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The Promise of RFID-based Sensors in the Perishables Supply Chain

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The perishables supply chain 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 U.S., 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. Due to the extremely large volumes of goods handled, the likelihood for problems increases (Sahin et al., 2007). The elimination of even a small percentage of spoilage, for example, adds up to a significant improvement to 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 the 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 should be an effective and efficient information system enhanced with RFID technology. Already, several companies have begun experimenting with RFID for perishables (see sidebar: Experimenting with RFID for Perishables). In this paper, we specifically explore the use of

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RFID-enabled 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 (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 radio frequency 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 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).

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-enabled 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.

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 classified as:

1. Passive tags: These tags have no power source of their own. They can only be powered up (activated for interrogation) when they enter into an electromagnetic field. These are the most commonly used tags and are also the cheapest.
2. 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, as referred to earlier, are primarily semi-passive tags.

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

Depending on the need, sensor-equipped tags used in cold chain can be active tags or semi-passive tags. 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 paper 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. 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):

- Periodic polling: In this method, the sensor is set to record the temperature at specified intervals; e.g., take temperature every 30 seconds, once per hour, once per day, etc. 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 record 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 will shorten battery life. A sample dataset produced by the periodic poling method is provided in Table 1. In this polling example, a single tag's data, taken every 15 minutes, is shown.

- Conditional recording: Tags may be set to record only when pre-set conditions are reached; e.g., only record data when temperature exceeds 45^{o}F. Sample data produced by the conditional recording method is provided in Table 2 (note: this is actual data taken from multiple tags from one of the sample applications described herein). As demonstrated in Table 2, the data only provides an indication that the condition was met – it does not indicate by how much the condition was exceeded or how long it exceeded the condition.

Table 1: Sample data log for periodic polling method

Tag ID	Date / Time	Temperature
3066	9/25/06 16:09	41.0
3066	9/25/06 16:24	41.0
3066	9/25/06 16:39	41.0
3066	9/25/06 16:54	39.2
3066	9/25/06 17:09	39.2
3066	9/25/06 17:24	39.2
3066	9/25/06 17:39	39.2
3066	9/25/06 17:54	39.2
3066	9/25/06 18:09	39.2
3066	9/25/06 18:24	37.4
3066	9/25/06 18:39	37.4
3066	9/25/06 18:54	37.4
3066	9/25/06 19:09	35.6
3066	9/25/06 19:24	35.6
3066	9/25/06 19:39	35.6
3066	9/25/06 19:54	35.6
3066	9/25/06 20:09	35.6
3066	9/25/06 20:24	35.6
…	…	…

Table 2: Sample data log for conditional recording method

Tag ID	Condition Type	Date / Time
6600929	Exceeded temperature limit	9/12/2007 2:01
6600930	Exceeded temperature limit	9/12/2007 4:46
6600931	Exceeded temperature limit	9/11/2007 17:31
6600933	Exceeded temperature limit	9/12/2007 3:31
6600936	Exceeded temperature limit	9/12/2007 6:01
6600937	Exceeded temperature limit	9/12/2007 10:31
6600941	Exceeded temperature limit	9/11/2007 17:31
6600942	Exceeded temperature limit	9/12/2007 5:01
6600945	Exceeded temperature limit	9/12/2007 11:46
6600946	Exceeded temperature limit	9/12/2007 6:01
6600950	Exceeded temperature limit	9/12/2007 7:31
…	…	…

Sample Applications

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 Figure 1). Does this really happen though? In reality, rarely! With temperature sensors, we can determine temperature for every case in the container (if we wanted) or by pallet / layer / position within the container (e.g., front of container, bottom layer, left rear corner of pallet). The sensors allow us to construct a profile of what the temperature really looks like in the container.

