RFID-Enabled Discovery of Supply Networks

Henry H. Bi and Dennis K. J. Lin

***Abstract*—Many organizations have very limited information about the supply networks in which they are involved. For the purpose of planning business strategies, tracing products, and assuring product quality, organizations are eager to know their entire supply networks, i.e., who are their suppliers' suppliers and who are their buyers' buyers. However, because an organization's higher-tier suppliers and buyers are not directly connected to the organization, it is difficult for the organization to obtain the information about all entities and their relationships in its supply networks. This paper aims at providing an innovative solution for organizations to discover their supply networks. We first propose a new taxonomy of supply networks, which provides a necessary and systematic framework for mapping supply networks based on the mapping purpose and available information. We then develop a methodology for discovering and mapping supply networks by means of radio frequency identification (RFID)-enabled capture and sharing of the information about the movement of products throughout supply networks. This research solves a real-world supply chain management problem of what supply networks can be discovered using RFID and Internet technologies and how to discover them.**

***Index Terms*—Discovery and mapping, radio frequency identification (RFID), supply chain management, supply networks, taxonomy.**

I. Introduction

SINCE the concept of supply chains was introduced [1], there has been enormous amount of research in the area of supply chain management. Because suppliers, manufacturers, distributors, retailers, and customers are typically interconnected like networks, researchers have recently begun to study the supplying and buying relationships of organizations from the perspective of networks, i.e., supply networks [2]–[11]. In comparison, supply chains are special cases of supply networks. In supply chains, organizations, which supply raw materials and parts, produce finished goods, and distribute products to customers, are usually arranged in linear chains [6].

In a supply network, each organization knows its immediate suppliers and buyers. For the purpose of planning business strategies, tracing products, and assuring product quality, the organization may also need to find its suppliers' suppliers and its buyers' buyers. For example, in order to solve the problems of frequently delayed shipments from suppliers and decreasing demands from buyers, the organization may need to visualize and analyze its supply network to identify which tier of suppliers is most responsible for delayed shipments and to find the tier of buyers where demands originally drop. However, for many organizations, the real pictures of their supply networks, which typically comprise multiple tiers of suppliers and buyers, remain unknown. In fact, about two-thirds of companies have very little information about the supply chains and networks in which they are involved [12].

This is because a supply network consisting of many suppliers and buyers at different tiers is not easy to discover. Consider an illustrative example. A retailer sells a product assembled by a manufacturer. After receiving a few requests for repairing a component of sold products, the retailer wants to figure out its supply network for this product in order to redirect these requests to the company producing that component. In addition, to redirect repairing requests for other components in the future, the retailer also wants to find out the producers of all the other components of this product. But this is a difficult task for the retailer, because most component producers may not have direct contact with the retailer, there can be more than one producer that makes the same component, there can be companies that produce and supply semifinished products containing the component in question to the manufacturers of finished goods, and there can be distributors between component producers and the manufacturers of semifinished and finished goods. Therefore, finding all suppliers and buyers at various tiers of an organization's supply network is not a trivial task. This example will be revisited in detail in Section IV.

By relating a unique identification number to every tagged object, radio frequency identification (RFID) technology can track the movement of the object throughout a supply network. The value of RFID comes in the form of increased visibility that will reduce inventory waste and out-of-stock losses [13]–[15]. Because it is feasible to use RFID technology to capture the information about the flow of products between suppliers and buyers, a significant research problem is *whether the increased visibility provided by RFID technology can also be utilized to discover supply networks, and how*.

A. Literature Review

In the business world, all organizations are internal networks and participate in external exchange networks [16], [17]. Supply networks reflect the networking relationships between internal units of organizations as well as between supplying and buying organizations. Such relationships include typical sequential ones and complex ones such as reciprocal exchange relationships and reverse loops [3]. Harland *et al.* propose a taxonomy of supply networks [18]. Four types of supply networks are identified according to the degree of network dynamics and the degree of focal company network influence. This taxonomy

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focuses on the managerial issues of networking activities. In another study, Mills *et al.* categorize supply networks into four strategic perspectives [19]: the upstream perspective for buyers, the downstream perspective for suppliers, the static network perspective for focal organizations, and the dynamic network perspective for the creation and evolution of supply networks. However, those existing taxonomy and categorization cannot be used for mapping the topology of supply networks.

In addition, much existing literature on the issues of supply networks, such as analysis [20]–[22], optimization [23]–[25], and management [19], is based on an implicit assumption that the information about supply networks has been obtained or can be obtained. But, in general, this assumption is not warranted. In practice, each company manages its own product information, and each company usually belongs to multiple supply networks; as a result, typically there is no central database for an entire supply network [26]. Moreover, many supply networks simply emerge rather than result from purposeful design by organizations [27]. Hence, most existing supply networks remain undiscovered.

Furthermore, the research in investigating supply networks is still in an early stage [28]. Although studies like surveys and case studies have been used to discover supply networks [18], [28], these methods are "time-consuming and costly" [18, p. 26]. For example, it took almost three years for the case studies of three supply networks of center console assemblies in the automobile industry [28]. In addition, because of the complexity of supply networks, case studies typically focus on part of supply networks [18]. The complete mapping of supply networks by case studies is usually not feasible [28]. Moreover, case studies cannot easily reveal the dynamics of supply networks that are continually changing.

Because supply networks are represented by the flow of products [18], and because RFID technology can capture the information about the flow of products between suppliers and buyers, RFID technology potentially provides a feasible tool for discovering supply networks.

B. Research Objective

The objective of this research is to provide an innovative solution to discovering supply networks using the data captured by RFID technology. The discovery of supply networks means finding the information about supply networks, which exist in the business world but still remain unknown, and then mapping such information into supply network models that can be visualized. To accomplish this research objective, we first propose an alternative taxonomy of supply networks for mapping supply networks based on the mapping purpose and available information. We then develop a methodology for discovering and mapping supply networks by means of capturing and exchanging RFID data through the EPCglobal Network [29]. A concrete example is used to demonstrate this methodology.

This paper makes two contributions. First, the proposed taxonomy contributes to the theory of supply networks. Unlike existing taxonomies of supply networks, this new taxonomy provides necessary and systematic guiding principles for organizations to discover and map their supply networks using RFID technology. Second, to the best of our knowledge, this work is the first formalization of RFID-based information management to extract business intelligence from RFID data for supply networks. This paper solves a real-world problem about which supply networks can be discovered using RFID technology and how to discover them. In addition, as a broader impact, this research is of significant value to the practice of supply chain management. Visualizing their multitiered supply networks, organizations are able to optimize the activities of planning business strategies, tracing products, and assuring product quality.

