Conceptual modelling for supply chain inventory visibility

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Visibility becomes increasingly important for companies that seek to globalise their supply chains due to the increasing complexity involved. This paper contributes to the research on Supply Chain Visibility (SCV) from an inventory perspective with a focus on inventory visibility, which is a critical part of SCV. The characteristics of Inventory Visibility (IV), which are inherited from SCV, are conceptually analysed. A theoretical model in terms of atom, single, and compound visibility, is developed based on the characteristics identified. A method for objectively measuring IV is presented together with a case example to demonstrate its convenience and usefulness.

1. Introduction

With globalisation, supply chains become increasingly complex and companies are more aware of the need to have better Supply Chain Visibility (SCV). Enslow (2006) reports that the lack of supply chain process visibility is a main concern for about 79% of the 150 large companies surveyed globally. This is verified by another recent survey of 400 supply chain executives worldwide (IBM, 2009). Presently, SCV is a favourite jargon in the supply chain management community with over 7,510,000 entries found on the Web (www.yahoo.com, 9 September 2009). However, it remains a popular buzzword albeit an ill-defined and poorly understood concept in the literature (Barratt and Oke, 2007). Indeed, SCV is a complex issue that involves people, process, technology, and information flow. From an IT perspective, SCV refers to an organisation’s ability to collect and analyse distributed data, generate specific recommendations, and match insights to strategy (Tohamy et al., 2003). Bartlett et al. (2007) have shown that increased supply chain visibility can be achieved through supplier–customer collaboration. While an increase in available supply chain data provides the illusion of visibility, it also adds to a company’s challenges. Moreover, 90% of all supply chains report that their global supply chain technology is inadequate to provide their finance organisation with the timely information required for budget and cash flow planning and management. The lack of visibility, complete or otherwise, is especially crippling for global supply chains, which can have pipeline inventory of $1 billion. Poor visibility and uncoordinated multi-tier processes for these companies can result in significant “just in case” inventory carrying costs, premium freight expenses, and extended cycle times.

SCV is an emergent area of interest for both practise and academia due to the advent of advanced IT technologies such as RFID and GPS (Bottani et al., 2010; Chang et al., 2010; Luo and Jiang, 2007; Melski et al., 2008; O’Neill and Newton, 2004). Despite its practical relevance, there is confusion and misunderstanding about SCV, and there is no commonly accepted definition of SCV (Francis, 2008). While some definitions for SCV exist (Barratt and Oke, 2007; Francis, 2008; Hsiao-Lan and Wang, 2007; McCrea, 2005; Rao, 2004; Tohamy et al., 2003; Vitasek, 2006; Zhang et al., 2008), they address SCV from different perspectives and have not captured the meaning, function, and essence of SCV holistically. SCV can be decomposed into inventory, demand, and logistics visibility based on the information available (Goh et al., 2009).

Inventory Visibility (IV) is an important aspect of SCV, as it provides companies with information about their inventories to make their supply chain as effective as possible. It supplies the latest and accurate data from in-stock inventory to in-transit inventory, and helps optimise the end-to-end supply chain process. Today, with RFID that enables item level track and trace (Delen et al., 2007; Griffiths et al., 2007; Zhou, 2009), some researchers define SCV only from an inventory perspective. For example, Christopher and Lee (2004) highlight that many supply chains suffer from limited inventory visibility. This means that a particular entity in the network is unaware of the status of upstream and downstream operations of the levels and flow of
inventory as it progresses through the chain. From the same perspective, Vitasek (2006) treats SCV as inventory management software applications that track and trace inventory globally at a line-item level, notifying the user of significant deviations from plan.

IV has three stages: shipment tracking, supply chain event/disruption management, and the continuous improvement of the supply chain. First, IV provides a means to track goods and materials. Second, higher IV, especially, visibility into the movement of inventory, aids better decision making in disruptive event management. Third, a measure of the degree of IV provides a key indicator for supply chain performance improvement. As IV is an emerging research topic, existing research is mainly focused on modelling its benefits and impact from different perspectives to emphasise its importance (Bottani and Rizzi, 2008; Gumrukcu et al., 2008; Lee and Ozer, 2007; Li et al., 2009; Sahin and Dallery, 2009; Yao and Dresner, 2008; Zhou, 2009). However, some research questions still persist, namely (i) how to objectively quantify IV?, (ii) what is the extent of visibility?, (iii) how to know if IV has improved?, and (iv) what is the improvement in IV?

