MIT
GLOBAL
SCALE
NETWORK

**WORKING PAPER**
Working Paper Number (17-02)

**May 12, 2017**

**Title:** Internet of Things and Supply Chains: A Framework for Identifying Opportunities for Improvement and Its Application

**Authors, Affiliations:**
Shardul Phadnis,
Malaysia Institute for Supply Chain Innovation

**MIT Global Scale Network**
**Working Paper Series**

# Internet of Things and Supply Chains: A Framework for Identifying Opportunities for Improvement and Its Application

Shardul Phadnis, Malaysia Institute for Supply Chain Innovation

## Abstract

Management and technology experts believe that the internet of things (IoT) has the potential to radically transform today's supply chains. Several practice-focused publications describe various ways in which IoT capabilities can affect the supply chains in positive and negative ways. However, no generic framework describing the peculiar effects of IoT on supply chains has yet emerged. This study presents a theoretical framework to articulate the distinct ways in which the IoT can influence the management of supply chains. The use of this framework is illustrated by applying it to identify opportunities for improving two supply chains: the supply chain described in the famed "Beer Distribution Game" and a revised version of that supply chain. This framework, grounded in the foundation of organizational information processing theory, can be of practical use in guiding organizations envision novel ways to improve the performance of their supply chains by deploying the IoT capabilities.

**Keywords:** Internet of things, Supply chain management, Information ecosystem

**Acknowledgements:**
This research was partially funded by a grant from C.H. Robinson.

**Corresponding Author:**
Shardul Phadnis
Malaysia Institute for Supply Chain Innovation
2A, Persiaran Tebar Layar, Seksyen U8, Bukit Jelutong
Shah Alam, 40150 Selangor, Malaysia
Email: sphadnis@misi.edu.my

# Internet of Things and Supply Chains: A Framework for Identifying Opportunities for Improvement and Its Application

## Abstract

Management and technology experts believe that the internet of things (IoT) has the potential to radically transform today's supply chains. Several practice-focused publications describe various ways in which IoT capabilities can affect the supply chains in positive and negative ways. However, no generic framework describing the peculiar effects of IoT on supply chains has yet emerged. This study presents a theoretical framework to articulate the distinct ways in which the IoT can influence the management of supply chains. The use of this framework is illustrated by applying it to identify opportunities for improving two supply chains: the supply chain described in the famed "Beer Distribution Game" and a revised version of that supply chain. This framework, grounded in the foundation of organizational information processing theory, can be of practical use in guiding organizations envision novel ways to improve the performance of their supply chains by deploying the IoT capabilities.

**Keywords**: Internet of things, Supply chain management, Information ecosystem

## 1 Introduction

Internet of Things (henceforth, "IoT") is defined as "a network of physical objects that contain embedded technology to communicate and sense or interact with their internal states or the external environment" (World Economic Forum, 2015). It is considered a key technological development that will contribute to the emergence of the Fourth Industrial Revolution (i.e., Industry 4.0), and is counted among the nine component technologies in the Industry 4.0

platform (Rose, Lukic, Milon, & Cappuzzo, 2016). Despite its argued revolutionary potential, the implications of IoT remain unclear to a vast majority of firms (The MPI Group, 2016). The World Economic Forum (2015) equates this state of ambiguousness with the state of understanding of the potential applications of the Internet in 1990s; it predicts that the IoT will dramatically transform the world just as the Internet did.

The juxtaposition of IoT's revolutionary potential and the lack of understanding of its implications is troublesome for the firms seeking to harness the technology's capabilities to seek competitive advantage. Given the technology's newness, few cases of success or failures of firms using IoT have been documented. Therefore, it remains unclear what a firm needs to do to improve the performance of its supply chain using the IoT capabilities. This paper seeks to shed some light on this matter by making three contributions. One, the paper highlights the salient features of the IoT that distinguish it from the present-day solutions commonly used for managing the supply chains. This distills the unique features of IoT as a technology that provides an information ecosystem for managing supply chains. Two, this paper presents a framework that can be used to envision the applications of IoT to improve performance of supply chains. Finally, three, the paper illustrate this framework by applying it to explore the ways in which IoT capabilities can be used to improve the supply chain in the "Beer Distribution Game"—one of the most widely played management simulation games in the world (Sterman, 1989)—and a related version of that supply chain.

The rest of this paper is organized as follows. Section 2 provides a brief review of the pertinent literature. I summarize a few fundamental publications of internet of things (IoT), and highlight that IoT is an information technology revolution. Following this, I review a few seminal works in the management literature that explore the role of information on the operational performance of supply chains. Building on this foundation, I propose a generic framework to explore novel opportunities for improving the performance of supply chains using IoT capabilities (Section 3). I illustrate the application of this framework to use the IoT capabilities to improve the supply chain in the “Beer Distribution Game” (Sterman, 1989) and a variation of the supply chain. The reason for choosing this supply chain is threefold: the “Beer Distribution Game” is one of the best-known management simulation games and has been played by thousands of people worldwide, the supply chain in this game is simple and representative of real-world supply chains, and the game is designed to demonstrate the effect of information availability (local vs. global) on the performance of supply chains (Section 4). Finally, I conclude the paper by commenting on the efficacy of IoT for improving supply chain performance.

