THE PROMISE OF RFID-BASED SENSORS IN THE PERISHABLES SUPPLY CHAIN

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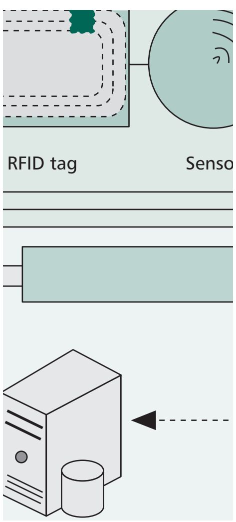

The authors provide a tutorial of RFID-based environmental sensors in the perishables supply chain. They also report on an exploratory study where they use RFID-based temperature sensors to examine the condition of perishable products in two long-distance product shipments.

ABSTRACT

Perishable goods present some of the biggest challenges for today's supply chain management due to the high number of product variations with different perishability characteristics, requirements to account for the flow of products, and large volumes of goods handled over long distances. The elimination of even a small percentage of spoilage can add up to a significant performance improvement for the business. The optimal management of the perishables supply chain depends on the level of granularity (and timeliness) of product visibility, which can be used to provide answers to questions such as "where is my product" and "what is the condition of my product." The foundation for such visibility is an effective and efficient information system enhanced with sensors and RFID technology. In this article, we provide a brief tutorial and applications survey of RFID-based environmental sensors in the perishables supply chain. We also report on the results and lessons learned of an exploratory study where we use RFID-based temperature sensors to examine the condition of perishable products in two long-distance product shipments.

INTRODUCTION

As the complexity of conducting business increases, researchers and practitioners are developing new and novel technologies to mitigate the adverse effects of these complexities. Increasingly, the world is becoming flatter, the supply chain involves worldwide endeavors, and competition is growing to be an all-inclusive global challenge. In this environment, managing business operations requires new and improved information technologies. Radio frequency identification (RFID), a promising technology for ubiquitous computing, has emerged in response to such needs. When combined with sensors, RFID can help manage objects that are environmentally sensitive (perishable products, raw materials, pharmaceuticals, etc.).

The perishables supply chain, in particular, needs help. Consider the following. The loss of perishable products is estimated at approximately $35 billion annually (Hoppough, 2006). In grocery retailers, more than half of all loss is attributed to perishable goods, although these comprise only a quarter of the inventory (Edwards, 2007). Almost one third of all customers cite dissatisfaction with product freshness as a key reason to avoid a particular store (Fresh Trends, 2005), and in the United States the number of food recalls is increasing at an alarming rate (Dang and Carson, 2007).

Perishable goods present some of the biggest challenges for supply chain management due to the high number of variants with different perishability characteristics, requirements to account for the flow of goods in some supply chains, and large volumes of goods handled over long distances. Although food represents a major portion of the perishables portfolio and is the focus of this article, there are many other products, including fresh cut flowers, pharmaceuticals, cosmetics, and auto parts, among others, that require strict environmental controls to retain their quality. As the volume of goods handled increases, the likelihood of problems increases. The elimination of even a small percentage of spoilage, for example, adds up to a significant improvement in the performance of the supply chain. Therefore, the optimal management of the perishables supply chain is of paramount importance to businesses in this market segment.

The success of today's highly volatile perishables supply chains depends on the level (and timeliness) of product visibility. Visibility should provide answers to the questions of "where is my product" and "what is the condition of my product." The foundation for such visibility could be an effective and efficient information system enhanced with sensors and RFID technology. In this article, we specifically explore the use of RFID-based temperature sensors and examine some sample applications of these sensors in monitoring the condition of perishable products in the supply chain.

RFID-BASED SENSORS

RFID is a technology that uses radio waves to automatically identify objects. The identification is done by the communication between the tag

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(a microchip that stores the unique identification code of the object along with an antenna) and the reader (an electronic interrogator that receives the stored identification information from the tag that falls within its RF range).