This paper is organized as follows. A taxonomy of supply networks is proposed in Section II. Section III explains RFID technology and the EPCglobal Network, which are used to discover supply networks in Section IV. Section V concludes with future research directions.

II. Taxonomy of Supply Networks

Theoretically, a *supply network* can be represented by a directed graph, in which a directed arc (s, t) denotes that there is a flow of products or services from node s to node t. A node in a supply network represents a company, an organizational unit, a location, or an individual. Because this paper focuses on RFID-enabled supply networks, we will hereafter emphasize organizations and their supply networks of products where RFID technology is mostly used.

A taxonomy is a logical classification of objects based on an analysis of the possible relations of the objects [30]–[32]. The *taxonomy of supply networks* is a logical classification of supply networks based on their focus and granularity, the number of different types of products involved in supply networks, and the modeling of network flows. This taxonomy will be used in Section IV to develop a methodology for discovering and mapping supply networks.

A. Focus of Supply Networks

The focus of a supply network is on a supplier and its buyers, a buyer and its suppliers, a focal organization having both suppliers and buyers, or an industrial sector that produces and sells a product or a group of products. An organization can be engaged in multiple supply networks.

1) Supplier Networks: A *supplier network* comprises a single supplier and its buyers of different tiers. The right part of Fig. 1 shows a supplier network with three tiers of buyers. A supplier network is useful for a supplier to know how its products reach customers through various distribution channels and how its products are used as the components of products produced by some of the buyers.

2) Buyer Networks: A *buyer network* consists of a single buyer and its suppliers of different tiers. The left part of Fig. 1 shows a buyer network with four tiers of suppliers. A buyer network provides valuable information regarding how raw materials, components, and products reach the buyer and how materials and components provided by suppliers at various tiers constitute semifinished and finished products up to the buyer.

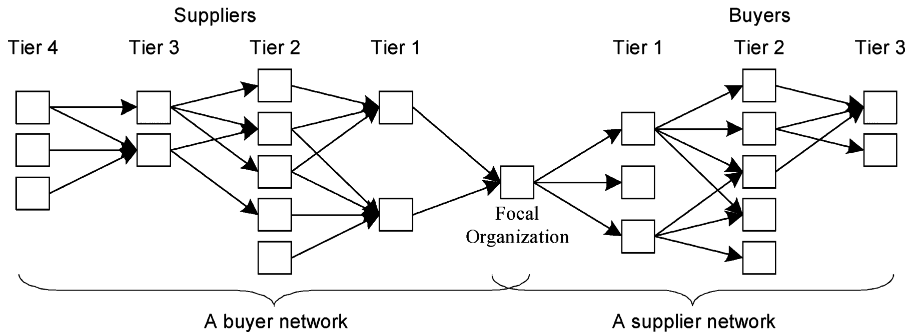

Fig. 1. Focal-organization supply network consisting of a buyer network and a supplier network.

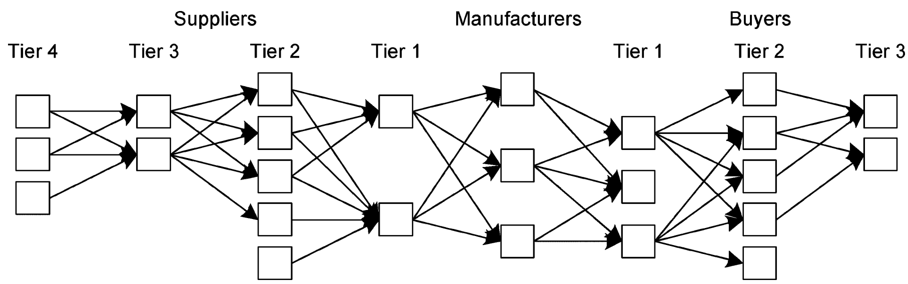

Fig. 2. Sector supply network.

3) Focal-Organization Supply Networks: A supply network looks different to each organization, which sees and manages itself as a focal organization [6]. A *focal-organization supply network*, which is a combination of a buyer network and a supplier network, comprises a focal organization and its suppliers and buyers of different tiers. Fig. 1, as a whole, is a focal-organization supply network. Such a network provides a complete picture about how a focal organization purchases materials and components, manufactures products, and distributes products.

4) Sector Supply Networks: A *sector supply network* for a product (e.g., desktops) or a group of products (e.g., desktops and laptops) comprises organizations in an industrial sector that supply materials and components, produce products, and sell products. A sector supply network usually consists of multiple focal-organization supply networks, in which the focal organizations produce the same product or the same group of products. Fig. 2 shows a sector supply network comprising three manufacturers, four tiers of suppliers, and three tiers of buyers.

More complex supply networks, such as industrial supply networks, can be defined. Such supply networks are too complex to be easily discovered or mapped. However, these complex supply networks can be decomposed into simpler ones like sector supply networks.

B. Granularity of Supply Networks

Supply networks can be described, with increasing detail, at an organizational level, geographical level, and local level. Supply networks can also be described at a national level, but this is beyond the scope of this study.

1) Organizational Supply Networks: In an *organizational supply network*, each node denotes a distinct organization.

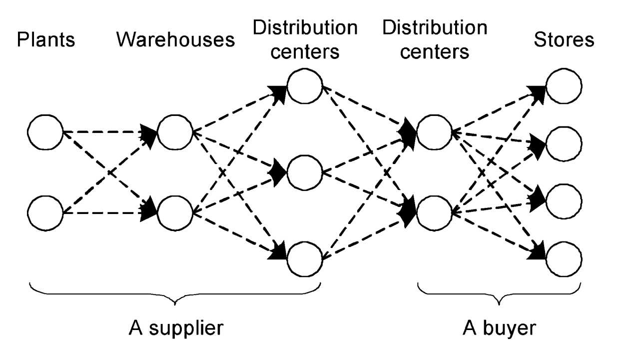

Fig. 3. Geographical supply network.

Figs. 1 and 2 are examples of organizational supply networks, in which rectangles denote organizations and solid arrows denote product flows between organizations.

2) Geographical Supply Networks: An organization may produce or stock products in different locations. In a *geographical supply network*, each node, called a *geographical node*, represents a distinct site where an organization's headquarters, a plant, a warehouse, a distribution center, or a store is located. Multiple geographical nodes may belong to a single organization. For example, Fig. 3 shows a geographical supply network with one supplier and one buyer, each of which has multiple geographical nodes. We use circles to denote geographical nodes and dashed arrows to denote product flows between geographical nodes.

