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Building a Dynamic RFID Data-Driven Supply Chain Management System: Imperatives and Guidelines

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Abstract: Drawing upon the domains of supply chain management, simulation, Dynamic Data-Driven Application Systems (DDDAS) and Radio Frequency Identification (RFID) technology, we propose the design and implementation of a dynamic RFID data-driven supply chain management system. In accordance with the DDDAS concept, the proposed artifact will be able to (1) model supply chain entities, (2) simulate supply chain events and activities, (3) use real-time RFID data to maintain a more accurate picture of the overall supply chain and (4) use the simulation results to control experiments. Based on an extensive literature review, we show that such an artifact would be both important and useful for businesses seeking to optimize the performance of their supply chains. We also discuss the design science research methodology that will be used to design, implement, evaluate and validate this artifact.

Key words: Supply chain, supply chain management, simulation, DDDAS, RFID.

INTRODUCTION

In today's dynamic and competitive business environment, the only constant is change (Bowersox and Closs, 1996; Johannesson and Palona, 2010). Causes of change vary: "Regulatory changes, globalization, increasing intensity in competition, increasingly demanding customers, new information technology and mergers and acquisitions" (Hung *et al*., 2004) are just a handful of examples. These changes pose great challenges to companies and can erode profit margins if management does not take wise, timely and decisive action. To stay ahead of the competition, companies must deal with changes effectively and efficiently.

Organizations have broadly adopted Enterprise Resource Planning (ERP) and Supply Chain Management (SCM) systems in order to better control and manage their diversified resources and geographically dispersed operations. Supply chain management has received much attention in both the academic and business worlds as a means of significantly reducing supply chain costs, improving operational efficiency and effectiveness and thus increasing profit margins (Lancioni *et al*., 2000). In addition, the nature of the competition has changed, from a competition between individual companies to one between supply chains, as more companies realize that they have to rely upon their supply chain partners to help them meet customer expectations (Cao *et al*., 2005). As a result, companies have shifted their concentration away from improving their internal efficiency and toward seeking ways to change, redesign and re-engineer their entire supply chain network (Huang and Gangopadhyay, 2004).

A supply chain is a system whose constituent parts include material suppliers, production facilities, distribution services, retailers and customers all linked together via the feed forward flow of materials and the feedback flow of information (Stevens, 1989; Sambasivan *et al*., 2009). Given its complexity, it is often difficult to reliably predict a supply chain's behavior. Both excessive demand variability due to information distortion (the so-called "bullwhip effect") and uncertainties within the supply chain system itself (Cao *et al*., 2005) contribute to the unpredictable behavior. Therefore, supply chain management systems are not always effective tools for supporting real-time decision making. This is particularly the case with respect to unplanned incidents, such as emergency customer orders, plant breakdowns and missed shipments (Darema, 2000).

Uncertainty in the supply chain is problematic because it hinders effective and efficient supply chain management. Reiner and Trcka (2004) argued that the main objective of problem-solving methods in supply chain management is to reduce uncertainty. Given the greater complexity and globalization of supply chains, it is very important for organizations to improve their supply chain responsiveness in order to reduce uncertainty and mitigate the associated risks (Cao *et al*., 2005).

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Simulation, as the process of mimicking reality, offers an ideal means to analyze supply chain variability and risk (Avni, 1999; Magableh and Mason, 2009). At the design stage, simulation allows different realizations of future supply chain scenarios. It also allows the limitations of the supply chain to be explored. In the operation stage, simulation allows supply chain management concepts, performance and risks to be quickly assessed. Avni (1999) stated that applying simulation technology to supply chains will enable us to "minimize inventory; ensure on-time delivery, optimize transportation and handling costs; experiment with alternative distribution channels; identify the impact of dynamic disturbance and develop strategies to respond to change."

Traditional supply chain simulations, however, cannot accept new data while running, which limits their predictive capabilities (Darema, 2000). The National Science Foundation (NSF) 2000 Workshop (Darema, 2000) envisioned the concept of Dynamic Data Driven Application Systems (DDDAS), in order to overcome the limitations of traditional supply chain simulations. Within the DDDAS framework, the applications/simulations and the experiments (or field data) form a symbiotic feedback system (Darema, 2000).