RFID technology has been successfully used in a wide range of applications including automated toll collection, tracking of children in theme parks, secured access to sensitive systems, livestock management, electronic payment systems, and automated manufacturing control systems. The current popularity of the technology is based on object identity and its ability to track (where is my stuff?) and trace (where was my stuff?) product in the supply chain (Niederman *et al.*, 2007), leading towards supply chain optimization (Delen *et al.*, 2007). Generally, the objects tracked by RFID can be of two main types (Cho *et al.*, 2007):

- Environmentally sensitive objects (e.g., food, medicine, blood) that are very sensitive to environmental conditions such as temperature and humidity
- Environmentally non-sensitive objects (e.g., durable products and machines) that are not affected by environmental conditions

In this work we focus on environmentally sensitive objects (i.e., perishable goods).

RFID can be combined with a sensor to monitor different elements in their environment, including temperature, humidity, shock, and vibration. The most popular of these is the temperature sensor. For simplicity and to keep the discussion focused, we examine the use of RFID-based temperature sensors in this article. Sometimes referred to as "data loggers," these sensors record temperature digitally and store the data until downloaded and reset by an RFID reader (Treat, 2008).

Unlike the pure passive tags commonly used in the retail supply chain, these sensors require power, which is usually supplied by a battery built into the RFID tag. Based on the power source, RFID tags can be generally classified as (Treat, 2008):

Passive tags: These tags have no power source of their own. They can only be powered up (activated for interrogation) when they enter an electromagnetic field. These are the most commonly used tags and also the cheapest.

Semi-passive tags: These tags have a battery as part of the tag, but the battery is used only to collect data, not to transmit data. The data loggers mentioned earlier are primarily semi-passive tags.

Active tags: These are "on" all the time, primarily for data transmission, but can also be used for data logging. Due to the continuous power requirement, they are significantly more expensive, heavier, and bulkier.

Depending on the need, sensor-equipped tags used in the perishables supply chain can be active or semi-passive. If the data needs to be communicated in real time, one should consider using active tags; otherwise, the use of semi-passive tags is preferred. The sample applications explored in this article used semi-passive tags.

One should also consider the issue of memory requirements (which may vary from a few data points to thousands) and the data collection procedures. Generally, as the memory requirement increases, so does the size and cost of the hardware. With respect to data collection, there are several alternatives (again, based on need):