3) Local Supply Networks: A *local supply network* shows the movement of products within a location. For example, Fig. 4 shows a local supply network in a supermarket store, where products move from a dock door, to a backroom, to sales floor, and eventually to a checkout point [33]. We use gray dots linked

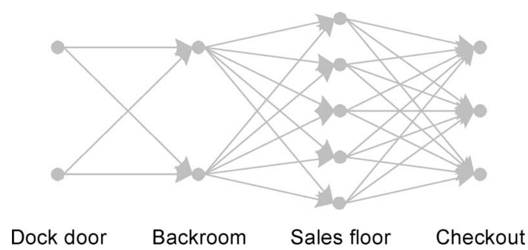

Fig. 4. Local supply network of a supermarket store.

by gray arrows to represent local supply networks. As illustrated later in Section IV, local supply networks provide the most detailed information about supply networks that can be captured by RFID technology.

Fig. 5 shows a supply network that conveys all the three levels of detail between two organizations. When such a supply network contains many organizations, the network will become huge and complicated. Thus, a layered approach is preferred for the modeling and analysis of complex supply networks.

C. Single-Commodity Versus Multicommodity Supply Networks

Depending on the number of the types of products involved, supply networks can be categorized into single-commodity and multicommodity ones. The former is typically the start point of mapping supply networks. But an organization may have hundreds or even thousands of different types of products. Multicommodity supply networks are therefore frequently used in practice.

1) Single-Commodity Supply Networks: A *single-commodity supply network* provides valuable information about how a particular product (e.g., soap) is produced and distributed and how materials are supplied to produce this product. Different companies may categorize products differently. For example, for a supplier of automobile parts, brake pads and brake shoes are two different products. But for an automobile maker, cars and trucks are two different products; brake pads and brake shoes are two parts that are used in cars and trucks. Hence, a supply network looks different to different organizations and should be mapped from the perspective of each individual organization.

2) Multicommodity Supply Networks: A *multicommodity supply network* represents producing and selling multiple types of products (e.g., soap, toothpaste, and shampoo) with necessary supplies [34]. A multicommodity supply network can be obtained by combining multiple single-commodity supply networks. Multicommodity supply networks are particularly useful for conveying the general flow of products between geographical locations or between organizations.

D. Modeling of Network Flows

If the quantified information about the flow of products is not considered, a supply network is represented by a directed graph, in which each arc (s, t) denotes that there is a product flow from node s to node t. The supply networks that we have discussed so far belong to this category. They are useful for showing the supplying and buying relationships in supply networks.

When the quantified information about the flow of products is modeled, a supply network is represented by a weighted directed graph. Each arc (s, t) is assigned a set of real numbers that represent the quantity of products flowing from node s to node t, an amount of time for moving products from node s to node t, or a combination of these data that, as shown later in Section IV, can be captured by RFID technology. Note that the cost of transporting products cannot be directly captured by RFID technology and thus is not considered in this paper.

Finally, it is worth mentioning that the completeness of supply networks is a relative concept. A supply network can be a complete one for an organization (e.g., an engine plant within an automobile company), but a partial one for another (e.g., the automobile company). Discovering and mapping complete supply networks is a challenging task. As demonstrated in Section IV, the deployment of RFID technology and the EPCglobal Network makes it possible to accomplish this task.

In summary, for a supply network, its focus indicates its horizontal scope across multitiered suppliers and/or buyers; its level of detail depicts the modeling granularity along the vertical dimension of organizational structure; its density is reflected in the number of products (possibly with the quantity of flows) in the supply network. Therefore, the value of this taxonomy of supply networks lies in that it is a comprehensive and systematic framework, which provides guiding principles for organizations to discover, map, and exploit their supply networks.

III. RFID and the EPCglobal Network

In this section, the RFID technology is introduced. Then, the data structure of the electronic product code (EPC) and the architecture of the EPCglobal Network are illustrated. RFID technology, together with the taxonomy of supply networks proposed in Section II, will be used to develop a novel methodology for discovering and mapping supply networks in Section IV.

A. RFID

A tag and a reader are two basic components of RFID technology. The tag is attached to an object that is to be identified. The tag consists of a microchip, which contains the identification information about the object to which the tag is attached, and an antenna to communicate that information via radio waves. The reader creates a radio frequency field and detects radio waves reflected back from the tag when the tag passes through the radio frequency field, thus identifying the object. Each tag is essentially a computing device that acts as a node in a network [35].

An RFID tag can be attached to a pallet, case, item, etc. Item-level tagging enables companies to have better visibility of their products [36]. In practice, item-level tagging has been used in various types of products, such as pharmaceutical products [37], clothes [38], books [39], tires [40], and avionics components [41]. Overall, about 200 million items were RFID tagged around the world in 2006 [42]. In particular, the Automotive Industry Action Group (AIAG) has developed B-11 [43], which is an RFID standard for tires and wheels and

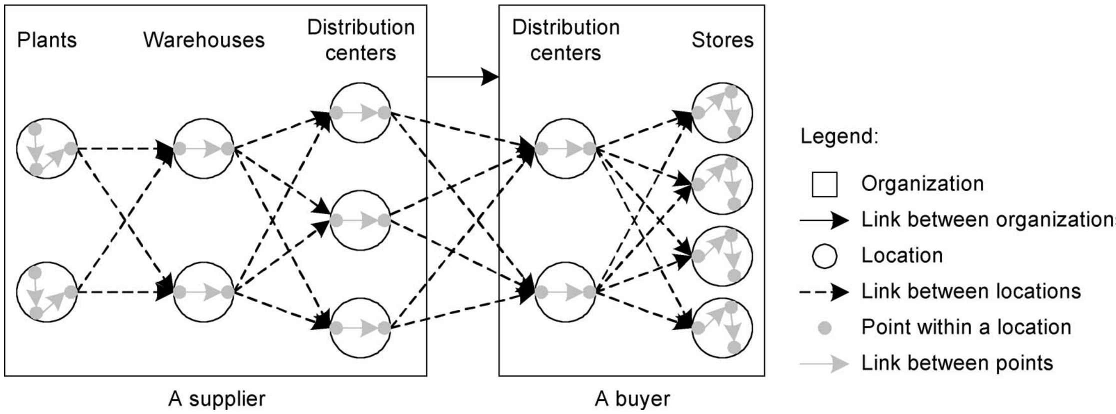

Fig. 5. Supply network containing three levels of detail.

is the first item-level RFID tracking and traceability standard in the world [44]. Clearly, RFID-tagged items can be used as components of products. In the automotive industry, for example, such practice "includes tagging parts that go deep inside a car, so that information about them could later be easily picked up with a reader, or tagging parts with information that an auto dealer's service desk could then use to find replacements" [45].