According to the SCV maturity model (Polese, 2002), the current solutions are targeted only at the functionality of the lower maturity levels. To achieve higher levels of maturity of SCV, there is a need to objectively quantify IV for supply chain performance improvement. This paper addresses such problems by providing a means for better SC collaboration and control, and continuous performance improvement. Thus, this paper seeks to contribute to a conceptual model of IV and provide some objective quantitative methods to measure IV for an actor in a supply chain, for a set of actors, and for a supply chain. The rest of this paper is organised as follows. Section 2 reviews the extant literature on IV. Section 3 develops the model for IV. A model based on set theory and objective quantitative methods for measuring IV is presented. Section 4 discusses the potential applications and their impact on practice and theory, and provides a case example together with a web based system to validate the conceptual model. Section 5 concludes with limitations and future research.

2. Literature review

The current research on IV mainly focuses on its importance, which can be summarised into two research streams: the impact of inventory information inaccuracy and the impact of IV on supply chain performance.

2.1. Impact of inventory information inaccuracy

Due to inventory inaccuracy, visibility is still a major issue confronting inventory management systems using AIDC technologies (Bailey and Francis, 2008; Sarac et al., 2010; Sahin and Dallery, 2009). Recent research suggests that it is unfair to assume that the availability of error free data on the flow of goods through an inventory system as well as the on-hand inventory level in facilities, where advanced item AIDC technologies are used, leads to an accurate inventory status (Sahin et al., 2008). These inaccuracies result from replenishment errors, employee theft, shoplifting, improper handling of damaged merchandise, imperfect inventory audits, and incorrect recording of sales. Rekik et al. (2009) have analysed the problem of store theft by optimising the holding cost under a service level constraint. Further, Sahin and Dallery (2009) have attempted to quantify the economic impact of poor visibility caused by inventory inaccuracy using a newsvendor framework for a wholesaler and retailers subject to inventory data inaccuracies. An assessment of the effect of various actions such as the deployment of a new data capture technology to tackle inventory inaccuracy is also studied (see e.g. Uckun et al., 2008).

Fleisch and Tellkamp (2005) use simulation to show that better IV, by eliminating inventory inaccuracy, can reduce a three-echelon supply chain cost as well as the out-of-stock level. The same conclusion has been drawn by another simulation of a two-echelon inventory system consisting of a retailer, a distribution centre, and a supplier that includes multiple item types and using cycle counting as the corrective action (Gumrukcu et al., 2008).

2.2. Impact of IV on supply chain performance

IV is critical for supply chain performance improvement and IV is identified as a significant performance indicator by Daugherty et al. (2006) who also discussed the importance of measuring IV. However, there is no measurement method yet. Chan (2003), through AHP, presents a formulisation of both quantitative and qualitative performance measurements for easy representation and understanding using visibility. Berry and Naim (1996) simulate the implications of various supply chain redesign strategies for the introduction of an IV system to a European PC maker. The benefits of IV and its improvement based on a global demand network are also reported in a case study (Kaipia and Harttala, 2006). Goel (2010) conducts a case study to quantify the benefits of gradual increase in the level of visibility for a supply chain in the automotive industry. Caridi et al. (2010a) study that up to what extent the supply chain configuration affects the supply chain visibility in terms of virtuality and complexity. They (Caridi et al., 2010b) also present a subjective measure of visibility for each supply chain node by combining overall judgments of visibility quantity, accuracy, and freshness to improve supply chain performance.

3. Model development for IV

IV is the capability of a supply chain actor (or player) to have an access to or to provide the required timely information/knowledge about the inventory involved in the supply chain from/to relevant supply chain partners for better decision support. There are two types of capability, namely, the capability to access information available in a supply chain and the capability to provide information available in a supply chain. Likewise, information/knowledge focuses on information or knowledge about physical inventory entities in a supply chain such as the stock level in a certain warehouse, which can be accessed via IT systems. It is impossible to deal with physical inventory entities directly in this study. The information/knowledge provide relevant state mapping of the physical world. However, the accuracy of the information about the physical inventory is an issue related to IV. Timeliness is an important factor for IV. The capability to provide or access information must be measured using a timeliness metric. Any out-of-date information about an entity in a supply chain has a negative impact on IV. The final objective of IV is for decision support, which should be able to be measured in terms of capability using a mathematical model.