## 2 Literature

The internet of things has been called “a global infrastructure for the Information Society, enabling advanced services by interconnecting (physical and virtual) things based on existing and evolving interoperable information and communication technologies” (Rose, Eldridge, & Chapin, 2015). It has also been described as “the point in time when more ‘things or objects’ were connected to the internet than people” (Evans, 2011), which is estimated to have been reached between 2008 and 2009. The same report predicts that by year 2020, 50 billion devices will be connected to the Internet; another report predicts the number to reach 100 billion by 2025 (Rose, Eldridge, & Chapin, 2015). The explosive growth of connected devices is no longer limited to smartphones and tablet computers, which provided the impetus for the trend. A recent definition of IoT by Rose, et al. (2015) highlights the increasing variety of “things” being connected to the Internet: “consumer products, durable goods, cars and trucks, industrial and utility components, sensors, and other everyday objects are being combined with Internet connectivity and powerful data analytic capabilities that promise to transform the way we work, live, and play". Rose, et al. (ibid) identify five technological advances as the enablers of the IoT revolution: ubiquitous connectivity, widespread adoption of the IP-based networking, cloud computing, miniaturization of computing devices, and advances in data analytics.

The different definitions of the IoT have one thing in common: they all project the IoT as a revolution of the information and communications technology. It is important to recognize this aspect when exploring the implications of IoT for supply chains. The important role of information in the management of supply chains has been examined in the scholarly and practitioner-focused literature. Deficient information sharing is one of the primary causes of emergence of the "Bullwhip effect," a term used to describe the phenomenon in which a manufacturer of a product experiences high variability in the orders for that product compared to the retailer selling it, even when the market demand for the product had no variation (Sterman, 1989). Lee, et al. (1997) attribute this effect to the distortion of information about the market demand as the information travels from the retailer to the manufacturer through the parties involved in the supply chain. Because of the negative effect of variability on the efficient functioning of a supply chain, the bullwhip effect and the potential remedies to eliminate it have been extensively studied. Some of today's widely-used industry practices, such as sharing point-of-sales data with the manufacturer, vendor managed inventory (VMI), etc. are intended to alleviate the deleterious consequences of the bullwhip effect.

Various types of information transverse and influence the functioning of supply chains. Lee and Whang (2000) describe five types of information shared in a supply chain: inventory levels, sales, demand forecasts, order status, and production schedule. The information transfer takes place via different modes such as direct information transfer (e.g., through electronic data interchange, vendor manager inventory, etc.), transfer through a third party, or through an information hub. The information shared influences behaviors of the parties using it. As a result, any distortion of the information can cause unintended disturbances in the supply chain. Lee, et al. (1997) suggest four potential causes of information distortion that create the bullwhip effect: *demand signal processing,* in which the retailer's orders to the wholesaler (who would then order from a distributor or the manufacturer) are based on the updated demand forecast, instead of the actual demand; *rationing game*, in which the retailer orders more than what is needed if she anticipates that the wholesaler would allocate less than what was ordered; *order batching*, in which the retailer orders periodically from the wholesaler and, as a result, the finite demand information is lumped into one order; and *price variations,* in which retailer orders different order quantities in response to the actual and anticipated changes in price. The net result of each of these four is that the orders placed by the retailer to the wholesaler exhibit a pattern different from that of the market demand.

Human biases also influence the information shared in the supply chain. Croson and Donohue's (2006) examination of the behavioral causes of bullwhip effect showed that the decision makers' *underweighing of the supply line*—i.e., not considering fully the amount of goods ordered but not received yet—was partly responsible for the phenomenon. Furthermore, their study showed that the tendency to underweigh the supply line persisted even when information on inventory levels was shared with the decision makers. Thus, it is not just the distortion of information shared in the supply chain that leads to the bullwhip effect; natural biases present in human decision making are also partly responsible. Adverse effects of human involvement in making of operational decisions are also observed in other decisions made in supply chains. For instance, Schweitzer and Cachon (2000) showed through experiments that human decision makers order suboptimal quantities when making one-time purchase decisions, such as ordering goods to fulfill a season's demand. These deviations from the optimal quantity are systematic, and can result in potential loss of revenue, especially more for high-margin products (Ho, Lim, & Cui, 2010). Some fundamental human biases, such as overconfidence, are shown to be the root causes of this effect (Ren & Croson, 2013).

Such supply chain maladies related to information exchange and human decision-making biases may be cured by using a different information and decision-making ecosystem such as the internet of things. Some of the emerging research on implications of IoT for supply chain management suggests that the IoT capabilities can help companies improve the efficiency of their supply chain operations and facilitate innovation (Rong, Hu, Lin, Shi, & Guo, 2015). In addition, IoT capabilities can also be used to track goods geographically and over time (as well as people; however, ethical ramifications of tracking people need to be considered), provide improved situational awareness, facilitate sensor-driven decision making, automate production processes, optimize resource use, and allow real-time sensing of unpredictable conditions (Chui, Löffler, & Roberts, 2010).

A study of the internet of things in logistics (Macaulay, Buckalew, & Chung, 2015), jointly published by the leaders in the domains of IoT (CISCO) and logistics (DHL), notes that IoT can enhance an organizations capabilities for measuring, controlling, automatizing, optimizing, learning, and monitoring various activities in the supply chain. The paper provides examples to illustrate how IoT could improve the outcomes of logistics processes. These examples include improvement of operational efficiency (fleet and traffic management, resource and energy monitoring, and connected production floor), improvement of safety and security (equipment and employee monitoring, health monitoring, physical security), enhance customer experience (connected retail, context-aware offers to customers), and engender new business models (firms become service providers, usage-based insurance). The report concludes by providing three use-cases of IoT in logistics: warehouse operations, freight transportation, and last-mile delivery.

A few studies explore the effects of IoT in specific industries. A graduate thesis and a subsequent article by researchers at the Malaysia Institute for Supply Chain Innovation explored the implications of IoT on the chemical industry (Phadnis, 2015; Ravi & Wu, 2015). The researchers mapped the existing flows of goods and information at a construction chemicals business, documented the state-of-the-art of the IoT capabilities available, and then conjectured various ways in which IoT capabilities could realistically be employed to enhance various activities in the supply chain (such as, process control, production planning, procurement, order fulfilment, etc.). They noted several potential benefits from the application of IoT: lower variability in ordered and shipped quantities, higher revenue with the same or lower finished goods inventory levels, lower work-in-progress and raw material inventories, fewer lost sales, automated procurement and production planning, improved process quality and safety, and so on.