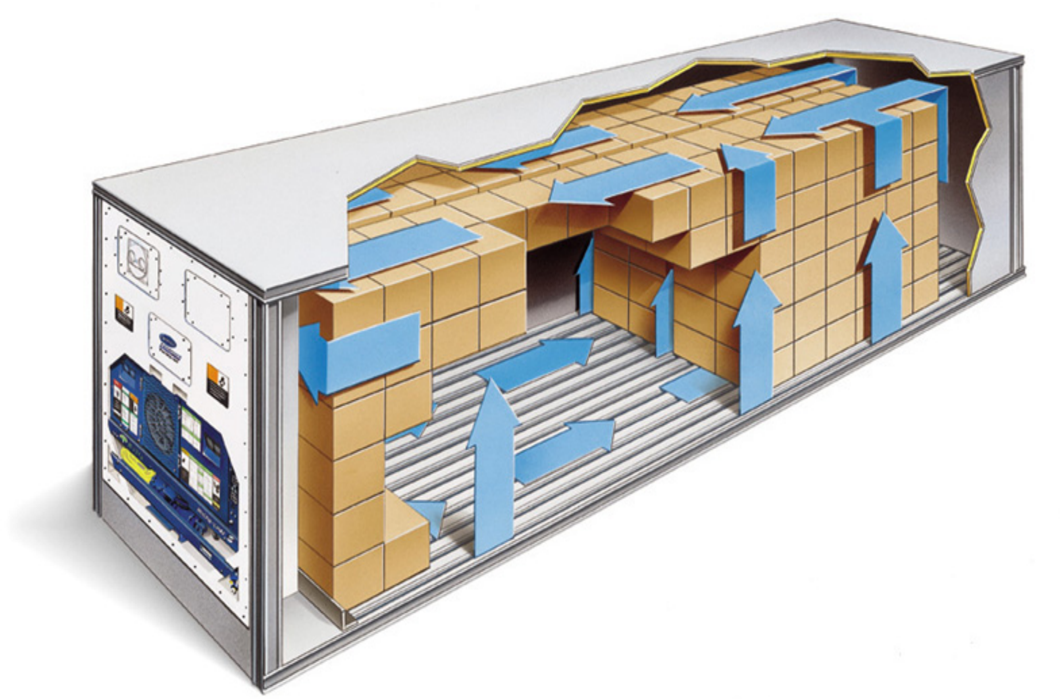

Figure 1: Graphical representation of ideal air flow in a container

To investigate the utility of RFID-enabled temperature sensors in providing information necessary to understand the condition of the product as it travelled through the supply chain, we placed semi-passive sensors on every box of a load of fruit moving from South America to the U.S. Figure 2 shows the temperature profile of that load of fruit. The fruit was loaded into a temperature controlled container (pre-set 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 profile on this 43' container. Pallets 10 and 22 – closest to the doors – are much warmer, on average, than all other pallets. Only one pallet (14) was very near the container set-point. 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, for example, a load of shrimp).