A product can be related to multiple RFID tags if it not only has its own tag but also is made of tagged components. Collision avoidance algorithms are developed to allow tags to be sorted and individually selected [46]. RFID readers can tell some tags to respond and others not to.

B. *EPCglobal Network*

The EPCglobal Network is a networking infrastructure for collecting, sharing, and accessing dynamic information about the physical movement of each EPC-tagged object as it passes throughout supply networks [47].

1) EPC Data Structure: EPC is an identification scheme for universally and uniquely identifying objects to which EPC tags (also called RFID tags) are attached. Each EPC number is a key that links an object (i.e., an item, case, or pallet) to detailed data about the object in information systems. There are two different lengths of EPC tag data that have been ratified by the EPCglobal Board: 64 bits and 96 bits [48]. Fig. 6 shows the EPC tag data structure of the 96 bit version [46], [48], [49]: Header identifies the version of EPC itself; General Manager Number identifies an organization that maintains the numbers in the fields of Object Class and Serial Number; Object Class refers to a unique type of product produced by an EPC general manager; Serial Number uniquely identifies each item within an object class. The EPC serial number allows individual item tracking, which is the key feature and advantage that distinguish EPC from a bar code standard UPC (universal product code) [46], [50], [51]. This feature enables RFID technology to capture the information about the movement of individual products in supply networks.

2) Architecture of the EPCglobal Network: Leveraging RFID and Internet technologies, the EPCglobal Network is a neutral medium that provides real-time and accurate data about

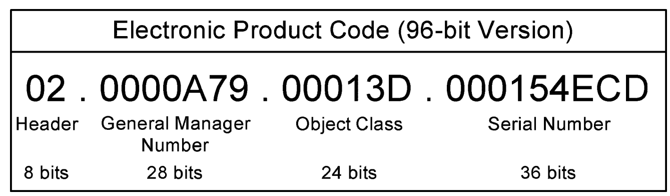

Fig. 6. EPC tag data structure.

individual products and their movement in supply networks. In the EPCglobal Network, such data are collected, shared, and utilized across supply networks around the world.

The EPCglobal Network comprises EPC, RFID technology, and supporting software. Fig. 7 shows the architecture of the EPCglobal Network that consists of five components [29], [52].

1) *EPC*: EPC uniquely identifies each object in motion in supply networks.
2) *ID system*: The ID system consists of EPC tags and EPC readers (also called RFID readers). A unique EPC is stored in each EPC tag, which is attached to a pallet, case, or item. An EPC tag communicates its EPC to an EPC reader via radio waves. The EPC reader delivers the information of the EPC to local information systems through the EPC Middleware.
3) *Middleware*: The EPC Middleware manages communication and data exchange between EPC readers and EPC Information Services (EPCIS) as well as information systems.
4) *Discovery Services*: The Discovery Services enable each organization's EPCIS to find where the data related to a specific EPC are; that is, the organization's EPCIS communicates with the Discovery Services to find the EPCISs of all the other organizations, whose readers have previously read the EPC tag in question. Object Naming Service (ONS) is a component of the Discovery Services. Given an EPC, ONS sends the Internet addresses for the EPCISs of all the other organizations, whose readers have previously read the EPC in question, to the EPCIS of the requesting organization.
5) *EPCIS*: EPCIS records information when a reader reads an EPC tag, and informs the Discovery Services of that read.

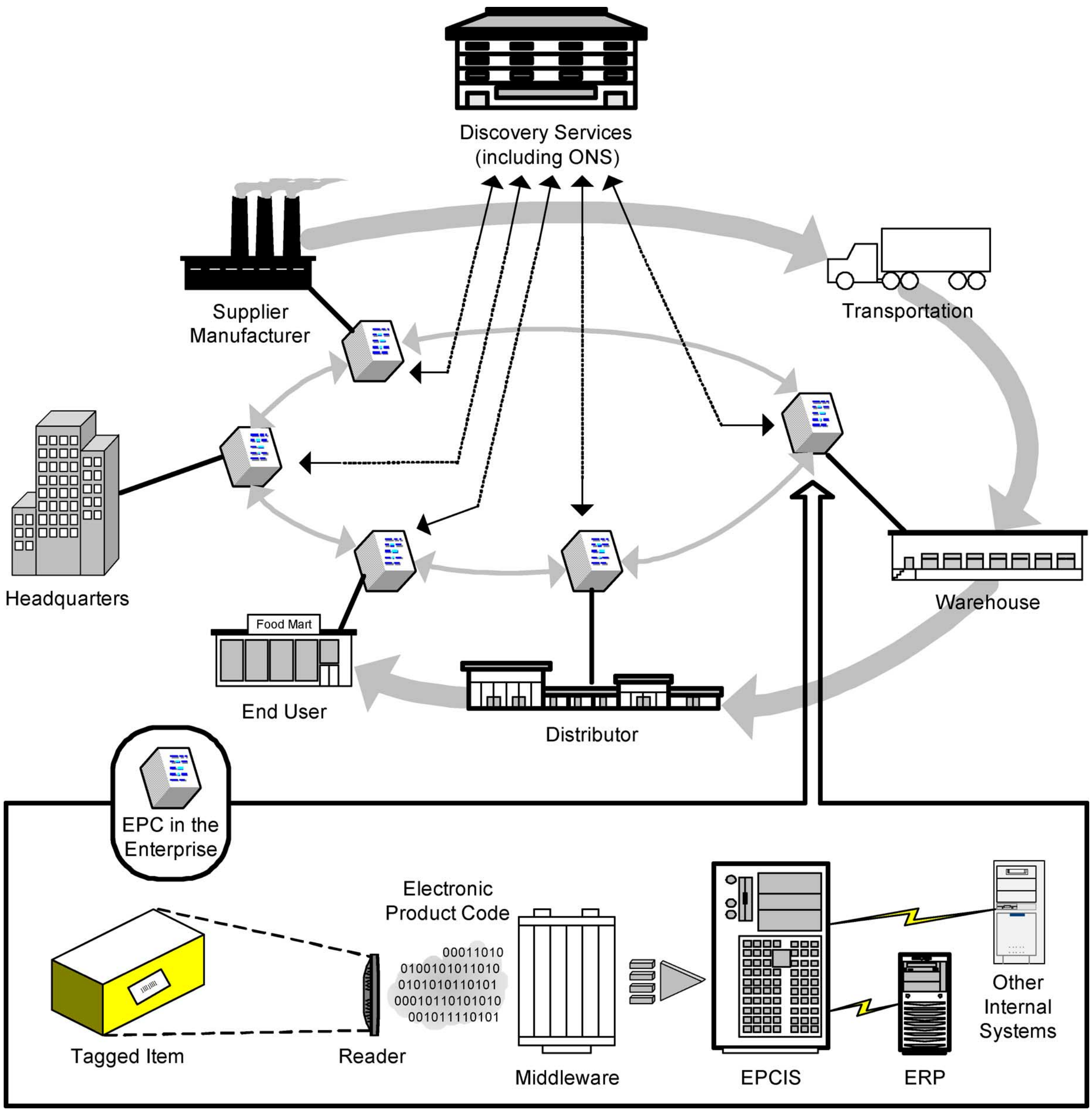

Fig. 7. Architecture of the EPCglobal Network (adapted from [29] and [53]).