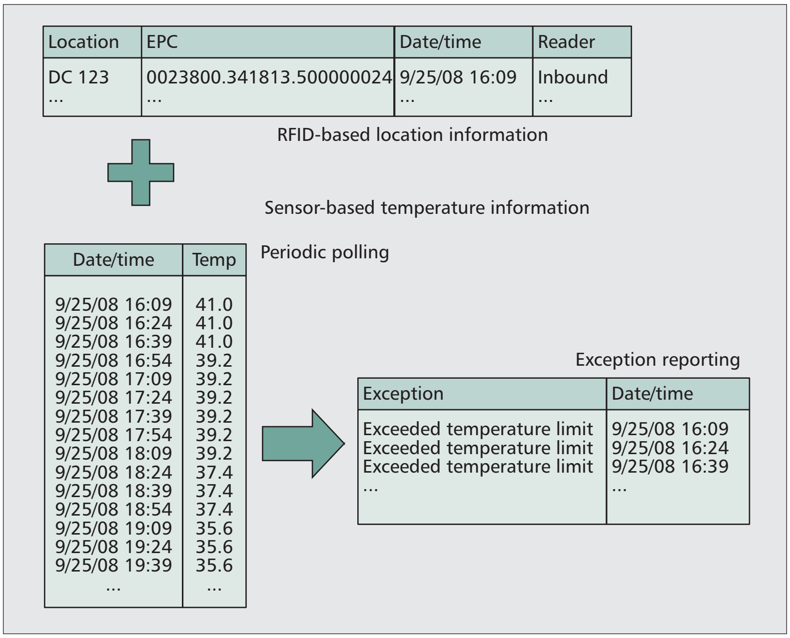

Figure 1. *Integration of sensor and RFID data for exception reporting.*

Periodic polling: In this method, the sensor is set to record the temperature at specified intervals; for example, take temperature every 30 s, once per hour, or once per day. Note that the frequency of polling will affect battery life and may be restricted by amount of memory. Tags can also be set to record the average temperature per time interval (e.g., record average temperature per hour) or only the minimum/maximum values during the time interval. Both of these methods, however, require almost constant monitoring in order to calculate average or min/max, which shortens battery life. A sample dataset produced by the periodic polling method is provided in Fig. 1. In this polling example, a single tag's data, taken every 15 min, is shown. This sensor generated data is combined with the RFID data to produce exception reporting where the temperature anomalies are identified by product, time, and potentially location.

Conditional recording: Tags may be set to record only when preset conditions are reached; for example, only record data when temperature exceeds 45°F. The advantage of this recording procedure is that it only records what seems to be important and hence does not consume large memory space.

System Architecture

The combination of RFID and environmental sensors creates a wireless sensor network (WSN) environment. Following the general principles of WSN design (Marin-Perianu *et al.*, 2007), the architecture of the RFID-based sensor network used in this study is designed as a three-tier architecture (a conceptual depiction of the architecture is shown in Fig. 2). In this architecture, there are two main tiers (i.e., front-end and

The system should be scalable to allow proper processing of continuously increasing number of sensors, tags and readers. It is also necessary for such systems to be flexible so that it accommodates the inclusion of different types of components on an as needed basis.

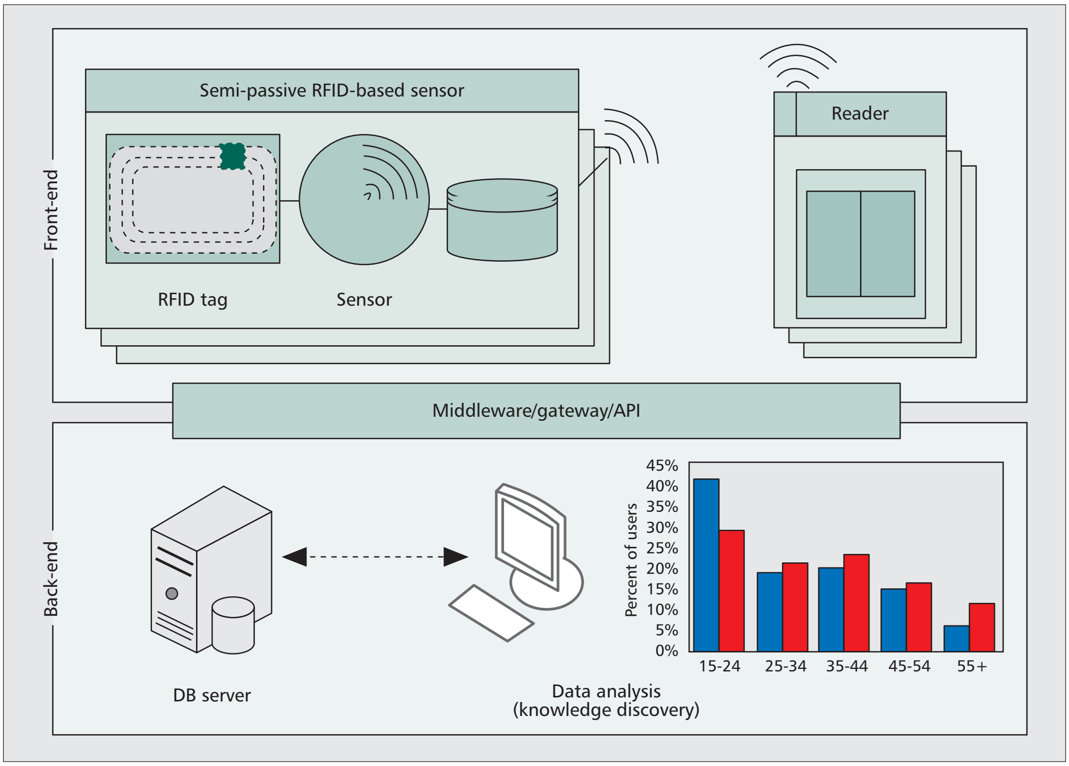

Figure 2. *A conceptual architecture of the RFID-based sensor network.*

back-end) connected to each other via a gateway tier.