Based on the above understanding of IV, a model can be developed using set theory.

3.1. Framework for IV

Consider a supply chain (see Fig. 1) with m actors/players and n information items/resources sharing in a supply chain using a four-tuple SC=(A, I, C, P), where
any actor model to conceptualise IV formally. Defined abstractly as primitive elements for a mathematical accessing information and providing information, these capabilities in this paper, we focus on inventory information items only.

Relation C captures the capability of accessing information while P captures the capability of providing information. For any information item, there is only an actor who provides it. The above supply chain model provides a means to further classify IV based on the nature of the information items. In general, they can be grouped into different clusters in terms of their origin. For instance, they can be further classified into groups such as inventory, demand, and process visibility. In this paper, we focus on inventory information items only.

Based on the two capabilities highlighted above, capabilities of accessing information and providing information, these capabilities can be treated as the key characteristics of IV as they can be defined abstractly as primitive elements for a mathematical model to conceptualise IV formally. Thus, IV can be described in terms of information items. For any actor \( a_i \in A \) in a supply chain, it has the visibility of another partner actor \( a_j \in A \) via an information item \( i_k \in I \). A typical IV framework can be formulated as a four-tuple \( V = (SC, \Omega, \Omega^2, \Omega^3) \), where

- \( SC \) is a typical supply chain;
- \( \Omega \subseteq A \times I \times A \) is the relation between actors A, information items I and actors A;
- \( \Omega^2 \) is a distinguished subset of \( \Omega \); and
- \( \Omega^3 \) is a distinguished subset of \( \Omega \).

As discussed, relation \( C = A \times I \) captures the capability of accessing information while \( P = I \times A \) captures the capability of providing information as defined in the supply chain. Relation \( \Omega \subseteq A \times I \times A \) captures the visibility from one actor to another actor in terms of an information item. Based on the above discussion, there are two atom/primitive visibilities defined based on the relations of the key characteristics of IV as follows:

**Definition 1.** An Atom Visibility (AV) is a 2-tuple \((a_j, i_k) \subseteq C\), representing the capability of actor \( a_j \) accessing information item \( i_k \), or \((i_k, a_i) \subseteq P\), representing the capability of actor \( a_i \) providing information item \( i_k \), where \( a_j \) and \( a_i \in A \) and \( i_k \in I \).

To ease notation, AV \((a_j, i_k)\) is denoted as \( a_j \rightarrow i_k \). Likewise, AV \((i_k, a_i)\) is denoted as \( i_k \rightarrow a_i \). The AV, from Fig. 2, shows that a solid line with arrow is used to denote an “accessing” relationship while a dotted line with arrow is for a “provided by” relationship. In Fig. 2, AV \( a_1 \rightarrow i_1 \) is an AV representation of actor \( a_1 \) who has access to \( i_1 \). AV \( i_1 \rightarrow a_2 \) is an AV representing that information item \( i_1 \) is provided by actor \( a_2 \).

**Definition 2.** A Single Visibility (SV) is a 3-tuple \((a_j, i_k, a_i) \subseteq \Omega\), representing the visibility of actor \( a_j \) to \( a_i \) on information item \( i_k \), where \( a_j, a_i \in A \), \( i_k \in I \), \((a_j, i_k) \subseteq C \) and \((i_k, a_i) \subseteq P \).

Similarly, SV \((a_j, i_k, a_i)\) can be denoted by \( a_j \rightarrow i_k \rightarrow a_i \). A sample SV \( a_1 \rightarrow i_1 \rightarrow a_2 \) indicates that actor \( a_1 \) has access to information item \( i_1 \), which is provided by \( a_2 \) (Fig. 2). For completeness in the theoretical framework, the symbol \( \phi \) is used to represent the null element in both sets \( A \) and \( I \) in the analysis. Thus, the AV \( a_1 \rightarrow i_1 \) and \( i_1 \rightarrow a_2 \) are actually a special case of SV, which can be represented as \( a_1 \rightarrow i_1 \rightarrow \phi \) and \( \phi \rightarrow i_1 \rightarrow a_2 \), respectively.

**Definition 3.** A Compound Visibility (CV) is defined as a set/collection of individual SV’s, \( \{ \Omega \} \) is an SV.