EPCIS also enables trading partners to exchange EPC-related data, which are stored in their local information systems. Each EPCIS communicates with other EPCISs to request access to the data related to the EPC in question. In the EPCglobal Network, actual access to data is managed at the local level by each EPCIS, such that each organization determines who can access its data.

In summary, the EPCglobal Network provides an infrastructure for RFID-enabled information management, in which EPC tags serve as pointers that wirelessly link EPC-tagged items, cases, and pallets to detailed product information stored in databases accessible through Internet.

IV. Discovering Supply Networks Using RFID

In this section, we first formalize the EPCglobal-Network-based information management. We then develop a methodology for discovering and mapping supply networks based on such information management and on the taxonomy of supply networks proposed in Section II. A concrete example is used to illustrate this methodology.

This methodology is based on an assumption that business partners in supply networks are willing to share information captured by RFID technology. This assumption can be justified from two aspects. First, RFID technology gives unprecedented visibility of material flows from raw materials to finished goods in supply networks [15], [54], [55]. Such visibility throughout supply networks requires unprecedented collaboration between supply-network partners to share information [56], because “RFID benefits for supply chains are derived mainly from information sharing among supply chain members” [57, p. 912]. Second, information sharing is required in many industries and can be enhanced by RFID technology. For example, in the food

TABLE I
ORGANIZATION-RELATED DATA STORED IN THE DISCOVERY SERVICES OF THE EPCGLOBAL NETWORK

Data	Interpretation
Organization	An organization that assigns EPC to its products
General Manager Number	A unique number related to a distinct organization
URL	The Internet address of an organization's EPCIS

industry, outbreaks of food poisonings call for "accurate tracing capabilities to identify sources of contamination and track contaminated foods to their destinations" [58, p. 213]. This may well go beyond immediate suppliers and immediate distributors of food. RFID technology can help achieve end-to-end traceability across the food supply chain [59]. In the automotive industry, 11.2 million vehicles were recalled in the United States in 2006 [60]. The safety recall of a defective auto part usually involves information sharing among auto part producers, distributors, auto makers, dealers, end users, etc., in automotive supply networks. In the pharmaceutical industry, the success in implementing RFID technology requires unprecedented collaboration between supply-chain partners to share the data captured at each point in a drug's movement from manufacturer to consumer [56]. Therefore, although there do exist companies that do not like to share information with their business partners [57], for organizations that want to be part of supply networks for the purpose of "reducing costs, achieving greater focus, and finding new opportunities for increasing revenue" (p. 43) [61], they are well motivated to exchange information with their business partners. Hence, for many industries, information sharing is feasible, and thus, the methodology presented in this section can be applied.

A. EPCglobal-Network-Based Information Management

Although there is nothing new about RFID technology described in this paper, this research is the first to formalize RFID-based information management for supply networks. Such information management addresses three issues that are related to the discovery of supply networks: (1) What data about organizations, products, and sales orders are available, and where are they stored? (2) What information about the movement of products throughout supply networks can be tracked using RFID technology? (3) What data for discovering supply networks can be deduced from the RFID data?

The EPCglobal Network also faces other challenging issues such as the management of the substantial amount of data generated by RFID technology, system security, costs, work environment, and industry standards [62], [63]. These issues are beyond the scope of this paper.

1) Organization-Related Data—Issue (1): As a central and neutral medium, the Discovery Services of the EPCglobal Network manage the organization-related data. As shown in Table I, the Discovery Services assign a unique General Manager Number to each organization that, in turn, assigns EPC to its products. The Discovery Services also keep the Internet address of each organization's EPCIS to facilitate information exchange between organizations.

2) Product and Sales Order Data—Issue (1): In the existing practice of production, sales, and purchasing, product and sales order data are stored in the information systems of organizations. In a manufacturer's EPCIS server and information systems, each EPC number is related to detailed information (in Table II) about an EPC-tagged product.

There are also sales order data stored in the information systems of both the supplier and the buyer, as shown in Table III.

3) Information Captured by EPC Readers—Issue (2): EPC readers placed at gateways throughout supply networks read each tagged object when it passes, and communicate the EPC identification number and the date, time, and location of the read to a local organization's EPCIS [29]. Table IV shows three data that are captured by EPC readers to the EPCglobal Network. A location can be the site of a manufacturer, warehouse, distribution center, or end user, as shown in Fig. 7.

4) Data Deduced for Discovering Supply Networks—Issue (3): Through the Discovery Services, organizations that have access to the same EPC number can find each other and then share the data (which are listed in Table I through Table IV) about an EPC-tagged object and its movement throughout supply networks. Such information sharing enables each organization to deduce useful data (in Table V) for discovering its supply networks.

B. Mapping Supply Networks

After figuring out the data that can be captured by RFID technology and shared for discovering supply networks, the next step is to use those data to map supply networks. Based on the taxonomy of supply networks in Section II and the data structure presented in Section IV-A, Table VI gives a novel four-dimension matrix for mapping supply networks. The following three steps, as summarized in Fig. 8, constitute a formal mapping schema for an organization to map a supply network based on Table VI:

Step 1: Determine the scope of the to-be-mapped supply network by locating a cell in Table VI. This step is accomplished through four substeps:

1) Determine whether each node in the to-be-mapped supply network is an organization, a geographical location, or a point within a location. This substep determines the granularity of the supply network. In Table VI, the dimension of *granularity* describes what the nodes in a supply network represent: organizations, geographical locations, or places of EPC readers. Because RFID technology is used to discover supply networks, for local supply networks we focus on the places of EPC readers.
2) Identify the problems (e.g., delayed shipments or decreasing demands) and the need for visualizing the supply network (e.g., analyzing which tier of suppliers delays shipments or which tier of buyers purchases less), and then determine whether to map the supply network with multitiered suppliers, multitiered buyers, or both. In Table VI, the *focus* dimension determines the shape of the supply network. Depending on the situation, we can also say a focal-location supply network or a focal-EPC-reader