Front-End Tier

The front-end tier includes RFID-based sensors, their intermediate data storage mechanisms, and interrogators (i.e., readers). In order for the system to work properly, these front-end components are to satisfy the following characteristics:

Energy efficiency: RFID-based sensors are essentially semi-passive tags and hence dependent on the onboard power source. In order to minimize energy consumption, sensory data polling is designed to be periodic. Although such a system configuration worked well for our experiments, if more frequent polling is needed, the energy budget issue has to be properly addressed.

Timeliness and reliability: Timely and reliable data collection and transmission are essential for WSNs. Data should be collected and transmitted in a timely manner that matches the purpose of the system. As such systems are often complex (i.e., made up of a variety of different components), the reliability of the network may be in question. Acceptable levels of reliability with respect to data transfer between the network components should be maintained.

Accuracy: Current RFID systems are prone to a wide variety of data problems such as misreads and duplicate reads. Often a hybrid solution, which integrates software and hardware configurations, is needed for accurate data collection. One should always keep in mind that the ultimate value of these systems depends on the usefulness of the data they generate.

Scalability and flexibility: The system should be scalable to allow proper processing of continuously increasing numbers of sensors, tags, and readers. It is also necessary for such systems to be flexible to accommodate the inclusion of different types of components on an as needed basis.

Back-End Tier

The back-end tier is composed of a database and a number of business analytics software modules. The data collected by the sensors are transferred to the database via the gateway. Data in this database is cleaned, integrated, consolidated, and organized in a time-series fashion. The business analytics software modules are intended to process the data to extract information and knowledge that is of some value to the business. These analytics include automated alert-based monitoring/notification, ad hoc information generation (using online analytics processing [OLAP] models), and novel knowledge discovery (using data mining techniques, e.g., clustering, classification, and association).

Gateway Tier

The gateway tier is meant to provide a proper connection/communication between the front-end and back-end components. As the system is composed of a number of heterogeneous components, their proper communication should be handled via middleware of proper protocols. Allowing loose coupling, the gateway should permit replacement of components in both front-end and back-end tiers without requiring an elaborate reconfiguration of its own. Recently, XML-based service oriented architecture type configurations have been proposed to properly design and implement such gateway architectures (Marin-Perianu *et al.*, 2007).