Radio Frequency Identification (RFID) is a means of capturing data about the location and status of assets in the supply chain without using a human to read or record the data (Zhang *et al*., 2006; 2010b). RFID technology can provide supply chain management systems with real-time product location information. Organizations can then use this real-time information to improve the quality and timeliness of their decision making (Zhang *et al*., 2006; 2008; 2010b).

The goals of this research are to propose and build a system that is able to model the interactions among supply chain entities and investigate the manner in which major events impact overall supply chain operations. Using the concept of DDDAS and the capability of RFID technology, we propose the design and implementation of a dynamic RFID data-driven supply chain management system. The proposed artifact, which is not now in existence, will simulate supply chain activities by incorporating real-time RFID data. In doing so, the system will be able to maintain a more accurate picture of the overall supply chain. Decision makers can also use the simulation to control field measurements and project the impact of various decision options (Darema, 2000).

To evaluate this system, a comparison study will be carried out. The results from two simulations, one with the traditional approach (i.e., in which the input data are fixed at the beginning of the simulation run) and the other with the DDDAS approach (i.e., real-time RFID data are fed into the system during the simulation run), will be compared. The evaluation metrics will be quality and timeliness of information and decision making.

RESEARCH BACKGROUND

This section provides an extensive literature review, organized according to the following principles: (1) supply chains are important; however, (2) supply chains misbehave; (3) simulations can help, but (4) traditional simulations have their limitations and (5) integrating the concept of DDDAS and RFID technology can not only overcome these limitations, but also significantly improve the effectiveness and efficiency of supply chain management.

Supply chain, supply chain management and the "bullwhip effect": A supply chain is a "network of organizations and business processes for procuring materials, transforming raw materials into intermediate and finished products and distributing the finished products to customers" (Laudon and Laudon, 2003). A typical supply chain involves five major types of stakeholders: suppliers, manufacturers, distributors, retailers and customers. Along this chain, materials and products flow downstream from suppliers to customers; while orders flow upstream from customers to suppliers. It is worth noting that some supply chain activities, materials, products and information can flow in either direction.

Supply Chain Management (SCM) has received tremendous attention in the business world as more and more companies realize that, in order to outperform the competition, they must rely on their supply chain partners (Cao *et al*., 2005). The expected benefits of SCM include throughput improvements, cycle time reduction, inventory cost reduction, transportation optimization, better prediction of disturbance propagation and increased customer responsiveness (Chang and Makatsoris, 2001).

SCM is a complex task because supply chains do not always behave as predicted. One reason is the so-called "bullwhip effect." This term describes the tendency for orders placed to suppliers to have larger variances than sales to the buyers, which causes a distortion that propagates up the supply chain in an amplified form (Steckel *et al*., 2004). The bullwhip effect can lead to such inefficiencies as "excessive inventory investment, poor customer service, lost revenues, misguided capacity plans, ineffective transportation and missed production schedules" (Lee *et al*., 1997).

A great deal of research has been done on the causes of the "bullwhip effect" and how to mitigate it. Lee *et al*. (1997) identified four major causes of the bullwhip effect:

(1) demand forecast updating, (2) order batching, (3) price fluctuation and (4) rationing and shortage gaming. Their suggestions for mitigating the bullwhip effect include avoiding multiple demand forecast updates, breaking order batches, stabilizing prices and eliminating gaming in shortage situations.

In addition to the bullwhip effect, uncertainties within the supply chain are another factor that can negatively impact the effectiveness and efficiency of SCM. Van der Vorst *et al.* (1998) identified four sources of uncertainty: order forecast horizon, input data, administrative and decision processes and inherent uncertainties. They also suggested that real-time information systems are necessary in order to bring about ideal SCM performance.