TABLE II
PRODUCT DATA STORED IN A MANUFACTURER'S INFORMATION SYSTEMS

Data	Interpretation
Product	The name and type of an EPC-tagged product
Object Class	A unique number related to a distinct type of product within an organization
Serial Number	A unique number related to a distinct item within an object class
BOM	Bill of materials – a product's components and their quantities
Packaging quantity	The number of selling units in a case or on a pallet

TABLE III
SALES ORDER DATA STORED IN A SUPPLIER'S AND A BUYER'S INFORMATION SYSTEMS

Data	Interpretation
Buyer's PO number	A buyer's purchase order number
Buyer	A buyer related to a buyer's PO number
Supplier	A supplier related to a buyer's PO number
Product	A product related to a buyer's PO number
Order quantity	The quantity of an ordered product

TABLE IV
DATA CAPTURED BY AN EPC READER TO THE EPCGLOBAL NETWORK

Data	Interpretation
EPC	An EPC identification number related to an EPC-tagged object
i	The location i of a tag read
t_i	The date and time of a tag read at location i

supply network instead of a focal-organization supply network. Note that sector supply networks are not included in this dimension. We argue that, currently, sector supply networks like Fig. 2 usually cannot be discovered using RFID technology, because no organization in Fig. 2 has access to all EPC numbers assigned by different organizations. In the future, however, it is possible that value-added infomediaries emerge in the need for solving certain sectorwide and even industrywide problems that individual organizations cannot address. Such infomediaries can build up sector supply networks and industry supply networks from multiple focal-organization supply networks.

3) Determine whether one or multiple types of products are to be represented in the supply network. The former focuses on the issues concerning only one product, whereas the latter emphasizes the aggregated supplying and buying relationships. In Table VI, the dimension of the *number of commodities* determines whether one or multiple types of products are involved in the supply network.
4) Determine whether quantified information about the flow of products and transportation time, which is shown in the dimension of *network flows* in Table VI, needs to be represented in the supply network. If network flows are not modeled, then directed links between nodes are sufficient; otherwise, network flows can be modeled by a flow quantity and/or an amount of time for transporting products between each pair of nodes. Note that cost, although an important parameter in network flows, cannot be directly captured by RFID technology.

Step 2: Determine the data needed for mapping the supply network and deduce those data (as shown in Table V) from the shared RFID data. For clear presentation, we do not fill up all cells in Table VI because much information would be redundant, but use three typical cells to explain the required data for mapping various supply networks:

1) For cell A, a focal-location supply network for multiple commodities is to be mapped using the following data: a set of locations including a focal location, a group of commodities, and the transit information of any of these commodities from upstream tier-1 locations to the focal location, from upstream tier-2 locations to upstream tier-1 locations, etc., and from the focal location to downstream tier-1 locations, then to downstream tier-2 locations, etc.
2) For cell B, a single-commodity organizational buyer network including flow information is to be mapped on the basis of the following data: a group of organizations including a buyer, a specific commodity, and the quantified flow of the commodity from tier-1 suppliers to the buyer, from tier-2 suppliers to tier-1 suppliers, and so on.
3) For cell C, a single-commodity local supplier network is to be mapped using the following data: the places of a set of EPC readers including one that acts as a "supplier" EPC reader, a commodity, and the information about the movement of the commodity from the "supplier" EPC reader to tier-1 EPC readers, then to tier-2 EPC readers, and so on. For example, in order to study how AA batteries are effectively moved from a backroom to several sales shelves and then to checkout points in a supermarket store, a single-commodity local supplier network can be used. In this network, the EPC reader in the backroom acts as the "supplier" EPC reader, EPC readers on sales shelves are tier-1 EPC readers, and those at checkout are tier-2 EPC readers.

Step 3: Use the deduced RFID data (in Table V) to map the supply network as a (weighted) directed graph, where nodes denote organizations, geographical locations, or sites of EPC readers and directed arcs denote the flow of products. Other meaningful information can also be revealed by the supply network, such as how many tiers of buyers and suppliers are in the network, who produces or distributes what, where EPC tags are assigned, and how long a product stays in a place or in transit from one location to another.

C. An Example

An example, which is related to the motivating example in Section I, is used to demonstrate how a supply network can be

TABLE V
DATA DEDUCED FROM THE SHARED RFID DATA FOR DISCOVERING SUPPLY NETWORKS

Data	Interpretation
k or $k_1, \ldots,$ and k_n	A product k or a group of products $k_1, \ldots,$ and k_n ($n \geq 2$)
(i, j)	There exists a flow of products from node i to node j
$x_{ij}(k)$ or $x_{ij}(k_1, \ldots, k_n)$	The quantity of the flow of product k from node i to node j, or the quantity of the flow of products $k_1, \ldots,$ and k_n from node i to node j
$\Delta t_{ij}(k)$ or $\Delta t_{ij}(k_1, \ldots, k_n)$	The amount of time for the flow of product k from node i to node j, or the amount of time for the flow of products $k_1, \ldots,$ and k_n from node i to node j

TABLE VI
FOUR-DIMENSION MATRIX FOR MAPPING SUPPLY NETWORKS

		Number of commodities ($n \geq 2$)							
		Single commodity: k	Multiple commodities: $k_1, \ldots, k_n$	Single commodity: k	Multiple commodities: $k_1, \ldots, k_n$	Single commodity: k	Multiple commodities: $k_1, \ldots, k_n$		
Focus	Supplier network					C		Without network flows: (i, j)	Network flows
								With network flows: (i, j), x_{ij}, Δt_{ij}	
	Buyer network							Without network flows: (i, j)	
		B						With network flows: (i, j), x_{ij}, Δt_{ij}	
	Focal-organization supply network				A			Without network flows: (i, j)	
								With network flows: (i, j), x_{ij}, Δt_{ij}	
		Organizational supply network: nodes – organizations		Geographical supply network: nodes – geographical locations		Local supply network: nodes – places of EPC readers			
		Granularity							

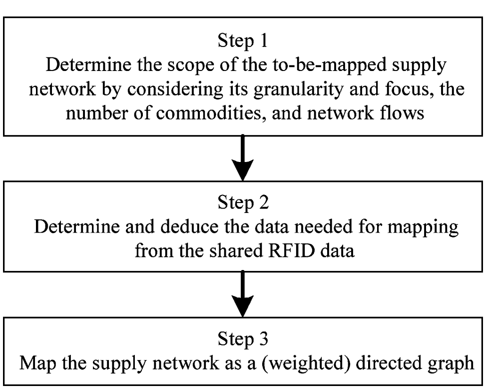

Fig. 8. Three-step mapping schema of RFID-enabled supply networks.