Another study explores the impact and the applications of IoT on the high-tech industry (Biswas, Ramamurthy, Edward, & Dixit, 2015). This whitepaper describes how IoT can increase sales and improve operations for four types of firms in the high-tech industry: semiconductor firms, contract manufacturers, distributors, and original equipment manufacturers (OEMs). The potential improvements in supply chain operations resulting from the application of IoT cited in the study include increase in the yield of semiconductor fabrication facilities, improvement of asset utilization, predictive maintenance, facilitation of anti-counterfeiting measures, improvement of product quality through more effective collaboration between the OEM and its supplier for product design and development, and so on.

The extant studies exploring the potential effects of using IoT to manage supply chains typically identify specific benefits (and threats). Some of these studies list the implications of IoT in more generic terms (e.g., Chui, et al., 2015; Macaulay, et al. 2015; Phadnis, 2015; Rong, et al., 2015; etc.), while others discuss them in the context of particular industries (e.g., Biswas, et al., 2015; Macaulay, et al. 2015; Ravi & Wu, 2015). However, no comprehensive framework for exploring the implications of IoT for the management of supply chains has yes emerged in the literature. The present study seeks to fill this gap by providing a generic framework that can be used to explore novel opportunities for enhancing the performance of supply chains in a chosen industry.

## 3 Framework for Envisioning Effects of IoT on Supply Chains

Given that internet of things (IoT) provides a new way of gathering and sharing information to make operational decisions for managing the supply chain, the proposed framework is based on the theoretical foundation of information processing and decision making in management. In the theoretical discourse on the association between information processing and decision making in organizations, Tushman and Nadler (1978, p. 614) note that "information processing refers to the gathering, interpreting, and synthesis of information in the context of organizational decision making." They elaborate the distinction between data and information by noting that information refers to the data that are "relevant, accurate, timely and concise [… that can] effect a change in knowledge." In another influential early work on information processing in organizations, Kiesler and Sproull (1982) call "managerial problem sensing" a precondition for managerial decision making and action, and suggest that problem sensing consists of three processes:

noticing (i.e., gathering data), interpreting the data to assign it actionable meaning, and incorporating the information with other information. These three processes parallel the three steps in organizational information processing identified by Tushman and Nadler (1978). The gathering data, interpreting it into information, and the change in knowledge effected by incorporation of new information, also called *sensemaking*, is central to the functioning of organizations because “it is the primary site where meanings materialize” and “inform and constrain [organizational] identity and action” (Weick, Sutcliffe, & Obstfeld, 2005). Thus, data gathering, data sharing, data interpretation and decision making are the fundamental processes in the information processing model of organizations.

Building on this theoretical foundation, I propose a framework for exploring the effects of IoT capabilities on the performance of supply chains. The framework consists of three components: data gathering, data sharing, and interpretation and decision making. For each component, the framework describes the salient ways in which IoT differs from the information technology solutions used for managing supply chains at present. The framework is presented in Figure 1 and described below.

INSERT FIGURE 1 ABOUT HERE

## 3.1 Data Gathering

One of the fundamental drivers of the growth of IoT is the increasing variety of objects connected to the internet. As Macaulay, et al. (2015) point out, “with the advent of IoT, Internet connections now extend to physical objects that are not computers in the classic sense and, in fact, serve a multiplicity of other purposes.” Such objects may include “consumer products, durable goods, cars and trucks, industrial and utility components, sensors, and other everyday objects" (Rose, et al., 2015). Different objects will collect and share different types of data, such as heartrate from a fitness tracker, driving speed of a car, or level of ink remaining in a printer cartridge. Thus, a natural consequence of the variety of objects connected to the interest is that an IoT information ecosystem will gather *more types of data*.

The number of objects connected to the internet is projected to reach 50 billion by 2020 (Evans, 2011) and 100 billion by 2025 (Rose, et al., 2015). This equates to an average of more than six connected objected per living human being by 2020 and over twelve by 2025. Thus, the same kind of data may be available from multiple sources. One example of this is the driving speed data from multiple connected cars in one geographic area. This information can be used to computer the average and variance of driving speed at a particular location at a given time. Thus, the IoT information ecosystem will also have *more sources contributing the data* of a given kind. More data points enable computation of reliable statistics.

Finally, due to their automated nature, data collection and transmission can both be performed more frequently than what may be plausible with the human involvement in either collection and/or transmission of data. Therefore, the third distinguishing feature of the IoT information ecosystem is that it allows *more frequent* data collection.

### 3.2 Data Sharing

A second fundamental driver of the growth of IoT is the widespread ability to connect computational devices to the internet (Rose, et al., 2015). In IoT, communication among devices is enabled not only by the commonly-used information technologies such as wired connections, local wireless networks (e.g., Bluetooth, Wi-Fi, RFID), and wide-area telecommunication networks (e.g., EDGE, 3G, LTE), but also by "operational technologies" such as the "more specialized, and historically proprietary, industrial network protocols and applications that are common in settings such as plant floors, energy grids, and the like" (Macaulay, et al., 2015, p. 4). The "always-on" connectivity allows the devices to share the collected data *instantaneously*.

