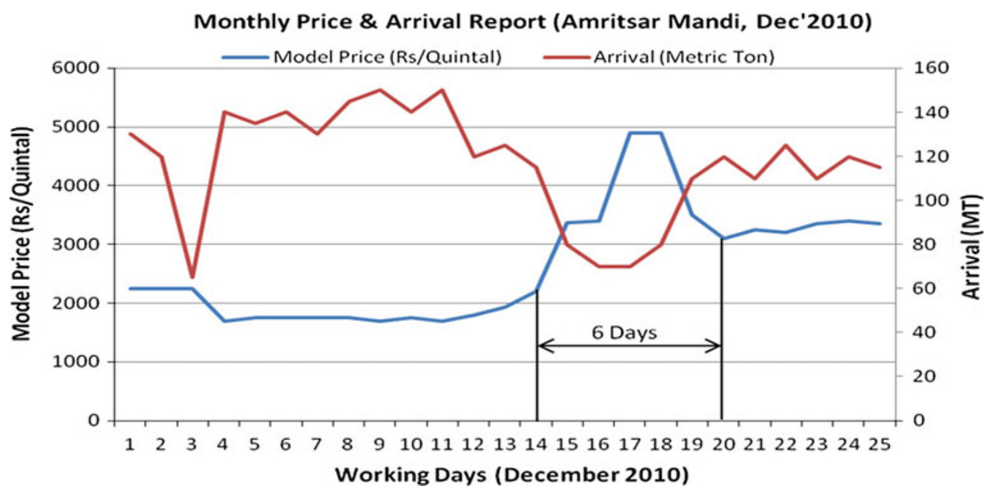

Fig. 8 Cluster 2: monthly price and arrival report (Amritsar Mandi, December 2010)

Table 4 Parameter comparison for Cluster 1 and Cluster 2

S. No	Parameter	Cluster 1 (Maharashtra and Gujarat)	Cluster 2 (Punjab and Haryana)
1	Number of agrimandis in a cluster	7	5
2	Average distance between two agrimandis in a cluster (km)	403	226
3	Average area covered/agrimandi (km sq)	72,003.43	18,914.8
4	Average no. of people served/agrimandi (million)	24.67	10.82
5	Degree of information sharing	Low	Relatively high
6	Time taken to dampen order volatility during crisis	11–15 days	6–8 days

to improve the situation, the management practice needs to focus on the following parameters:

(i) Degree of interaction or information sharing
(ii) Number of suppliers in a tier
(iii) Mean distance between suppliers

In the real world scenario, the managerial attention could be directed toward one or more parameters. For rigorous quantification, suitable relevant combination of parameters [30, 32–34] in the context of more complex multi-item scenario might also be considered depending on the degree of efforts needed to improve them.

5 Conclusion

In the context of vibration theory, the critically damped system will reach the equilibrium position in the shortest time. This happens when the damping coefficient reaches the critical value. Further, the damping coefficient is expressed in terms of viscosity, area and depth. Relying on the vibrations analogy, these terms are explained in the supply chain situation. Ideally, the combination of these relevant parameters must be such that any supply disturbance can be handled in the shortest possible time. In order to understand the phenomena, an onion supply case has been analyzed. A relative comparison is useful in investigating the interaction of various parameters concerning a supply case, and this comparison has been shown clearly.

In the present case, cluster 2 performed well because of an appropriate level of (i) mean distance between agrimandies, (ii) average area covered/agrimandi and (iii) degree of information sharing. In order to generalize the findings, damping coefficient needs improvement if underdamping is observed in the supply system by a manager. For analyzing the situation, following questions should be explored:

(i) Is there any scope for enhancing the degree of information sharing?
(ii) Is there any possibility to increase the number of suppliers in a tier?
(iii) Should the mean distance between suppliers be reduced?

Generally speaking, this situation can be improved by an increase in the number of suppliers in a tier and degree of interaction, along with a decrease in the mean distance between suppliers. However, there are supply system constraints in practice and thus suitable option or a combination of suitable options should be focused and implemented. Further, the proposed methodology needs to be tested for other business sectors as well. Concerning the case-specific environment, additional parameters might be included to explain the supply system behavior better.

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