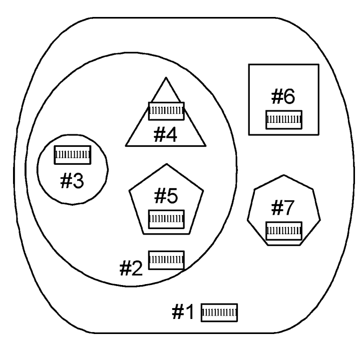

Fig. 9. Product structure.

discovered and mapped using RFID data. Suppose that a retailer *A* sells a product that is assembled by a manufacturer *B*. Every product item and each of its components are attached an EPC tag. The structure of the product with seven EPC tags is shown in Fig. 9. Note that component #2 is a subassembly that consists of three smaller components.

Step 1: Determine the scope of the to-be-mapped supply network by locating a cell in Table VI. After receiving a few requests for repairing component #4, retailer *A* decides to figure out its buyer network at the organizational level for this product in order to redirect these repairing requests to the company that produces component #4. Retailer *A* is also interested in finding the amount of time for the flow of products between entities in this buyer network. Thus, retailer *A* locates cell *B* in Table VI.

TABLE VII
RFID DATA SHARED THROUGH THE EPCGLOBAL NETWORK

No.	Event	Company	Date	Ship to/from
1	Assign EPC to component #4	*C*	6/1/2007	n/a
2	Assign EPC to component #5	*C*	6/3/2007	n/a
3	Assign EPC to component #3	*D*	6/7/2007	n/a
4	Ship component #3	*D*	6/8/2007	To *E*
5	Receive component #3	*E*	6/9/2007	From *D*
6	Ship component #4	*C*	6/13/2007	To *E*
7	Ship component #5	*C*	6/13/2007	To *E*
8	Receive component #4	*E*	6/14/2007	From *C*
9	Receive component #5	*E*	6/14/2007	From *C*
10	Assign EPC to component #2	*E*	6/17/2007	n/a
11	Ship component #2	*E*	6/27/2007	To *F*
12	Receive component #2	*F*	6/29/2007	From *E*
13	Ship component #2	*F*	7/6/2007	To *B*
14	Receive component #2	*B*	7/8/2007	From *F*
15	Assign EPC to component #6	*G*	7/12/2007	n/a
16	Assign EPC to component #7	*H*	7/13/2007	n/a
17	Ship component #7	*H*	7/14/2007	To *B*
18	Receive component #7	*B*	7/15/2007	From *H*
19	Ship component #6	*G*	7/19/2007	To *B*
20	Receive component #6	*B*	7/22/2007	From *G*
21	Assign EPC to product #1	*B*	7/27/2007	n/a
22	Ship product #1	*B*	8/3/2007	To *A*
23	Receive product #1	*A*	8/5/2007	From *B*

TABLE VIII
DATA DEDUCED FROM THE SHARED RFID DATA IN TABLE VII FOR MAPPING A BUYER NETWORK (UNIT OF Δt: DAY)

From \ To	*A*	*B*	*C*	*D*	*E*	*F*	*G*	*H*
A								
B	#1 $\Delta t_{BA}=2$	(#1) $\Delta t_{BB}=7$						
C			(#4) $\Delta t_{CC}=12$; (#5) $\Delta t_{CC}=10$		#4, #5 $\Delta t_{CE}=1$			
D				(#3) $\Delta t_{DD}=1$	#3 $\Delta t_{DE}=1$			
E					(#2) $\Delta t_{EE}=10$	#2 $\Delta t_{EF}=2$		
F		#2 $\Delta t_{FB}=2$				#2 $\Delta t_{FF}=7$		
G		#6 $\Delta t_{GB}=3$					(#6) $\Delta t_{GG}=7$	
H		#7 $\Delta t_{HB}=1$						(#7) $\Delta t_{HH}=1$

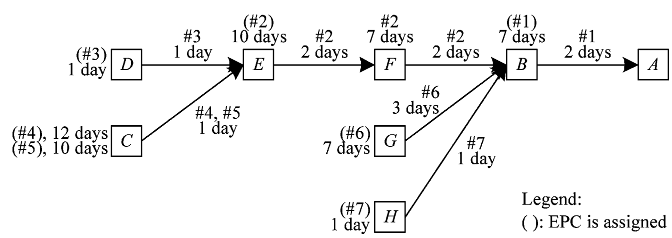

Fig. 10. Organizational buyer network mapped from the data in Table VIII.

Step 2: Determine and deduce data for mapping a single-commodity organizational buyer network with flow information. Those data include product #1 and its components, supplying organizations at different tiers, supplying relationships between organizations, and the amount of time for product flows between organizations.

After an RFID reader selectively reads seven EPC tags in a product received on August 5, 2007, retailer *A*'s EPCIS server sends a query containing those seven EPC numbers to the Discovery Services of the EPCglobal Network. The Discovery Services return the Internet addresses for the EPCISs of the companies that assign those seven tags and that (as distributors) read any of these tags. Then, retailer *A*'s EPCIS server sends a query with the related EPC number to each EPCIS of those companies, respectively, and summarizes the replies from the EPCIS servers of those companies in the order of events in Table VII. For simplicity of illustration, we assume that the RFID data in Table VII reflect general scenarios for all products that are the same as the one received on August 5, 2007, and that companies assign EPC to components or products on the same day when they are produced. Note that information on locations is omitted in Table VII, because an organizational network is of interest in this example.

On the basis of the shared RFID data in Table VII, retailer *A* deduces the data, as shown in Table VIII, which are to be used to map this buyer network. The data in each filled cell in Table VIII indicate a link between two companies, the component or product involved, and an amount of time used to transport this component or product from one company to another. If in a cell the "from" company is the same as the "to" company, then the data in this cell indicate an amount of time that a component or product stays in this company. If in a cell a component or product number is placed in parentheses, this means that the company assigns EPC to this component or product. For instance, the data in cell (*B*, *A*) mean that it takes 2 days to ship product #1 from company *B* to company *A*; the data in cell (*B*, *B*) reveal that company *B* assigns EPC to product #1, and that product #1 stays in company *B* for 7 days before it leaves company *B*.