The automated nature of data sharing also obviates the need for human operators to collect, process, or analyze the data before it is shared. Sharing data in the raw form is advantageous because the data get shared without getting subjected to human biases that are known to influence selective collection and processing of data (Ditto & Lopez, 1992; Edwards & Smith, 1996; Kunda, 1987). One of the robust findings in psychology informs that people "are likely to examine relevant empirical evidence in a biased manner" when they hold strong opinions about the issue (Lord, Ross, & Lepper, 1979). Automated data sharing can circumvent this problem. Therefore, the second key feature of an IoT information ecosystem is that data is *shared without distortion*.

Finally, connectivity over the internet allows the connected devices to exchange data with each other or a common cloud-based platform directly (with the appropriate communications protocol), regardless of their place in the supply chain. Thus, a firm can exchange relevant data with another firm in its supply chain even if the firms are not direct suppliers or customers of each other. For example, the point-of-sales data at a retail store does not have to reach the product's manufacturer from the retailer, through a distributor and a wholesaler; the point-of-sales data at a store can be sent either directly to the manufacturer or uploaded to a cloud-based platform where the manufacturer can access it. Thus, the third distinguishing feature of the IoT information ecosystem is that it allows data to be *shared in a non-serial fashion* with the supply chain partners.

### 3.3 Interpretation and Decision Making

Another fundamental driver of the growth of the IoT is the advances in data analytics (Rose, et al., 2015). Macaulay, et al. (2015, p. 6) note that “the use of analytics and complementary business applications (e.g., data visualization) is crucial if organizations are to capture and make sense of the data generated from connected devices.” The automated processing of data ensures that the analysis is not influenced by human biases (e.g., Kunda, 1987; Lord, et al., 1979). It also ensures that data are analyzed consistently using the predefined algorithms. Of course, the use of algorithms is not a panacea: the design and selection of algorithms themselves are not immune to human biases and can arguably have monumental consequences, such as the 2008 Global Financial Crisis (O'Neil, 2016). Firms need to be aware of these dangers. However, well-designed algorithms can make data processing consistent and free it from the vagaries of biased human decision making. Thus, one salient feature of the IoT information ecosystem is its *algorithmic decision making*.

The second important feature of IoT-based decision making is the ability to get quick and frequent feedback. Due to the automated collection and instantaneous sharing of data, an IoT-controlled system can take several small actions, measure outcomes, obtain feedback, and make corrections based on the feedback. This rapid action-correction loop could be prohibitively expensive with human involvement in data collection, sharing, or decision making. Management research has long established that “if the action-outcome-feedback links are short and frequent, the individual [or, firm] is in a good position to learn about, and thus comprehend, the probable effects of actions on outcomes: short links enhance the ability to improve decision making by taking corrective actions” (Hogarth & Makridakis, 1981, p. 120). Thus, the second key feature of the IoT information ecosystem is the *feedback-based nature of decision making*.

Finally, the vast amount of data collected through IoT devices can enable predictive decision making. More accurate forecasts, enabled by larger volume of relevant data, can help optimize a particular system with fewer resources. For example, more data about sales or online searches can help predict demand with smaller variance, and as a result, a supply chain can provide the same level of product availability with smaller inventory. Thus, the third distinguishing feature of the IoT information ecosystem is the *predictive decision making*.

## 4 Application of the Framework

In this section, I demonstrate the use of the above framework by applying it to envision opportunities for improving the performance of an existing supply chain using IoT capabilities. I use the supply chain depicted in the “Beer Distribution Game” (Sterman, 1989) and one variation of it for the demonstration. I choose this supply chain because of its simple structure and its familiarity to a large number of management scholars and practitioners. I begin with a brief description of the supply chain in the Beer Distribution Game and follow it up with a depiction of the modified supply chain designed by deploying IoT capabilities.

### 4.1 The “Beer Distribution Game”

The "Beer Distribution Game" is a “role-playing simulation of an industrial production and distribution system” (Sterman, 1989, p. 326). It was developed in the 1960s at the Massachusetts Institute of Technology to demonstrate some key dynamics in the supply chains. It has been played all over the world by thousands of people “ranging from high school students to chief executive officers and government officials” (ibid). The supply chain in the game delivers one product (i.e., cases of beer) through four stages or echelons—retailer, wholesaler, distributor, and factory—with only one firm at each echelon. The retailer orders the product from the wholesaler to meet the market demand; the wholesaler fulfills the demand from its inventory, and orders the product from the distributor, who in term, fulfills the demand from its inventory and orders the product from the factory, which produces (i.e., brews) the necessary quantity to meet the demand. There is a lag of two weeks between the placement of an order and receipt of the goods between each pair of consecutive stages. The game is played over several "periods," with each period equivalent to one week. The objective of the game is to minimize the total cost for the supply chain over the duration of the play. Each case of beer carried in the inventory costs $0.50 per week, and each lost sale due to not having any inventory at the retailer costs $1 per week.

Each firm, manned in the game by a player, has to make only one decision in each period: determine the quantity to order in the next period. The only exception is the factory, which decides the quantity of to produce (i.e., place an order on itself). The key feature of this game is that each player (i.e., firm) "has good local information but severely limited global information" (Sterman, 1989, p. 328). The players are told not to communicate with each other; thus, no player except the retailer has any knowledge of the consumer demand in the market. Furthermore, the market demand is not known in advance; the retailer discovers the market demand as the game progresses. The players are told of the two types of costs incurred in the game and the game's objective of minimizing the total cost. However, they are not given specific guidelines for determining their order quantities. Thus, each player may decide the quantity to order based on the quantity of the product ordered by her customer, her interpreted pattern of customer's orders, her anticipated future orders, and any other metrics she considers relevant for determining the order quantity.