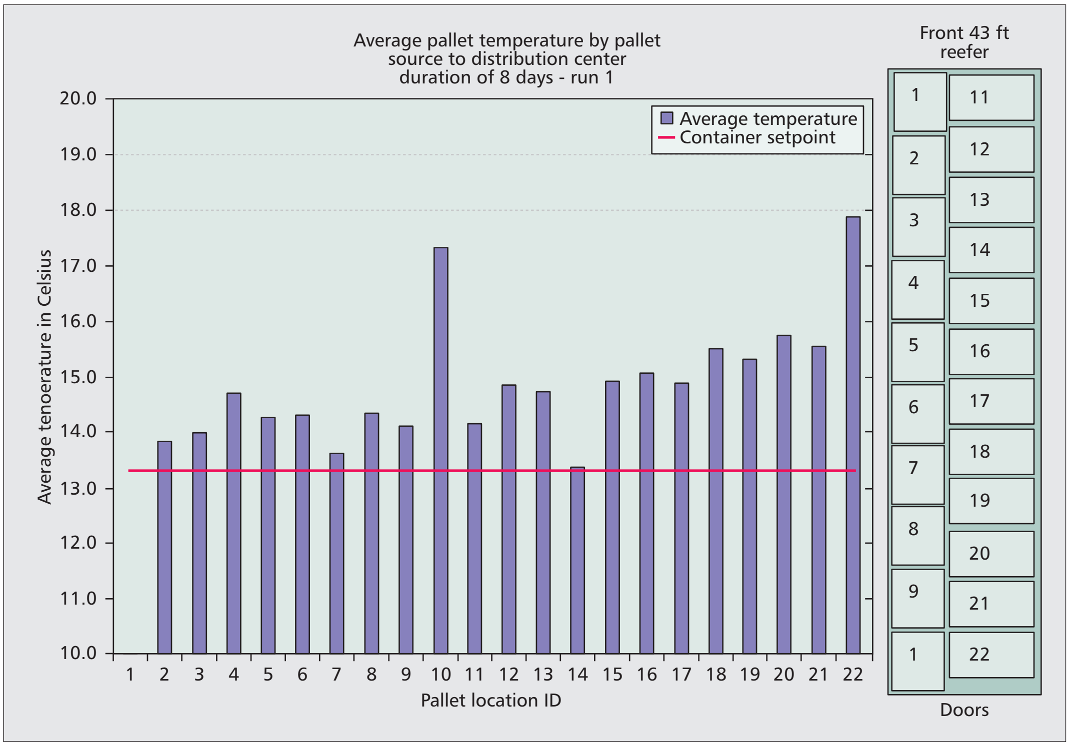

Figure 3. *Time-variant temperature profile for all pallets in a container.*

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Using RFID-Based Sensors in the Perishables Supply Chain

To evaluate the utility of RFID-based sensors in a perishables supply chain, we ran two in-field tests following a three-step process:

Pre-transportation: Before placing the semi-passive RFID tags on the products, the tags were initialized and calibrated using the specific reader. *Initialization* erases the existing memory and resets the clock (as needed). *Calibration* ensures that each of the tags is functioning within their specified limits. For example, the tags we used had an effective temperature accuracy of approximately ±0.18°C (Jedermann and Lang, 2007). Tags were calibrated by placing them in an environmental chamber for a 24-h period and modifying the temperature periodically during that time. Then the temperature on each tag was checked against the set temperature. Any tag exhibiting a deviation more than 0.20°C was discarded. Finally, the tags were re-initialized and deployed.

During transportation: Tags used periodic polling (described earlier) to collect data during transportation (i.e., *sensing*). Each temperature data point was stored on the tag (i.e., *recording*).

Post-transportation: Data was downloaded from each tag and *consolidated*, *validated* (e.g., did a tag record abnormally high or low temperatures that would indicate a malfunctioning tag), and *analyzed* in a variety of ways discussed later.

Each of the field tests implemented a three-tier WSN architecture as follows. First, the front-end tier consisted of semi-passive tags and readers. The tags served as the storage devices, the payload of which (i.e., the recorded time-series temperature data) was downloaded at the destination. Second, the gateway tier was facilitated by the readers, which captured the data from the tags and sensors and transmitted it to a network computer connected to the network of readers. Finally, the back-end tier was represented by a simple access database that stored the raw temperature data in a relational form. Data analytics were then run against this multidimensional data.

Test 1: Bananas from South America

For this test, we placed RFID-based sensors on every box of a load of bananas moving from South America to the United States. Figure 3 shows the temperature profile of that load of fruit. The fruit was loaded into a temperature controlled container (adjusted with a preset temperature) and the doors were sealed. The product then made its way via truck, ship, and train to a warehouse in Arkansas. Note the interesting temperature profile on this 43 ft container. Pallets 10 and 22 — closest to the doors — are much warmer, on average, than all other pallets (note: each wooden pallet contained 48 boxes of bananas). Only one pallet (14) was very near the container setpoint (i.e., in this instance, the preset temperature of the container was 13.3°C). In this case, because the product was fruit, the warmer temperatures for pallets 10 and 22 would accelerate ripening, but would not raise safety concerns (compared to, e.g., a load of shrimp).