Steckel *et al.* (2004) and Chen *et al.* (2000) analyzed the impact of shortening the time lags within the supply chain and suggested that shorter time lags are better. Lee *et al.* (2000) as well as Croson and Donohue (2003) examined the issues related to Point of Sale (POS) information sharing. Both findings suggest that sharing POS information helps reduce some components of the bullwhip effect. However, Steckel *et al.* (2004) found that whether the sharing of POS information is beneficial depends on the nature of the demand pattern.

Simulation and supply chain management: Simulation is "the process of designing a model of a real system and conducting experiments with this model for the purpose of understanding the behavior of the system and/or evaluating various strategies for the operation of the system" (Shannon, 1998). Some have argued that simulation is indispensable as a means of approaching and solving real-world problems (Banks, 1999). Drawing upon the work of other researchers, Banks (1999) developed a list of simulation benefits, including "choose correctly, time compression and expansion, understand 'why?', explore possibilities, diagnose problems, identify constraints, develop understanding, visualize the plan, build consensus, prepare for change, wise investment, train the team and specify requirements".

Given the high costs associated with changes in business strategy and operations, simulation has been widely used in supply chain management (Hung *et al.*, 2004). Kleijnen and Smits (2003) distinguished four types of simulation for SCM: spreadsheet simulation, system dynamics, discrete-event dynamic system simulation and business games. Spreadsheet simulation was made possible with the introduction of spreadsheet software; however, it has been deemed "too simple and unrealistic" (Plane, 1997; Powell, 1997).

System dynamics was developed by Forrester (1961), who viewed companies as systems with six types of flows: material, goods, personnel, money, orders and information. Using Forrester's model, Lee *et al.* (1997) identified the amplification in Forrester's supply chain as one of the bullwhip effects. Discrete-event dynamic system simulation is closer to reality because it can represent business activities, such as placing and fulfilling an order. Tiger and Simpson (2003) applied discrete-event simulation to a supply chain management context to assist in decisions where time and flexibility are essential.

One of the most common illustrations of the bullwhip effect is the "beer game," which mimics how beer is supplied to customers by tracing the product from the customer order up through the supply chain. As part of the "game," constraints are placed on the order and fulfillment process at various points in the supply chain in order to illustrate how and why the bullwhip effect occurs. The beer game model has been built into supply chain simulations as a means of studying the bullwhip effect (Croson and Donohue, 2003; Steckel *et al.*, 2004).

DDDAS and supply chain management: Traditional simulations only allow fixed inputs when the simulation is launched. As such, a traditional simulation must be stopped and restarted from the beginning in order to feed new field data into the model. This lack of flexibility limits the capabilities of these applications (Darema, 2000).

The NSF 2000 Workshop (Darema, 2000) envisioned the concept of dynamic data driven application systems (DDDAS). Within the DDDAS framework, field data can be used in an "online" fashion to steer the simulations. The simulations can then be used to control experiments or other field measurements, forming a symbiotic feedback system (Darema, 2000).

DDDAS projects can be funded through four NSF programs: NGS (next generation software), ITR (information technology research, DDDAS section), DDDAS and SENSORS. According to http://www.dddas.org/projects.html, over 30 DDDAS projects have been funded through these four NSF programs since 2000. Most of these simulation projects are related to the natural sciences, such as earth science, chemistry, biology, or meteorology. Some are related to software engineering and algorithms. To the best of our knowledge, none are related to the supply chain concept. Our literature search only generated one research (Celik *et al.*, 2010) on supply chain and supply chain management using the concept of DDDAS.

RFID and supply chain management: RFID is a technology that can uniquely identify objects using radio frequency transmissions (Xiao *et al.*, 2007). RFID was first

used in World War II to identify ships and airplanes as "friend or foe" (Levinson, 2003). However, it has recently gained greater attention in various industry sectors, in the media and in academic research (Loebbecke, 2005). The popularity and increased usage of RFID is based upon the increased maturity of the technology and the reduction of deployment costs (Want, 2004). RFID works by embedding tags (chips) in the objects of interest, using tag readers to track the chips and storing the location information gathered by the readers in an application system (Zhang *et al*., 2006, 2010b).