The customer demand is set at four cases per week for each of the first four weeks of the game. The demand experiences one unannounced one-time increase to eight cases per week in week five; after that, the demand remains stable at eight units per week for the rest of the game. This one small change creates major fluctuations in the supply chain. Sterman (1989) notes that almost all runs of the Beer Distribution Game exhibit the same three qualities: oscillation, amplification, and phase lag. Order quantities and inventory levels of all four firms *oscillate* over time. The inventory levels of the retailer decline first, followed by the decline in inventory levels of wholesaler, distributor, and the factory in that order. The declines generally cause severe shortages throughout the supply chain. To compensate for this, the players increase their order quantities. This swings the inventory levels in the opposite direction, and the "inventory in many cases substantially overshoots its initial levels" (ibid, p. 330). The magnitude and variable of orders is *amplified* from the retailer to the factory; the peak order rate at the factory can be about twice as high as that at the retailer. Finally, because of the time lags between the stages, the order quantities exhibit a *phase lag*, such that the peak orders at the factory occur, on average, about four weeks after the peak orders at the retailer.

These phenomena are also observed in the real world. Sterman (1989, p. 336) notes that the "production-distribution networks in the real economy exhibit the three aggregate behaviors generated in the experiment, i.e. oscillation, amplification from retail sales to primary production, and phase lag." The oscillations are caused by the failure to account for the goods in the pipeline (i.e., the products ordered but not received yet) when placing orders as well as incorrect assumption about market demand. The amplifications are the result of lack of visibility to the true demand for the parties upstream in the supply chain and their over-adjustments to the disturbances observed in their own demand. Another result of the lack of visibility is that the players representing the firms upstream in the supply chain have incorrect assumptions about the true demand. Sterman (1989, p. 335) shows that "the majority of subjects [playing the wholesaler, distributor, or factory roles in the game] judge that customer demand was oscillatory," when it reality it is stable throughout the game barring one fluctuation in week five. Finally, the phase lag is a natural result of the time lags in the placement of orders by the parties in the supply chain.

Overall, three aspects of this supply chain engender this phenomenon: *lack of visibility of market demand* to all parties except the retailer, the *time lag between placing and receiving the orders*, and the *failure to keep track of the inventory in transit*. The decision makers in the game use an anchoring-and-adjustment heuristic (Tversky & Kahneman, 1974) to determine the order quantity: they anchor on the *expected* demand from their customers and then adjust the order quantity to “reduce the discrepancy between the desired and actual stock” and “maintain an adequate supply line of unfilled orders” (Sterman, 1989, p. 324).

## 4.2 “Beer Distribution Game” with IoT Ecosystem

In this section, I describe how the framework presented earlier in the paper can be used to think of ways in which the potential causes of the undesirable dynamics in the Beer Distribution Game’s supply chain can be mitigated by deploying IoT capabilities. To do this, I present a list of initiatives, envisioned with the help of the framework, to improve the supply chain performance using IoT capabilities. The initiatives are presented in Table 1. I first present three initiatives targeted to improve performance of the supply chain described in the “Beer Distribution Game” (Section I of Table 1), which is a rather simplified version of a real-world supply chain. Following this, I present four initiatives to improve the performance of a modified version of the supply chain based on the game (Section II of Table 1).

INSERT TABLE 1 ABOUT HERE

### *4.2.1 Initiatives for Supply Chain in “Beer Distribution Game”*

The first initiative is to share point-of-sales data from the retailer with the wholesaler, distributor, and the factory. This involves collecting a *new type of data* (i.e., retail sales) in addition to that mentioned in the game, and *sharing it without distortion* (i.e., sharing raw sales data, instead of orders data from retailer and other firms) and in a *non-serial manner* (i.e., the sales data is sent directly from the retailer to the wholesaler, distributor, and factory, instead of having to traverse serially through the supply chain). This provides complete visibility to all the players about the nature of market demand, and can help make correct assumptions about market demand by three firms that do not see the market demand directly. This can result in *lowering the total cost* by reducing the overall inventory carried in the supply chain, while simultaneously *increasing product availability* by reducing the stock-out situations.

The second initiative is to forecast customer demand based on point-of-sales data and share it with all firms in the supply chain. This initiative is enabled by the first one. Besides the features of the framework used to enable the first initiative, this initiative involves the use of *algorithmic* and *predictive decision making* (i.e., a forecasting heuristic to predict demand, although a very simple forecasting algorithm can suffice in the Beer Distribution Game) instead of relying on manual judgment to determine order quantities, as done in the game. It also involves the use of *more types of data* than in the game: the firms can develop one forecast of the market demand and is share it among all four parties in the supply chain. The benefit of this initiative is that it allows all parties in the supply chain to work to meet one common goal. The outcome of this initiative is same as the first: it can *lower cost* by reducing inventory in the supply chain and, simultaneously, *increase product availability*.

The third initiative is to provide real-time visibility of inventory in the supply chain and use multi-echelon inventory optimization. Inventory visibility in the supply chain described in the Beer Distribution Game can be enabled by attaching RFID tags or similar sensors to the cases of product shipped, which can be scanned and geotagged as they move from one facility to another. This initiative involves the use of *more types of data* (i.e., location data collected from product moving through the supply chain) collected from *more sources* (i.e., the location data is collected from several cases, even from a single batch) and shared *instantaneously, without distortion* (i.e., raw location data, instead of a summary report stating the amount of product at a location) and in a *non-serial manner* (i.e., shared with all parties in the supply chain through a common cloud-based platform) so that the inventory in the supply chain could be optimized using sophisticated *algorithms* (i.e., using multi-echelon inventory management algorithms, instead of manually determining the optimal inventory levels at each echelon). The benefit of this initiative is likely to be particularly evident when the consumer demand experience a small change—which disturbs the equilibrium in the game and causes severe oscillations of inventory levels and order quantities in the supply chain—as the adjustments to the inventory levels are based on a multi-echelon inventory optimization algorithm, instead of the overcorrection of a human decision maker typically observed in the game. Thus, the result is a more cost-*effective response to unexpected changes* in demand.