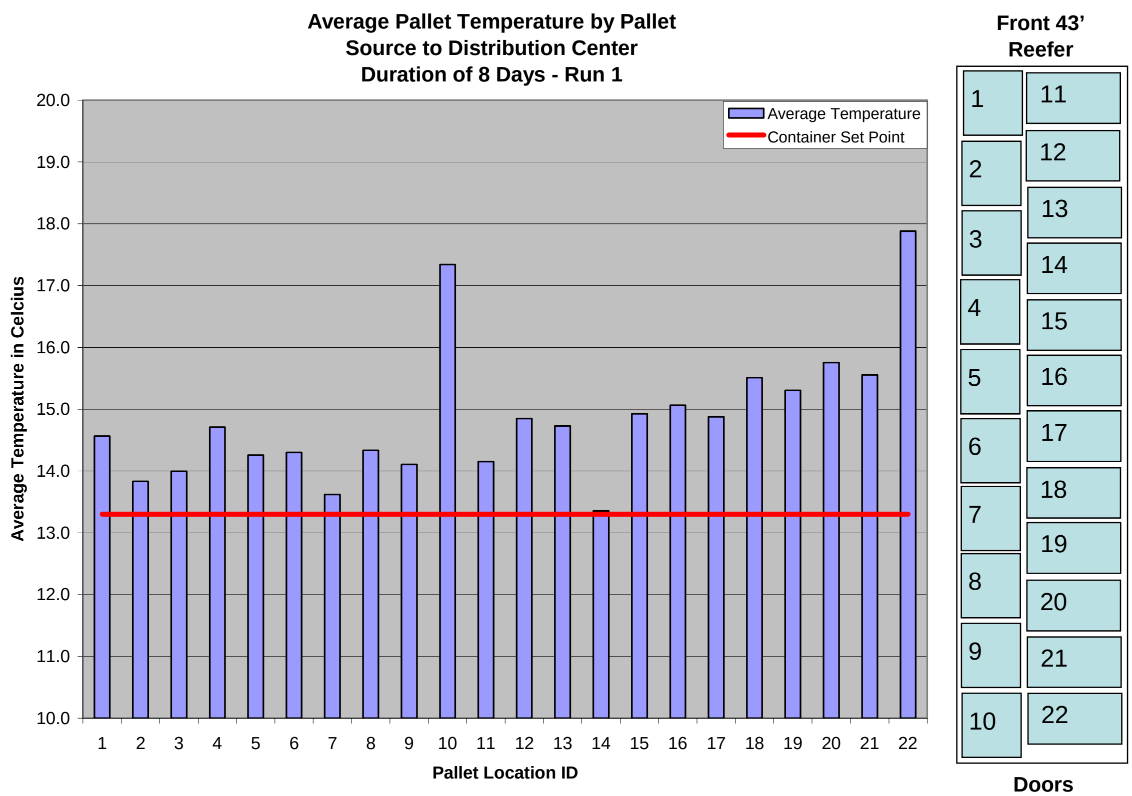

Figure 2: Time-variant temperature profile for all pallets in a container

The same trial was conducted again (same product type, same transportation source, route, and destination) with the exception of using a 40' container instead of a 43' container. The pallet load configuration (i.e., position in container) was different due to the container size. Specifically, the pallets were stacked in like fashion side by side instead of one straight and one turned as in the 43' container. This new pallet configuration changed the airflow within the container and, ultimately, changed the temperature profile. RFID-enabled sensors provide the opportunity to examine the effects of changing a variable (i.e., in this case, container size and subsequent pallet configurations) on the temperature profile.

As a second sample application, we examined a load of vegetables moving from the west coast of the U.S. to the east coast (total duration: 4 days). Figure 3 shows the average temperature by position in a 53' 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. This would suggest an airflow problem. 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 32-40^{o}F). 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 of the pallet in the middle of the container. Also, in contrast to the product from South America (Figure 2), one of the coolest places in this container was at the back (next to the doors).

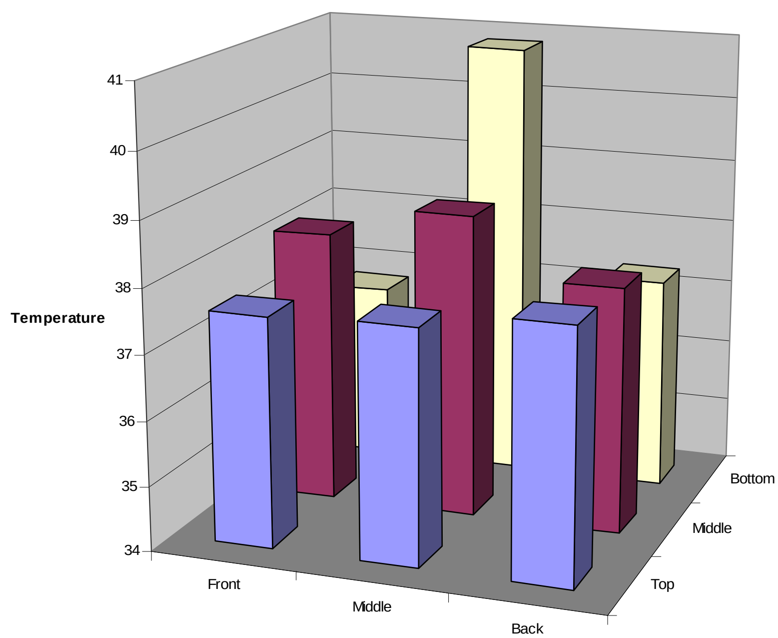

Figure 3: Temperature profile by position in container

For each of these applications, we intentionally provided two different views of the temperature profile within the container. With the data from the sensors, we can examine the profile in many different ways. For example, we have also examined the data longitudinally (i.e., plotted the data over time by location in the container) and by interior versus exterior of the pallet. The data provides a view of what happened to the product (relating to temperature) from many different angles.

The interesting thing about the two graphs presented here is the disparate patterns produced. 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. If all were homogenous, then the solution would be simple. The more we understand about these patterns, the more we can improve the process. There is much opportunity to use this data to improve food quality and safety.

Using the Data to Improve Food Quality and Safety

As product moves through the supply-chain, the environment can change its condition and, thus, its quality and safety level. RFID-enabled environmental sensors provide insight into the changing environmental conditions experienced by the product, and provide the data necessary to determine to what extend those changes affected the quality or safety of the product. Without sensors, one can get various single-point estimations of the environmental conditions – e.g., temperature at the time of loading, temperature at time of delivery, etc. – but do not have visibility between these point estimates.

The two previous examples can be used to investigate how this data might be used to improve food quality and safety. In the first case, the two pallets nearest the door were, on average, too warm. Because data was collected on an hourly basis, one can determine, with precision, how long the fruit experienced various temperatures. Again, in this instance, the warm temperatures merely accelerate ripening. For the retailer with this knowledge, they would know to move these two pallets of product through the distribution center to the store and onto the sales floor sooner than the other pallets since they would have fewer days of shelf life. No safety issues, but quality could be compromised.