For example, the following set (see Fig. 3) is a compound visibility:

\[(a_1 \rightarrow i_1 \rightarrow a_2, a_1 \rightarrow i_2 \rightarrow a_3, a_2 \rightarrow i_3 \rightarrow a_1, a_3 \rightarrow i_1 \rightarrow a_1, a_3 \rightarrow i_3 \rightarrow \phi, a_4 \rightarrow \phi \rightarrow \phi)\]

A CV can be used to represent the visibility for a supply chain as shown in Fig. 3 where actor \( a_1 \) has visibility to actors \( a_2 \) and \( a_3 \) via information item \( i_1 \) and \( i_2 \), respectively. Actor \( a_2 \) has visibility to \( a_1 \) via information item \( i_3 \). Actor \( a_3 \) has visibility to \( a_1 \) via information item \( i_1 \), and has capability to access information item \( i_3 \) where there is no provider. It provides information item \( i_3 \) in which no other actor in the supply chain is able to access.
Theorem 1. It is not hard to prove the following theorem. For any CV, there exists a cover. Lemma 1. there exists another AV and 3.2. Operations and properties

Definition 7. Let for any . We note that actor is an actor set . We now introduce some rules for calculating IV. As discussed, a compact CV and represents a compact CV and a perfect CV, which is discussed later.

Definition 8. Let for any . Further, as the mapping from to is one-to-one, the desired result follows directly.

Definition 12. A CV is compact if it is irredundant. A CV is irredundant if all its subsets are disconnected.

Theorem 2. For any meaningful CV, there is one and only one minimum cover.

Proof. Let . For any meaningful CV, from Lemma 1, it is easy to prove that there is a cover for . Let such that , , or , and then three possibilities exist: (a) , (b) , or (c) . In case (a), there is an actor and , such that there exists an SV which is compact if it is irredundant. A CV is irredundant if all its subsets are disconnected.

Definition 13. A CV is perfect if (1) it is compact, and (2) for any , and any , there is a to form a meaningful where .

We represent the compact for , and a perfect CV for , as shown in the framework . Figs. 4 and 5 show the sample compact CV and a sample perfect CV, respectively.

Theorem 3. The cardinality of a perfect compact is .

Proof. Let . For any , and any , we can see that there are combinations of and . Further, as the mapping from to is one-to-one, the desired result follows directly.

Definition 14. The degree of inventory visibility of a SC in is defined as

where is a combination function and is a measure function for an SV . In this definition, the combination function could be an integral function or the usual summation operator. is a measure function with being in the interval for . For simplification, we assume that is a normal sum function and for every . Therefore, Eq. (1) can be
Deg(Ω′|V) = \frac{\sum_{\omega \in Ω′} μ(\omega)}{\sum_{\omega \in Ω} μ(\omega)} = \frac{|Ω′|}{|Ω|} \quad (2)

where |Ω′| and |Ω| are the cardinalities of Ω′ and Ω, respectively. For example, with 4 actors and 5 information items in the perfect CV (Fig. 5), there are 20 meaningful SVs:

\[ Ω′ = \{a_1 \rightarrow i_1 \rightarrow a_2, a_1 \rightarrow i_1 \rightarrow a_2, a_1 \rightarrow i_2 \rightarrow a_3, a_1 \rightarrow i_2 \rightarrow a_3, a_1 \rightarrow i_3 \rightarrow a_4, a_1 \rightarrow i_3 \rightarrow a_4, a_1 \rightarrow i_4 \rightarrow a_5, a_1 \rightarrow i_4 \rightarrow a_5, a_1 \rightarrow i_5 \rightarrow a_6, a_1 \rightarrow i_5 \rightarrow a_6, a_1 \rightarrow i_6 \rightarrow a_7, a_1 \rightarrow i_6 \rightarrow a_7, a_1 \rightarrow i_7 \rightarrow a_8, a_1 \rightarrow i_7 \rightarrow a_8\} \]

A compact CV is shown in Fig. 4, which is the minimum cover for a typical CV shown in Fig. 3. There are 4 meaningful SVs as follows:

\[ Ω′ = \{a_1 \rightarrow i_1 \rightarrow a_2, a_1 \rightarrow i_2 \rightarrow a_3, a_1 \rightarrow i_3 \rightarrow a_4, a_1 \rightarrow i_3 \rightarrow a_4\} \]

Therefore, |Ω′| = 4

From Eq. (2)

\[ \text{Deg}(Ω′|V) = \frac{|Ω′|}{|Ω|} = 4/20 = 0.2 \]

By extending Definition 14, we can define the degree of visibility for any actor in an SC. Let Ω′ = \{ω∈Ω: ω = (a_3, i_4, a_4) ∈ Ω′ and (ω) = a_3\}. The degree of visibility for any actor in an SC can be defined as follows.