If we look at the inside of a transport container, what we might expect to see (from an airflow and temperature perspective) is a nice uniform temperature and airflow (as denoted by the blue arrows in Fig. 4). We found, though (as shown in Fig. 3), a much different pattern. The sensors allowed us to construct a profile of what the temperature really looked like in the container. In this case, the airflow was not uniform as the temperature varied by pallet.

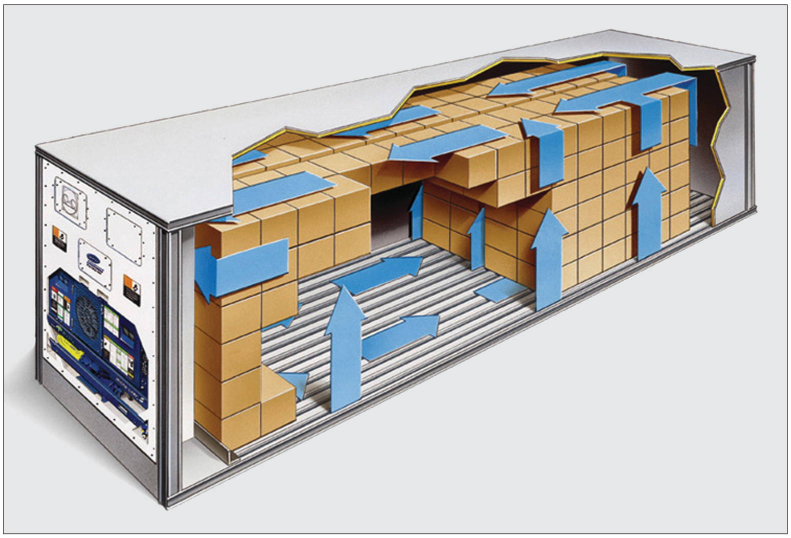

Figure 4. *Graphical representation of ideal air flow in a container.*

Test 2: Bagged Leafy Vegetables from the U.S. West Coast

As a second test, we examined a load of bagged leafy vegetables (in cardboard cases) moving from the west coast to the east coast of the United States (over a total duration of 4 days). Temperature tags were placed in each case at the source of packing (i.e., when the bagged vegetables were put into the case). Figure 5 shows the average temperature by position in a 53 ft container. Note the interesting temperature profile in this case: the boxes on the bottom of the pallet in the middle of the container were the warmest, and the boxes on the bottom of the pallet in the front of the container were the coolest. Rather than uniform temperatures throughout the container, temperatures varied considerably by location. On the top of the pallet, it did not matter if it was at the front, middle, or back of the container — the temperature was fairly uniform and within proper range (proper range is 0 to 4.4°C). In the middle of the container, however, the temperature rises from the bottom to the middle to the top of the pallet. It appears that the cool air is making it across the top of the pallet, but is not getting down to the middle or bottom layers.

For each of these tests, we intentionally configured different views of the temperature profiles within the container. With the data from the RFID-based temperature sensors, we examined the environmental profile of products by pallet and by location in the container. There are many other ways we could also look at the data, such as longitudinally, where we can see what happens to the temperature over time.

The interesting thing about the graphs developed based on the data obtained from these applications is the fact that rather disparate patterns were observed. Obviously, there is no such thing as a "standard temperature profile." Thus, RFID-based sensors offer the opportunity to better understand the conditions of perishables as they pass through the supply chain; and hopefully, with time and much data, a temperature profile can be constructed for many different scenarios.

Challenges

RFID-based (temperature) sensors worked well in our tests. Their use by others has also suggested that the technology has a very promising future. Overall, the sensors provided tremendous insight into the conditions faced by products as they pass through the supply chain — insight that is not possible with single-point estimations. However, RFID (as a fast growing technology) has a number of challenges. Based on our experience and insights gained from the sample applications presented herein, we elaborate on some of the current challenges and lessons learned in using RFID-based sensors.

First, establishing a WSN is difficult. The challenges are best positioned against our framework presented earlier (front-end, back-end, and gateway tiers).