### *4.2.2 Initiative for Revised "Beer Distribution Game" Supply Chain*

Below I describe a more realistic version of the supply chain based on the game, without deviating too far from the original design, to demonstrate the benefit of the proposed framework for identifying opportunities for improving performance of the supply chain. Assume that the supply chain consists of one factory, one or more distributors and wholesalers, and multiple retailers each with one or more stores. We still assume that the supply chain delivers the same category of product, but now assume that there are multiple product variants made by the factory and delivered through the supply chain. We assume that consumers have preferences amongst the different variants of the product. Section II in Table 1 presents four initiatives for improving this supply chain.

The first initiative is to predict sales of different products at different stores (i.e., different geographic regions). This initiative uses *more types of data* (such as, profiles of consumers based on their web activity and social media posts; consumer shopping regions based on their credit card usage, geotracking records from mobile phones or fitness trackers; listing of events that influence product consumption in region; regional weather; etc.) collected from *more sources* (i.e., more consumers for whom such data is available), *shared in a non-serial manner* (i.e., shared over a cloud platform with all parties in the supply chain) and processed to identify patterns using *predictive machine learning algorithms*. The benefit of this initiative is that it enables the use of causal forecasting models to predict demand. This can forecast demand more accurately based on the demand drivers, instead of using simple time-series extrapolations of historical patterns. This can *improve product availability* as well as *reduce product spoilage* due to inventory aging and obsolescence.

The second initiative is to offer unscheduled expedited deliveries from a centralized warehouse, based on real-time product availability at retail stores. This initiative uses data about stock levels in retail stores collected *frequently* (i.e., using real-time updates of inventory levels based on point-of-sales transactions) and transmitted *instantaneously*, *without distortions* (i.e., sharing raw inventory data, as opposed to order data) and in a *non-serial manner* (i.e., shared with all firms involved in the supply chain over a cloud-based platform) for *algorithmic predictive* analysis to determine if any unscheduled expedited deliveries need to be made to any stores to avoid lost sales due to product stock-outs at the store. The benefit of this initiative is that it allows a retailer to augment periodic store replenishments with expedited deliveries to minimize stock-outs and lost sales. Thus, the supply chain becomes *more agile in responding to* *unexpected changes* in the market demand.

The third initiative is to allow products to be customized for individuals and/or for special occasions, such as birthdays, anniversaries, and other special events. This initiative relies on the use of *more data* (i.e., biographic details and product preferences of consumers shared via social media, product and/or packaging designed by consumers themselves for the special event and shared with the factory over its social media interface), *more sources of data* (i.e., data from more consumers) shared *in without distortion* in a *non-serial manner* (i.e., shared by consumer directly with the producer, instead of going through the retailer). The benefit of this initiative is that consumers can *customize products* for their own events, and the producer's factory can ship the product directly to the consumer instead of sending the customized product through the four-tiered supply chain.

The fourth initiative is to create product promotions customized for individual consumers, for specific time of the day, and offered at convenient retail stores. This initiative relies on usage of *more types of data* (i.e., consume profile based on social media, shopping habits and product preferences, present location of the consumer, etc.) collected from *more sources of data* (i.e., data collected for a large number of consumers) at *high frequency*, as well as *algorithmic and predictive decision making* (i.e., the use of algorithms to identify the optimal offers for each consumers for the a specific time of the day and offered at a particular retail location). Furthermore, the algorithms can be *feedback-based* so they can learn by measuring the "hit rate" (i.e., the proportion of time a consumer bought the marketed product) and updating the algorithm itself to improve the hit rate. This can *increase sales* due to better matching of product offering with the customer need (i.e., higher value).

In conclusion, this section portrays the use of the framework to identify opportunities for improving the performance of a supply chain. In this case, the illustration is made by identifying the opportunities for the supply chain in the "Beer Distribution Game," and then for a more realistic version of the same supply chain. The examples presented for this context are meant to be illustrative, not exhaustive. The opportunities for improving the supply chains described above are practically unlimited; the few initiatives mentioned in this paper are a small tip of the iceberg.

# 5 Discussion

It is widely believed that the internet of things (IoT) will radically transform today's supply chains. Several publications describe the potential benefits and threats of IoT (e.g., Biswas, et al., 2015; Chui, et al., 2010; Evans, 2011; Macaulay, et al., 2015; Phadnis, 2015; Rose, et al., 2015; The MPI Group, 2016). However, no generic framework has yet emerged that can describe IoT's implications for supply chains. This study takes a step to fill this gap in the literature. It presents a framework, based on the theoretical foundation of information processing in organizations, to explore the implications of internet of things for the management of supply chains.

One of the basic tenets of the information processing model of organizations states that "the greater the task uncertainty, the greater the amount of information that must be processed among decision makers during task execution in order to achieve a given level of performance" (Galbraith, 1974, p. 28). Given that the a fundamental task of supply chain managers is to make operational decisions that seek to achieve an optimum level of performance in uncertain conditions, the proposed framework can help one explore the opportunities for deploying the IoT capabilities to elevate the performance of supply chains from their present levels.

The proposed framework is illustrated by applying it to identify opportunities for improving the performance of two supply chains: supply chain in the "Beer Distribution Game"

(Sterman, 1989) and a version of that supply chain modified to include more real-world features. The opportunities presented here are certainly not exhaustive, but are chosen to illustrate the framework in a concise manner.