Step 3: Use the deduced RFID data to map the buyer network. Based on the data in Table VIII, retailer *A* maps its organizational buyer network for product #1 in Fig. 10. This network provides useful information to retailer *A*. First, this network consists of four tiers of suppliers. Second, the number in parentheses (e.g., (#3)) of a component or product is placed beside a node (e.g., company *D*) that assigns EPC to this component or product. The number of days that a component or product stays in a company is also placed beside a node (e.g., 1 day for component #3). Each arc is related to the transportation of a component or product and an amount of time for shipping it. The longest time period from producing a component to receiving product #1 by retailer *A* is 43 days for component #4. Third, company *F* seems to be a distributor rather than a manufacturer, because it does not assign any EPC. Finally, retailer *A* can contact company *C* directly for the problems of component #4.

The aforesaid example illustrates how to discover an organizational buyer network involving flows of a single commodity and its components with item-level tagging. In comparison, if case- or pallet-level tagging is used for a product and its components, then fewer tiers of suppliers may be found directly through the EPCglobal Network by a company that purchases the product. This is because the company does not have the EPC information on the components of the product. As a result, through the EPCglobal Network, the company can still find the manufacturer and distributors of the product, but cannot directly discover the tiers of component suppliers.

In addition to the aforesaid example, we discuss other scenarios related to Table VI as follows.

1) Consider an organizational supplier network of a single commodity with item-level tagging. Suppose that, for the purpose of accurate product safety recalls, a manufacturer of an EPC-tagged component (e.g., tires) needs to find out all companies that distribute this component, use this component to produce finished products (e.g., vehicles), or distribute finished products. In this case, there are two types of buyers that are to be discovered. First, for the companies that distribute this component or use this component to produce finished products, they record and track the EPC of this component in their information systems. The component manufacturer can find those companies directly through the EPCglobal Network. Second, to discover the companies (e.g., automobile dealers) distributing finished products that contain this component, the component manufacturer needs to first find out the companies that produce finished products. Then, those companies can use the EPC of finished products to help discover the distributors of finished products. In comparison, if case- or pallet-level tagging is used, the supplying relationships still can be found by tracking the movement of components and finished products. But it is difficult, if not impossible, to track how each component is used in producing a product.
2) A geographical supply network may belong to a single organization or extend across multiple organizations. To find a geographical supply network across multiple organizations, information exchange between organizations through the EPCglobal Network is required. Suppose that, in order to optimize the flow of a group of products in terms of transportation time, a supplier tries to find the geographical supply network (similar to Fig. 3) extended from (1) its three plants to; (2) its five warehouses, to (3) its eight distribution centers, and then to (4) buyers' distribution centers. The network connections between the tiers (1), (2), and (3) within the same organization can be found through the organization's information systems that record EPC tag reads at different locations for any of those products. The network connections between the tiers (3) and (4) can be found via information exchange through the EPCglobal Network. In addition, based on EPC tag reads during a period of time, the average time for a specific type of product that is transported between two locations or stays in the same location can be calculated.
3) A local supply network for a tagged item can be easily found from a local information system that records EPC tag reads of that item at different places within a location. Such a local supply network is useful. For example, it can help the customer to quickly locate a product on the sales floor in a supermarket; it can also be used to find a misplaced item, which is in a place (i.e., a node in the network) different from the place where the other identical items are.
4) A focal-organization supply network consists of a buyer network and a supplier network, and thus, can be mapped by discovering those two networks first. A supply network of multiple commodities can be built up by combining multiple single-commodity supply networks. A supply network with network flows can be mapped by adding flows of products to a supply network without network flows.
5) It should be noted that, in addition to representing quantified information of product flows, RFID-enabled supply networks can be used to monitor the quality of products. For example, RFID solutions have been developed to locate, track, and protect perishable products (e.g., food and flowers) [64]. Specifically, an EPC tag with temperature logger is attached to a perishable product with configured threshold for alerting services. A field inspector is used to read the EPC tag and suggest a service—accept, inspect, or reject. The change in quality can be clearly indicated between the reads of the EPC tag at different locations or in different organizations, and thus, can be monitored in an RFID-enabled supply network.

V. Conclusion and Future Research

In this paper, we have developed an innovative methodology for using RFID technology to discover supply networks. We have also proposed a new taxonomy of supply networks, which provides necessary and systematic guiding principles for mapping various supply networks. Leveraging RFID technology, an organization is able to visualize not only its supply networks at the organizational level, but also its internal and geographical supply networks at more detailed levels (e.g., warehouses, distribution centers, and stores) with focus on one or multiple types of products.

Given that most existing organizations have little information about their customers and suppliers that are beyond their immediate trading partners, RFID-enabled discovery of supply networks brings significant value to the research and practice of supply chain management. From the practical perspective, RFID-enabled discovery of supply networks is feasible and effective by means of extracting business intelligence from RFID data. The shared RFID data (about the movement of products in supply networks) through the EPCglobal Network can be used to map various supply networks such as buyer networks, supplier networks, and focal-organization supply networks.

This research also has important managerial implications. First, the dynamics of supply networks largely depends on the topology of supply networks [65]. Good design of the topology of supply networks, after they are discovered, can strategically optimize their reliability against failure at nodes [66]. Second, discovering and visualizing supply networks makes it possible for an organization to optimize its purchasing and supplying strategies [5]. Using accurate information on the movement of products throughout supply networks, the organization can formulate strategies for minimizing inventory holding costs, improving forecasting accuracy, and reducing transit time. Third, outsourcing of manufacturing [67] and logistics [68] is leading to more and more supply networks involving organizations in different countries and continents [69]. In order to trace products and assure product quality in those complex supply networks, organizations need to be able to pinpoint where components are produced, where products are assembled, and where components or products are stored and how they are distributed. This can be facilitated using RFID-enabled organizational and geographical supply networks.

Looking forward, there are still many challenging issues related to RFID-enabled supply networks. First, because RFID technology generates a substantial amount of data, computational algorithms need to be developed for mining RFID data so that different types of supply networks can be mapped. Second, this proposed methodology for data collection and sharing can be further developed for RFID-enabled knowledge integration and management [11]. Integrated knowledge management throughout supply networks can facilitate collaborative planning, forecasting, and replenishment (CPFR) [70] as well as collaborative new product development involving manufacturers, suppliers, and customers [71]. Third, supply networks change over time [72]. This proposed methodology needs to be extended to use RFID technology to effectively monitor dynamically changing supply networks, such as changes of suppliers and buyers, introduction of new products, and variations of production, purchasing, and sales. Fourth, each organization needs to ensure that its focal-organization supply networks are in alignment in order to make both of its buyers and suppliers satisfied [73]. A future research issue is to advance this proposed methodology so that RFID-enabled supply networks can be aligned in both product flows and information flows. Finally, although sector supply networks and industry supply networks can be built up from multiple organizational supply networks, this proposed methodology needs to be extended to provide detailed guiding principles for infomediaries to discover and map sector and industry supply networks.

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