Front-end tier: Establishing an RFID-based WSN represents some technology challenges, primarily in the front-end tier of the network. In particular, considerations include:

- Starting and stopping of tags: With current technology, the tags must be manually started and stopped. This is very labor intensive and cannot continue with a large proliferation of tags. The technology must advance such that tags are started and stopped merely by passing through an RFID-enabled portal, for example. Already, companies are working on semi-passive solutions with read ranges of 10–30 ft (compared to the 1–3 in read range for the tags used in this study) (Jedermann and Lang, 2007).
- Tag calibration: Temperature and time must be calibrated in order for the recorded data to be accurate and usable for further analysis. In our own tests, approximately 1 in 20 tags were not calibrated properly (on either time or temperature). Time pieces used in sensors are often inexpensive to keep the overall cost of the tag low. Time precision, however, is extremely important. For example, if data polling is done every 15 min and a tag is off by 1 min per 15 min poll, over the course of 8 days (the time of test 1 described earlier), the tag would be off by approximately 750 min (or about 12 h). For temperature calibration, Jedermann and Lang (2007) found temperature accuracy to be in the range of ±0.1°C to ±0.4°C (from an investigation of three tag types).
- Multisensor environments: The environment is likely to require multiple types of sensors, such as semi-passive temperature sensors and passive tags for identification. Currently, these require two different architectures. Obviously, requiring an organization to install multiple architectures is neither scalable nor flexible.

Back-end tier: Capturing data is easy; turning data into useful, actionable information is hard. Overall, though, one must remember that sensors are just another data carrier, and the true value of the technology lies in the value of the data (and ultimately the information) it provides. Unfortunately, technology to adequately make use of the data in real time is lacking. In most cases, as in the applications we have presented, the data is collected, analyzed, and then reported "after the fact." While this provides an opportunity to explain what happened, it does not prevent the leafy vegetables from spoiling, for example. For RFID-based WSN success, the back-end tier must be able to provide real-time feedback regarding the environment (e.g., the temperature is too high) so that action can be taken to avert problems. As we move forward, predictive modeling or the ability to anticipate problems before they occur will provide tremendous value. In these situations, the WSN could anticipate and act in (e.g., via interaction with environmental controls) a situation before damage occurred and without human intervention.

Gateway tier: As indicated earlier, the ideal WSN will contain a variety of sensor types. While this will require an architecture (front-end tier) to support the various sensor types, the gateway tier will become crucial to providing proper communication between the front-end and back-end components. Currently, handling data from a variety of sources is very difficult.

Second, much of the difficulty in establishing RFID-based WSNs is due to standards; or, more accurately, the lack thereof. Every RFID-based sensor used for our applications utilized a proprietary communications protocol (i.e., tags and readers from different manufacturers were not interoperable). Thus, each used their own front-end, gateway, and back-end tiers — no sharing, no interoperability. Companies will be less likely to adopt these computing technologies if proprietary solutions dominate the marketplace. Rather, there must be a standard interoperable solution to encourage broad adoption. At some point, standards must exist to support the front-end, gateway, and back-end tiers of an RFID-based WSN.