Although this paper focuses on identifying opportunities for improving supply chain performance using the IoT, several issues need to be addresses before these implementation can be realized. Firms in a supply chain collaborating through a cloud-based IoT solution need to ensure that the devices used for collecting and sharing information are secure to prevent malicious hacking of the network or snooping attempts for industrial espionage. Firms will also need to use devices and cloud platforms with compatible information-exchange protocols to enable inter-device communication. Uninterrupted power supply and network connectivity will be necessary for optimum performance of a supply chain's IoT implementation. Furthermore, ethical issues related to individual privacy need to be addressed before information about individual consumers can be collected and used for commercial purposes. Data ownership issues will also need to be addressed to for the data collected from consumers as well as individual firms.

Assuming the implementation hurdles can be overcome, the opportunities for improving performance of supply chains by leveraging IoT capabilities are practically limitless. They are bounded only by our creativity. A framework based on a strong theoretical foundation, such as the one presented in this study, can help practitioners identify such opportunities. After all, we strongly believe that "nothing is as practical as a good theory" (Lewin, 1945)!

## 6 Bibliography

Biswas, D., Ramamurthy, R., Edward, S. P., & Dixit, A. (2015). *The internet of things: Impact and applications in the high-tech industry.* Teaneck, NJ (USA): Cognizant.

Chui, M., Löffler, M., & Roberts, R. (2010). The internet of things. *McKinsey Quarterly*(2), 70-79.

Croson, R., & Donohue, K. (2006). Behavioral causes of the bullwhip effect and the observed value of inventory information. *Management Science, 52*(3), 323-336.

Ditto, P. H., & Lopez, D. F. (1992). Motivated skepticism: Use of differential decision criteria for preferred and nonpreferred conclusions. *Journal of Personality and Social Psychology, 63*(4), 568-584.

Edwards, K., & Smith, E. E. (1996). A disconfirmation bias in the evaluation of arguments. *Journal of Personality and Social Psychology, 71*(1), 5-24.

Evans, D. (2011). *The internet of things: How the next evolution of the Internet is changing everything.* San Jose, CA: Cisco Internet Business Solutions Group.

Galbraith, J. R. (1974). Organization design: An information processing view. *Interfaces, 4*(3), 28-36.

Ho, T.-H., Lim, N., & Cui, T. H. (2010). Reference dependence in multilocation newsvendor models: A structural analysis. *Management Science, 56*(11), 1891-1910.

Hogarth, R. M., & Makridakis, S. (1981). Forecasting and planning: An evaluation. *Management Science, 27*(2), 115-138.

Kiesler, S., & Sproull, L. (1982). Managerial response to changing environments: Perspectives on problem sensing from social cognition. *Administrative Science Quarterly, 27*(4), 548-570.

Kunda, Z. (1987). Motivated inference: Self-serving generation and evaluation of causal theories. *Journal of Personality and Social Psychology, 53*(4), 636-647.

Lee, H. L., & Whang, S. (2000). Information sharing in a supply chain. *International Journal of Manufacturing Technology and Management, 1*(1), 79-93.

Lee, H. L., Padmanabhan, V., & Whang, S. (1997). Information distortion in a supply chain: The bullwhip effect. *Management Science, 43*(4), 546-558.

Lewin, K. (1945). The Research Center for Group Dynamics at Massachusetts Institute of Technology. *Sociometry, 8*(2), 126-136.

Lord, C. G., Ross, L., & Lepper, M. R. (1979). Biased assimilation and attitude polarization: The effects of prior theories on subsequently considered evidence. *Journal of Personality and Social Psychology, 37*(11), 209-2109.

Macaulay, J., Buckalew, L., & Chung, G. (2015). *Internet of things in logistics: A collaborative report by DHL and CISCO in implications and uses cases for the logistics industry.* Troisdorf, Germany: DHL Customer Solutions & Innovations.

O'Neil, C. (2016). *Weapons of math destruction: How big data increses inequality and threatens democracy.* New York: Crown Publishers.

Phadnis, S. S. (2015, Aug). *Connecting supply chains to the Internet of Things*. Retrieved from Supply Chain Frontiers: http://ctl.mit.edu/pub/newsletter/supply-chain-frontiers-58-connecting-supply-chains-internet-things

Ravi, R., & Wu, L. (2015). *Demystifying Industry 4.0: Implications of internet of things and services for the chemical industry.* Unpublished master's thesis, Malaysia Institute for Supply Chain Innovation, Shah Alam, Malaysia.

Ren, Y., & Croson, R. (2013). Overconfidence in newsvendor orders: An experimental study. *Management Science, 59*(11), 2502-2517.

Rong, K., Hu, G., Lin, Y., Shi, Y., & Guo, L. (2015). Understanding business ecosystem using a 6C framework in Internet-of-Things-based sectors. *International Journal of Production Economics, 159*, 41-55.

Rose, J., Lukic, V., Milon, T., & Cappuzzo, A. (2016). *Sprinting to value in Industry 4.0.* Boston Consulting Group.

Rose, K., Eldridge, S., & Chapin, L. (2015). *The internet of things: An overview.* Geneva, Switzerland: The Internet Society.

Schweitzer, M. E., & Cachon, G. P. (2000). Decision bias in the newsvendor problem with a known demand distribution: Experimental evidence. *Management Science, 46*(3), 404-420.

Sterman, J. D. (1989). Modeling managerial behavior: Misperceptions of feedback in a dynamic decision making experiment. *Management Science, 35*(3), 321–339.

The MPI Group. (2016). *The internet of things has finally arrived.* The MPI Group.

Tushman, M. L., & Nadler, D. A. (1978). Information processing as an integrating concept in organizational design. *Academy of Management Review, 3*(3), 613-624.

Tversky, A., & Kahneman, D. (1974). Judgment under uncertainty: Heuristics and biases. *Science, 185*(4157), 1124-1131.