Compared with barcodes (the primary form of product identification in supply chains), RFID technology offers numerous advantages such as a longer reading range, simultaneous multiple reads, higher durability, possible item-level differentiation, updatable information state and the elimination of the line-of-sight data acquisition requirement (Delen *et al*., 2007; Loebbecke, 2007). As such, RFID technology carries the promise of bringing "total transparency" to supply chains by feeding SCM systems with detailed real-time information regarding the location of products in the supply chain. This real-time information, in turn, enables management to make more informed, real-time decisions. "Promoters (of the RFID technology) describe a supply chain where all assets are in perfect visibility through production, distribution, retail and consumption" (Twist, 2005). Using RFID-enabled supply chain management systems may be an important means of optimizing the agility, adaptability and alignment of the supply chain (Curtin *et al*., 2007), which can provide partnered companies with a sustainable competitive advantage (Lee, 2004).

Much research has been conducted regarding the use of RFID technology in supply chain management (Atkinson, 2004; Karkkainen, 2003; Luckett, 2004; Smith, 2005; Zhang *et al*., 2006, 2010b). For example, Karkkainen (2003) built an RFID-based data capture system for short shelf-life goods. This system increased the efficiency of the data capture process, which produced more location information, aided in the creation of better forecasts and optimized stock replenishment processes.

Summary of imperatives: A dynamic RFID data-driven supply chain management system would be a very useful tool to organizations, but prior literature and other sources indicate that no such tool exists. Using the DDDAS approach, we propose the design and implementation of just such a system. This proposed system will be able to simulate supply chain activities using real-time RFID data.

RESEARCH METHODOLOGY

Since the purpose of this research is to build an IT artifact, the design science paradigm appears to be a good fit. This section first provides an overview of design science and its research guidelines. It then presents the detail of the design and implementation of the artifact to fulfill the research objectives. Finally, it provides an outline of artifact evaluation and validation.

Overview of design science: Design science is one of the two prevailing research paradigms in the information systems discipline (Hevner *et al*., 2004). The design science paradigm has its roots in engineering and the sciences of the artificial (Simon, 1996). Design science involves building an artifact to solve a perceived problem (Hevner *et al*., 2004). Design is both a process (set of activities) and a product (artifact) (Walls *et al*., 1992). The two design processes are building the artifact and evaluating it. The four types of artifacts are constructs, models, methods and instantiations (March and Smith, 1995). The research proposed herein will be carried out in accordance with the seven guidelines (Table 1) established by Hevner *et al*. (2004).

The artifact: description, design and implementation: The proposed research is to build an artifact: a dynamic RFID data-driven supply chain management system. This artifact will have the characteristics of a DDDAS outlined in the NSF 2000 Workshop (Darema, 2000). The artifact will be able to (1) model the interactions among supply chain entities, (2) model the manner in which major events impact the overall supply chain operations, (3) use real-time RFID data during its execution to maintain a more accurate picture of the overall supply chain and (4) analyze ways to mitigate the impact of major disruptive events, such as emergency customer orders, plant breakdowns, or missed shipments.

First of all, the supply chain structure will be finalized. Usually, a typical supply chain consists of a number of organizations fulfilling differentiated roles: suppliers, manufacturers, wholesalers or distributors, retailers and customers. These organizations interact (exchange of goods and information) with each other, especially with their nearest neighbors along the supply chain.

The simulation design will adopt a discrete-event simulation structure. According to Ingalls (2002), the structural components of a discrete-event simulation include entities, activities and events, resources, global

Table 1: Design science research guidelines (Hevner *et al.*, 2004)

Guideline	Description
Guideline 1: Design as an Artifact	Design science research must produce a viable artifact in the form of a construct, a model, a method, or an instantiation.
Guideline 2: Problem Relevance	The objective of design science research is to develop technology-based solutions to important and relevant business problems.
Guideline 3: Design Evaluation	The utility, quality and efficacy of a design artifact must be rigorously demonstrated via well-executed evaluation methods.
Guideline 4: Research Contributions	Effective design science research must provide clear and verifiable contributions in the areas of the design artifact, design foundations and/or design methodologies.
Guideline 5: Research Rigor	Design science research relies upon the application of rigorous methods in both the construction and evaluation of the design artifact.
Guideline 6: Design as a Search Process	The search for an effective artifact requires utilizing available means to reach desired ends while satisfying laws in the problem environment.
Guideline 7: Communication of Research	Design science research must be presented effectively both to technology-oriented as well as management-oriented audiences.

variables, a random number generator, a calendar, system state variables and statistics collectors. Entities are objects in the supply chain environment that require definition (Banks, 1999). In a supply chain, organizations are the primary types of entities and the interactions among them are events and activities.