**Definition 15.** The degree of visibility for actor a_3 in an SC in \( V = (SC, Ω, Ω′, Ω″) \) is given by

\[ \text{Deg}(a_3|V) = \text{Deg}(Ω′|V) = \frac{\sum_{\omega \in Ω′} μ(\omega)}{|Ω|} \quad (3) \]

This formulation can be simplified based on Definition 14 as follows:

\[ \text{Deg}(a_3|V) = \frac{|Ω′|}{m \times n} \quad (4) \]

**Theorem 4.** \( a_i \in A, \exists Ω′ = \{ω∈Ω: ω = (a_i, i_j, a_j) ∈ Ω′ and (ω) = a_i\} \), where \( V = (SC, Ω, Ω′, Ω″) \), such that

\[ \sum_{j=1,\ldots,m} \text{Deg}(a_j|V) = \frac{|Ω′|}{m \times n} \quad (5) \]

**Proof.** Let \( Ω′ = \{ω∈Ω: ω = (a_3, i_4, a_4) ∈ Ω′ and (ω) = a_3\} \), where \( j = 1,\ldots,m \). It is easy to prove that Ω′ and Ω″ are disconnected for any \( j \neq k \), therefore, \( U_{j=1,\ldots,m} Ω′ = Ω″ \).

For example, Fig. 4 shows a compact CV, we know Ω′ = \{a_1 \rightarrow i_1 \rightarrow a_2, a_2 \rightarrow i_2 \rightarrow a_3\}, Ω′ = \{a_3 \rightarrow i_3 \rightarrow a_4\}, Ω″ = \{\}. Then we can calculate \( \text{Deg}(a_1|V) = 2/20, \text{Deg}(a_2|V) = 1/20, \text{Deg}(a_3|V) = 1/20, \) and \( \text{Deg}(a_4|V) = 0/20 = 0 \). Therefore

\[ \sum_{j=1,\ldots,4} \text{Deg}(a_j|V) = 2/20 + 1/20 + 1/20 + 0/20 = 0.2 \]

which is equal to \( |Ω′|/(4 \times 5) = 20/0 = 0.2 \).

**Definition 16.** Let \( A′ \) be a subset of \( A \) then the degree of visibility for a set of actors \( A′ \) in an SC is \( V = (SC, Ω, Ω′, Ω″) \) is defined as

\[ \text{Deg}(A′|V) = \sum_{a_i \in A′} \text{Deg}(a_i|V) \quad (6) \]

Similarly, the above formulation can be simplified from Definitions 14 and 15 as follows:

\[ \text{Deg}(A′|V) = \sum_{a_i \in A′} \frac{|Ω′|}{|Ω|} = \sum_{a_i \in A′} \frac{|Ω′|}{m \times n} \quad (7) \]

The above two formulations can be used to quantify a set of actors, such as suppliers, manufacturers, distributors, and retailers, and their visibility in a supply chain.

4. Experimental results and discussion

The above conceptual model contributes to both research and practice for a better understanding of IV. Due to the uncertainty in inventory visibility and the lack of a model to describe IV quantitatively, most research quantify the effects of visibility using stochastic processes (Lee and Ozer, 2007). This model provides a theoretical foundation of accurately quantifying information for visibility than its current assumption for improving the effect of analytical models such as the bullwhip effect.

In practice, the conceptual model can be applied in many ways. First, the definition and the mathematical model of IV is an initial attempt to provide a unified concept of IV to eke a better understanding of IV in a typical supply chain for better collaboration. They are general enough to capture the key characteristics of IV so that it can be applied to any supply chain. The concept is well defined and proven in mathematical theory. It can be used as a basis to communicate IV between partners in a supply chain. Further, a better understanding of IV provides better strategic and tactical decision support for supply chain professionals to overcome visibility loss in communication (Francis, 2008). Thus, it helps to improve the effectiveness and efficiency of decision making on inventory.