Weick, K. E., Sutcliffe, K. M., & Obstfeld, D. (2005). Organizing and the process of sensemaking. *Organization Science, 16*(4), 409–421.

World Economic Forum. (2015). *Industrial internet of things: Unleashing the potential of connected products and services.* Gevena, Switzerland: World Economic Forum.

# 7 Figures and Tables

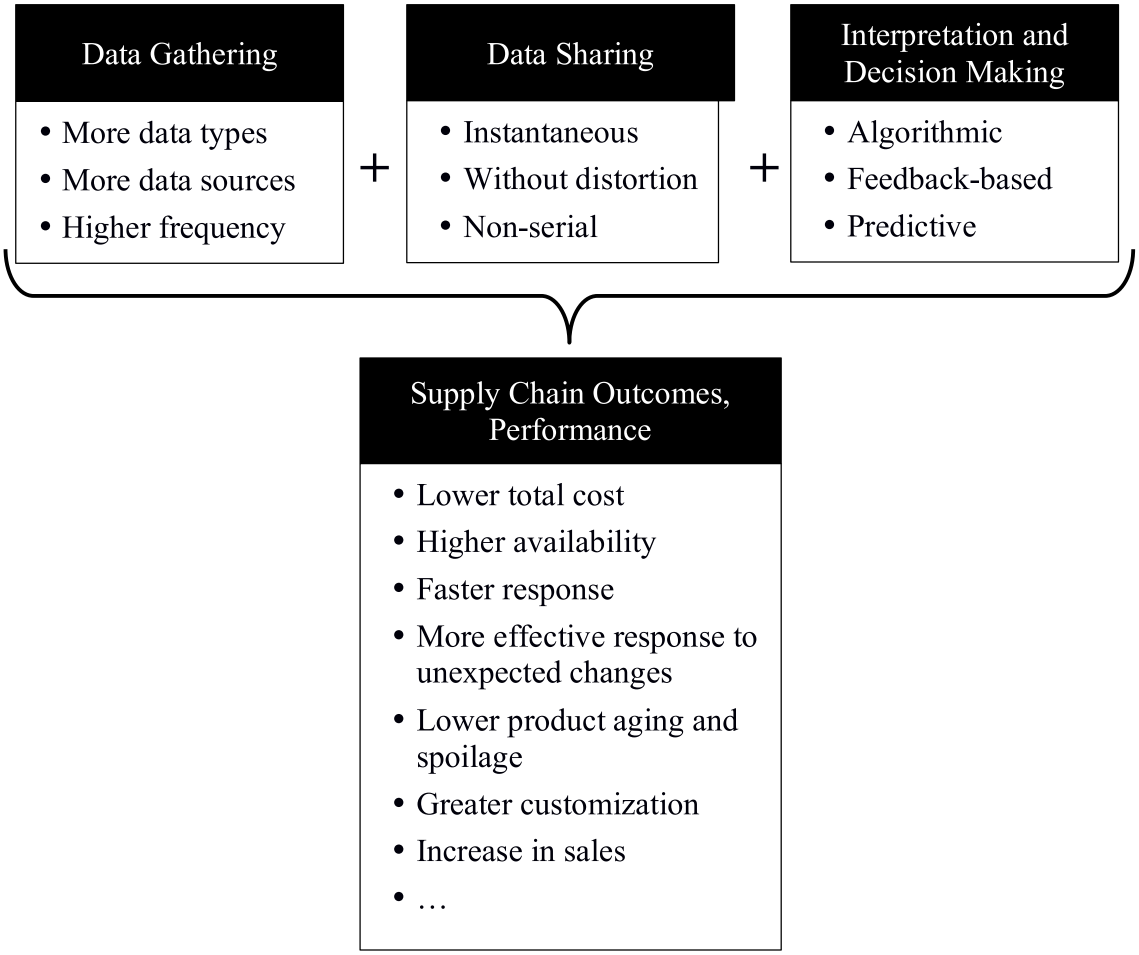

**Figure 1: Framework for exploring opportunities to improve supply chain performance using internet of things**

| **Initiatives to Improve Supply Chain Performance using IoT Capabilities** | **Data Gathering** | | | **Data Sharing** | | | **Decision Making** | | |
|---|---|---|---|---|---|---|---|---|---|
| | More Data Types | More Data Sources | Higher Frequency | Instanta-neous | Without Distortion | Non-serial | Algorithmic | Feedback-based | Predictive |
| Section I: Supply chain in “Beer Distribution Game” | | | | | | | | | |
| 1. Sharing retailer’s point-of-sales data with other firms in the supply chain | ✓ | | | | ✓ | ✓ | | | |
| 2. Forecasting customer demand based on point-of-sales data and share within the supply chain | ✓ | | | | | | ✓ | | ✓ |
| 3. Multi-echelon inventory optimization, with real-time visibility of inventory in the supply chain | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | | |
| Section II: More realistic supply chain based on “Beer Distribution Game” (one factory; multiple products; multiple retailers and wholesalers) | | | | | | | | | |
| 1. Predicting sales of different products at different retail stores based on consumers’ electronic footprint, listing of local events, weather conditions, etc. | ✓ | ✓ | | | | ✓ | | | ✓ |
| 2. Unscheduled expedited deliveries based on real-time product availability at retail stores using centralize storage | | | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ |
| 3. Customized product packaging for individuals and events | ✓ | ✓ | | | ✓ | ✓ | | | |
| 4. Product promotions customized to individual consumers, for specific time of the day and offered at specific retail stores | ✓ | ✓ | ✓ | | | | ✓ | ✓ | ✓ |

**Table 1: Initiative to improve performance of supply chain in the “Beer Distribution Game” using IoT capabilities**