Third, calculating the return on investment (ROI) for new technologies, such as RFID-based sensors, is a challenge. RFID-based sensors are not cheap ($5 and up). Thus, the costs must be offset by a corresponding value proposition. For our applications, the reduction in spoiled products, the increase in quality that would promote sales, and the reduced risk of losing a customer due to poor quality products are all considerations. Given the current environment of using these sensors to indicate what happened (explanatory) rather than what will happen (predictive) limits the payback on the technology. However, as one quick example of how RFID sensors provide an ROI, consider the second example of the bagged leafy vegetables. We will assume that the tags cost $5 each and that we will apply one tag to each of 22 pallets on the truck (total tag cost of $110). We will further assume that 20 loads are going per day, five days per week, 50 weeks per year. Tag costs are therefore about $550,000 per year (110 × 20 × 5 × 50). Each truck will need a reader (assuming 20 trucks and $300 per reader = $6000). Overall, costs are less than $600,000. In this particular case, the payback comes from reduced spoilage or increased sales. If a company knows their spoilage history, an estimated reduction in spoilage could be used to construct a sensitivity analysis (based on various reductions in spoilage) to determine payback. A similar analysis could be conducted with potential sales increases. Another dimension to consider is a potential reduction in liability due to any public health damage if spoiled products are sold/consumed. This example (of $600,000) assumes that tags are used one time. The payback gets easier if tags can be reused. But how do you reuse without disrupting existing processes? Although there are several possible solutions, such as a drop box for tags or prepaid envelopes, a good universal solution must be found to make the economics of the tags more palatable. As tag prices decline, this will become less of an issue. However, the semi-passive nature of sensors (i.e., requiring a battery) will keep the price higher than passive tags, thus requiring companies to find a way to reuse the tags. Reusing the tags will help companies create a better value proposition for their use. For example, passive RFID tags used for identification purposes (but not containing a sensor) cost around 10 to 12 cents each. Assuming an RFID-based sensor costs $5, the tag would only need to be used 50 times to equal the price of a passive tag (disposable after a single use). Finally, ROI is tied to the current lack of standards. Until we have standards in place (as discussed earlier), an ROI will be difficult because of the proprietary systems that must be purchased. In one field test we conducted, the perishable product supplier had to use sensors from six different manufacturers to satisfy the requirements of six different retailers (i.e., each retailer requested a specific sensor from a specific manufacturer). With standards, this situation would not occur, and the supplier could use a standard sensor that could be applicable across many retailers.

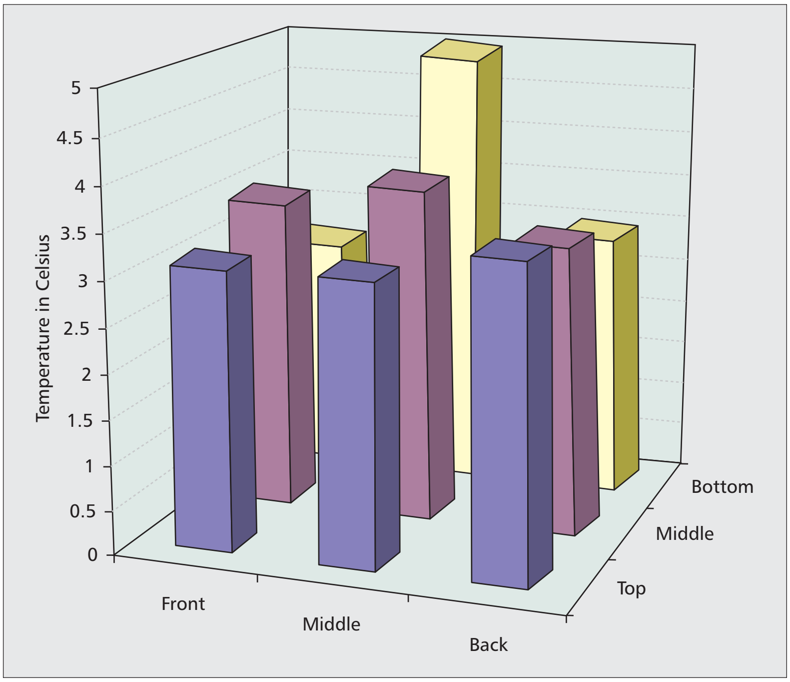

Figure 5. *Temperature profile by position in container.*

Conclusion

RFID-based sensors offer great promise to the perishables supply chain. With these sensors, companies will not only know where the product is/was, but can have insight into the conditions

RFID-based sensors offer great promise to the perishables supply chain. With these sensors, companies will not only know where the product is/was, but can have insight into the conditions faced by that product as it passed through the supply chain.

faced by that product as it passed through the supply chain. Overall, armed with the knowledge of the environmental conditions, companies can make better decisions regarding the use of the product (i.e., shelf life, disposal, promotional pricing, etc.), ultimately leading to higher quality and safer products for the consumer and hence more profitable business practices.

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