Second, the model can be developed further as an evaluation tool for companies to objectively assess IV. This method can help them to select suppliers for collaboration based on the assessment of the visibility of the suppliers. Third, the model can be integrated with other systems to monitor IV in a supply chain. Finally, the model can be used to provide a numerical measure of IV for supply chain performance improvement.

4.1. Case example

To validate the conceptual model, we conduct an experimental validation through a prototype system to investigate IV in a pharmaceutical supply chain. The chain comprises a principal a_1, who produces medications, 2 pharmaceutical distributors a_2 and a_3, and 3 pharmacies a_4, a_5, and a_6 located in different hospitals. The principal supplies to the two distributors. Distributor a_2 is the supplier for pharmacies a_4 and a_5, and a_3 is the sole supplier for pharmacy a_6. We focus only on two types of information items, monthly inventory levels and weekly inventory levels for the medications produced by the manufacturer for the different hospital locations. We use \( i_1, i_2, i_3, i_4, i_5, \) and \( i_6 \) to denote the monthly inventory levels at the warehouses of a_1, a_2, a_3, a_4, a_5, and a_6 respectively. Likewise, \( i_7, i_8, i_9, i_{10}, i_{11}, \) and \( i_{12} \) denote the weekly inventory levels at the warehouses of a_1, a_2, a_3, a_4, a_5, and a_6 respectively. A compact CV can be identified after studying its visibility as follows:

\[ Ω′ = \{a_1 \rightarrow i_1 \rightarrow a_2, a_1 \rightarrow i_2 \rightarrow a_2, a_1 \rightarrow i_3 \rightarrow a_2, a_1 \rightarrow i_4 \rightarrow a_4, a_2 \rightarrow i_4 \rightarrow a_4, a_2 \rightarrow i_5 \rightarrow a_4, a_2 \rightarrow i_6 \rightarrow a_4, a_2 \rightarrow i_7 \rightarrow a_1, a_1 \rightarrow i_8 \rightarrow a_2, a_2 \rightarrow i_8 \rightarrow a_2, a_2 \rightarrow i_9 \rightarrow a_4, a_2 \rightarrow i_9 \rightarrow a_4, a_2 \rightarrow i_{10} \rightarrow a_4, a_2 \rightarrow i_{10} \rightarrow a_4, a_2 \rightarrow i_{11} \rightarrow a_4, a_2 \rightarrow i_{11} \rightarrow a_4, a_2 \rightarrow i_{12} \rightarrow a_4, a_2 \rightarrow i_{12} \rightarrow a_4, a_2 \rightarrow i_{13} \rightarrow a_3, a_2 \rightarrow i_{13} \rightarrow a_3, a_2 \rightarrow i_{14} \rightarrow a_3, a_2 \rightarrow i_{14} \rightarrow a_3, a_2 \rightarrow i_{15} \rightarrow a_3, a_2 \rightarrow i_{15} \rightarrow a_3\} \]
where $m_i$ is defined by Eq. (6) as follows:

$$\text{Deg}(m_i) = \frac{\sum_{j \in O} \mu(j)}{\sum_{j \in O} \mu(j)}$$

The inventory visibility of the distributors can be gained from Eq. (2), the degree of visibility of the supply chain can be computed as follows:

$$\text{Deg}(O) = \frac{\sum_{j \in O} \mu(j)}{\sum_{j \in O} \mu(j)} = \frac{21}{6 \times 12} = 0.2917$$

where $m = 6$ and $n = 12$.

In this supply chain, the principal $A_1$ is able to access information items $i_1, i_2, i_3, i_4, i_5, i_6, i_7, i_8,$ and $i_9$. Based on Eq. (4), the degree of visibility of $A_1$ is

$$\text{Deg}(A_1) = \text{Deg}(O) = \frac{21}{6 \times 12} = 0.2917$$

Similarly, we compute the degrees of visibility for the rest of the actors as follows:

$$\text{Deg}(A_2) = \frac{6}{6 \times 12} = 0.0833$$

$$\text{Deg}(A_3) = \frac{4}{6 \times 12} = 0.0556$$

$$\text{Deg}(A_4) = \frac{2}{6 \times 12} = 0.0278$$

$$\text{Deg}(A_5) = \frac{2}{6 \times 12} = 0.0278$$

$$\text{Deg}(A_6) = \frac{2}{6 \times 12} = 0.0278$$

The inventory visibility of the distributors can be gained from Eq. (6) as follows:

$$\text{Deg}(D) = \text{Deg}(A_2) + \text{Deg}(A_3) = 0.0833 + 0.0556 = 0.1389$$

Similarly, we compute the degrees of visibility for the principal and the pharmacies. After the assessment, distributor $A_3$ finds it has less visibility than its competitor $A_2$. To improve its IV, it conducted BPR and implemented some policies and enabled IT systems to facilitate greater information sharing on inventory across the chain. Post-implementation, another assessment was conducted. Fig. 6 summarises the details of the two visibility assessments, showing an overall IV improvement of the supply chain from 0.2917 to 0.4583.

The prototype system is developed as a web-based system which can be accessed via the Internet and provides detailed values of IV for any selected actor, principal/manufacturer, pharmacy, and the supply chain using the techniques described in Eqs. (2), (5), and (7).

There are two main functionalities as demonstrated by the prototype system. The first is to specify the AVs, which is done through the configuration module (Fig. 7). An information item such as “Daily inventory status @ SGH” is selected by the user first, then an actor such as “Pan-Malayan” who is designated to access the information item is selected from any group of actors. The AV namely “Pan-Malayan—Daily inventory status @ SGH” is finally generated by clicking “Add” button below the AV list box. In Fig. 7, the two types of AVs are shown in two separate list boxes. After all the AVs have been specified, the system generates SVs in the background based on Theorem 1.

The other functionality is implemented in the Evaluation Module, which provides the calculation of the degree of IV for any actor, a group of actors, and the supply chain itself. This can be done based on Eqs. (2), (5), and (7) after all SVs are generated. Table 1 shows some results of the IVs in a supply chain.

### Table 1

<table>
<thead>
<tr>
<th>Actor</th>
<th>IV Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_1$</td>
<td>0.2917</td>
</tr>
<tr>
<td>$A_2$</td>
<td>0.0833</td>
</tr>
<tr>
<td>$A_3$</td>
<td>0.0556</td>
</tr>
<tr>
<td>$A_4$</td>
<td>0.0278</td>
</tr>
<tr>
<td>$A_5$</td>
<td>0.0278</td>
</tr>
<tr>
<td>$A_6$</td>
<td>0.0278</td>
</tr>
</tbody>
</table>

### 5. Conclusion

IV is an important research area on SCV for companies due to its complexity and importance. To realise the benefits of IV, there is a need for an unambiguous, commonly understood, and accepted definition to clear any misunderstanding and confusion. A mathematical model of IV has been developed, which is beneficial to supply chain professionals to clearly communicate on SCV, which is a critical issue for many companies keen to operate in an end-to-end environment.
The IV model presented in this paper is comprehensive. It helps to assess IV for better supply chain decision making. Introducing the concepts of AV, SV, and CV helps to formally conceptualise IV. The proposed measurement methods derived from the model to measure visibility, the capability of providing and accessing information are new and provide a performance indicator for IV. A detailed case study of extending the concept for assessing a pharmaceutical supply chain is presented in Zhang et al. (2010).

However, as in every research, there are limitations. We note for the record that our proposed model assumes a deterministic nature of visibility. It specifically excludes partial IV, i.e., we do not consider the situation of partial information accessibility to an actor or for that matter partial information provision by an information item. We reserve this for another paper.

Finally, several future research areas are possible. First, the analysis of the economic impact of the conceptual model presented in this paper is worth pursuing to help in better decision making. We can extend the technique used in assessing IV to include the assessment of SCV. This involves process modelling, measurement matrix definitions, and the interpretation of the results. The current IT architecture for improving SCV emphasises on sharing, especially providing information in a supply chain as real time data can be captured through RFID. This creates a challenge for supply chain professionals to access the right information at the right time. How to reduce data redundancy in the information models addressing SCV is critical.

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Table 1
Sample outputs of IV assessment for a pharmaceutical supply chain.

<table>
<thead>
<tr>
<th>Actors</th>
<th>Inventory visibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply chain</td>
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<tr>
<td>Manufacturer</td>
<td>0.033133</td>
</tr>
<tr>
<td>Wholesaler</td>
<td>0.016566</td>
</tr>
<tr>
<td>Pharmacy</td>
<td>0.011295</td>
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</tbody>
</table>

References