In the second example, a similar situation arises – perhaps the middle / bottom boxes were too warm and should be rejected by the retailer. Armed with the sensor data, the retailer would know immediately upon receipt the product had been exposed to unacceptable temperatures and should be rejected. If some product is in danger of spoiling, does a receiver reject the entire load, a partial load, or none of the load? Without the proper information, a receiver may be forced to reject the entire load when, in reality, only a few boxes or pallets are in danger of spoiling. With environmental sensors, it is possible to determine precisely those boxes or pallets that are in danger. Then, the receiver can make the decision to reject only a portion of the load or, perhaps, accept the entire load and negotiate with the supplier for a lower price on those particular items that may have a shortened shelf life. Rather than relying on visual cues or heuristics (such as the color the product), data from the environmental sensors can be used to precisely determine remaining shelf life or quality.

Although we did not witness it in our two applications, it is easy to see how a temperature sensitive product, such as fresh meat, could be exposed to inappropriate temperatures which could affect its safety. With RFID-enabled sensors, the retailer would know this before accepting the product and potentially moving it to the sales floor.

Conclusion

Our sample applications using RFID-based sensors on perishable goods indicates that temperature profiles are not homogenous. In the sample applications, temperatures varied by position on the pallet (e.g., top, middle, bottom), by load configuration (i.e., the position of the pallets), by container type, by product type, and by packaging material (e.g., corrugated box versus plastic tote). The obvious impact of many variables suggests that continuous environmental monitoring is necessary to fully understand the conditions at the pallet and/or case level. Overall, RFID-enabled (temperature) sensors worked well. The sensors provided tremendous insight into the conditions faced by the product as it passed through the supply chain – insight that is not possible with single-point estimations.

However, RFID is a fast growing technology with a number of challenges. Based on our experience, some of the current challenges in using RFID-based sensors include:

- Cost of tags and tag recycling: tags are not cheap ($5 and up); thus, it is necessary to recycle the tags to get the most use out of them. But how do you recycle 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.

- Starting/stopping 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 the tags. The technology must advance such that tags are started/stopped merely by passing through a portal (for example).

- Tag calibration: temperature and time must be calibrated in order for the data to be good. Currently, the reliability is not great. These must get better.

- Standards: Every RFID-based sensor used for our applications utilized a proprietary communications protocol (i.e., tags and readers from different manufacturers were not interoperable). Companies will be less likely to adopt if proprietary solutions dominate. Rather, there must be a standard, interoperable solution to encourage broad adoption.

- EPC and environmental data: as more retailers and suppliers tag their product with EPC (passive UHF), it will be imperative to match this data with the environmental data to show not only the condition of the product, but where it is/was (automatically without having to manually connect the two). With EPC data and environmental sensor data, imagine the total visibility that one can achieve at the case and/or pallet level during the entire supply chain – from source to shelf.

RFID-based sensors, as demonstrated by the applications presented herein, 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. Overall, armed with the knowledge environmental conditions, companies can make better decisions regarding the use of the product (i.e., shelf life, disposal, etc.); ultimately leading to higher quality and safer products for the consumer.

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SIDEBAR: Experimenting with RFID for Perishables Material

Some applications for RFID in the perishables supply chain:

- Samworth Brothers Distribution (U.K., sandwiches, pastries, etc.): real-time temperature monitoring in their trucks by drivers (http://www.rfidjournal.com/article/articleview/2733/).
- Fresh Express: using RFID to look at flow through of the product coupled with expiration dates (http://cache-www.intel.com/cd/00/00/33/74/337466_337466.pdf).
- Starbucks: using temperature tracking for food preparation products going to their retail outlets (http://www.rfidjournal.com/article/articleview/2890/).
- U.S. Army: investigated the impact of temperature on shelf life of rations (http://www.rfidjournalevents.com/live2007/industry_defense.php).
- Sysco: used RFID to check load conditions without opening doors (http://www.rfidjournal.com/article/articleview/1652/).
- A southern regional restaurant chain (700 restaurants): used temperature monitoring to determine conditions of beef patties, eggs, onions, etc. (http://www.sensitech.com/PDFs/coldchain_info/achieving_xcellence_CC.pdf).
- TNT: looked at temperature profiles of products moving from Singapore to Bangkok (http://www.rfidjournal.com/article/articleview/2726/).