"Entities have attributes. Attributes are characteristics of a given entity that are unique to that entity. Attributes are critical to the understanding of the performance and function of entities in the simulation... Activities are processes and logic in the simulation. Events are conditions that occur at a point in time which cause a change in the state of the system. An entity interacts with activities. Entities interacting with activities create events." (Ingalls, 2002)

The artifact will be implemented with Java, an object-oriented programming language. The object-oriented point of view is the predominant paradigm for software design (Zhang, 2010; Zhang *et al.*, 2010a). The object-oriented paradigm incorporates such concepts as abstract data types, encapsulation, inheritance and message passing (Nance and Sargent, 2002; Zhang, 2010). Some have argued that this approach gives programmers the ability to focus on design issues rather than coding and debugging (Horstmann, 2006). Java was chosen because of its object orientation, power, safety, simplicity and breadth of the standard library. With Java, every entity will be implemented as a class. A class has both data and methods. Data define an object's states; methods are actions that an object can take. Within the supply chain, both organizations and events can be implemented as classes.

The artifact: evaluation and validation: The evaluation and validation of an artifact are crucial components of design science (Hevner *et al.*, 2004; March and Smith, 1995). To evaluate the proposed artifact, a two-phase study will be carried out. In phase one, several supply chain management experts will be asked to evaluate the concepts used to model the supply chain, its relationships among entities and its major events. This is to validate the design and make sure that the grounding for this artifact is sound.

In phase two, a comparison study will be carried out. The results from two simulations, one with the traditional approach, the other with the DDDAS approach, will be compared and the results will be analyzed. The metrics will be the quality and timeliness of information and decision making (Zhang *et al.*, 2006, 2008, 2010b).

DISCUSSION

A dynamic RFID data-driven supply chain management system would be useful for both IS researchers and practitioners. Incorporating real-time RFID data into supply chain management simulation improves existing static input simulation tools by enabling the creation of more accurate scenarios. Decision-makers can use the simulation results to control field measurements and more accurately project the impact of various decision options, thus improving the quality and timeliness of their decision making.

Although the benefits associated with the creation of this artifact are clear, the proposed research faces several obstacles. The design science research methodology poses interesting challenges. To evaluate and validate the IT artifact is one thing, to design and implement it is another. Design and implementation of the proposed IT artifact will require domain experts with broad knowledge bases and technical skills. These experts have to have solid understanding of supply chain and supply chain management, simulation, dynamic data-drive application systems and radio frequency identification technology. They also have to possess strong hands-on technical skills, especially the needed object-oriented programming skills.

Other factors to consider include the time needed and costs associated with building the proposed artifact. An

entire supply chain system integrated with RFID technology might take years to build and cost several thousands-if not millions-of dollars. However, it is our judgment that such an IT artifact and the associated improvements in the quality and timeliness of decision making make it well worth the time, cost and effort.

CONCLUSION

This study proposed the design and implementation of a dynamic RFID data-driven supply chain management system. It reviewed related concepts including supply chain management, simulation, dynamic data-driven application systems and radio frequency identification technology and showed both the importance and the usefulness of such an artifact for businesses seeking to optimize the performance of their supply chains. It also proposed, explained and discussed a design science research methodology, which is to be used to design, implement, evaluate and validate this artifact in future empirical studies.

The contribution of this paper is twofold. It illustrates the need for such a dynamic RFID data-driven supply chain management system. It also provides a concrete agenda for designing, implementing, evaluating and validating such an artifact for IS researchers and practitioners who are interested in integrating RFID technology with supply chain management systems, using the concept of DDDAS.

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