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Table of Contents

Abstract / Executive Summary

Inventory systems are at the heart of production and supply chain operations. Their performance depends heavily on how accurately and quickly organizations can record material movements and stock levels. Barcoding and Radio-Frequency Identification (RFID) are two key identification technologies that support this goal by enabling fast, reliable data capture at different stages of the material flow.

This article explains and correlates principles and techniques for barcoding and RFID with central themes from our class such as, deterministic and stochastic inventory models, material requirements planning (MRP), and production planning and control. The literature suggests that barcoding is a low cost and mature method for item identification whereas RFID provides automated, non-line-of-sight tracking and real time visibility with higher implementation costs.

A simple warehouse example illustrates how identification technologies support receiving, storage, picking, and shipping processes. The report then presents real world implementations, focusing on Zara's use of item-level RFID and examples from warehouse and logistics operations, where RFID has enabled more frequent stock counts, higher inventory accuracy, and faster order fulfillment. Limitations such as cost, technical issues, and integration challenges are critically discussed.

Overall, the analysis shows that barcoding and RFID are not just IT tools; they are tightly coupled with inventory control decisions, safety stock levels, and planning systems. Their proper use can reduce waste and non–value-added activities, consistent with the goal of modern production systems to increase value and reduce inefficiencies.

1. Introduction

A production system can be described as an arrangement of resources, processes, and activities which derive products and services from limited inputs. In this model, inventory is vital to separating stages, taking and dealing with variance, and helping service the customer. One fundamental part of inventory management is the accuracy of the recorded inventory information along with the pace of the recording of such information.

Historically, this information was captured manually, which is a time consuming and error prone process. Barcodes and RFID technologies have revolutionized this manual process throughout the years as technology advanced. Barcodes encode product data into printed symbols that are readable by scanners, and RFID uses radio waves to identify items using tags and readers. Both seek to minimize low added value activities such as manual counting, searching and error correction which are considered waste (Muda) in production processes.

The objective of this report is to:

- Summarize the main concepts and methods related to barcoding and RFID in inventory systems.
- Link these technologies to inventory models, MRP/ERP, and production planning concepts discussed in our course.
- Review relevant literature and real world implementations.
- Provide illustrative examples and a simple mathematical model highlighting their impact on inventory costs and performance.
- Critically assess their limitations and practical challenges.

2. Review of Related Literature

2.1 Barcoding in Inventory Systems

Barcoding has been extensively applied in retailing and manufacturing since the 1970s. A conventional one dimensional (1D) barcode encodes a product identifier that is linked to more detailed information in a database. Some 2D codes such as QR and Data Matrix store more data in a smaller space.

Key characteristics from the literature include:

- Much lower cost per label
- High data accuracy (barcodes must be printed clearly as well as scanned correctly in order to apply high accuracy)
- Requirement for short scanning distance.
- Typically achieved by one-by-one scanning of items.

Barcoding is used extensively for supermarkets, pharmaceutical inventory, warehouses and manufacturing lines. A good throughput capability can be achieved with the addition of conveyors and fixed scanners, while it is compatible with extant MRP and ERP systems.

2.2 RFID in Inventory Systems

RFID systems include tags on items or containers, antennas, readers, and middleware that connects them to enterprise systems, whereas, Tags can be either passive (no battery, powered by the reader signal) or active (battery powered, with longer range).

The literature highlights several benefits:

- Non line of sight reading (tags can be inside boxes or hidden behind items).

- Ability to read multiple tags simultaneously at the same time, reducing counting time.
- Real time or near real time visibility of inventory, especially when integrated with warehouse management systems (WMS) or ERP.

Real world trials show that RFID can vastly improve inventory accuracy. In Many of retail pilots, stores using RFID reported accuracy levels above 95%, versus much lower accuracy levels in control stores. Another line of work indicates that, in cases of high inventory inaccuracies, RFID supports service level improvements and reduced lost sales through reliable stock information.

2.3 Comparison Between Barcoding and RFID

Comparisons highlight that barcoding and RFID are not rivals but rather complementary technologies:

- **Cost:** Barcodes and scanners and generally cheaper, making them more feasible for low margin, higher volume operations or simply for units that are typically lower in unit value. However, RFID has a higher upfront cost due to tags, readers, and infrastructures.
- **Speed and Labor:** RFID are more attractive than barcoding in terms of Speed and Labor as they tend to have the ability to scan hundreds of items with tags simultaneously at once, whereas barcoding required line of sight and one by one scanning of items.
- **Accuracy and Environment:** typically, both methods tend to have slight issues with performances. While RFID is faster, its performance can be affected by factors such as type of metals used, liquids interactions that can possibly damage the tags, and radio interference, whereas barcodes also tend to fail sometimes when labels are damaged or dirty.

- **Applications:** Barcodes remain dominant in point of sale and simple warehouse environments. RFID is more common in item-level apparel retail, asset tracking, outdoor yards, and complex warehouse operations requiring frequent counts or real-time location.

3. Underlying Concepts, Techniques, and Methods

In this section, we will be connecting barcoding and RFID to our course content such as inventory models, stochastic demand, MRP/CRP/ERP, and production planning and control.

3.1 Role in Deterministic Inventory Models (EOQ, ROP, Safety Stock)

The classic deterministic models such as the Economic Order Quantity (EOQ) assume that demand and lead time are known and that inventory is correctly recorded to reflect physical stock. However, realistically, inventory records suffer from errors due to theft, mis-scanning, misplaced items, and data entry mistakes.

RFID and barcoding help reduce these errors:

- **More accurate Average on-hand inventory (I):** Automated scans and systematic transaction capture keep the inventory record closer to physical reality.
- **Better estimation of demand (D or λ):** Reliable sales and issue data allow planners to compute more accurate average demand for EOQ and reorder point (ROP) calculations.
- **Reduced need for high safety stock:** When inventory accuracy improves and variability in recorded stock decreases, safety stock can be reduced without harming service levels, lowering holding cost h.

From a modeling perspective, one can view the effect of RFID/barcoding as reducing the "inventory inaccuracy" parameter, which affects both the reorder point and safety stock size in continuous review models.

3.2 Role in Stochastic Inventory Control

In stochastic models with uncertain demand and lead time, such as the single-period (newsvendor) model or continuous review (Q, R) systems, the service level and shortage risk depend on the distribution of demand and the quality of the inventory information.

Research indicates that RFID can help reduce the impact of inventory inaccuracy and shortages by providing better visibility, which helps firms such as Zara choose a more accurate order up to levels that better align with actual demand. In practical terms, this means fewer stockouts and fewer emergency replenishments.

3.3 Integration with MRP, CRP, and ERP

Materials Requirements Planning (MRP) and Capacity Requirements Planning (CRP) translate the Master Production Schedule (MPS) into time phased plans for required materials/ components as well as ensuring necessary capacity. They rely on constraints such as labor time available, bills of materials, and inventory records.

Barcoding and RFID contribute by:

- Inventory records used by MRP are likely to become more accurate by capturing receipts and issues.
- Supporting MRP generated planned order releases with confirmation scans or reads at each operation.
- Giving the CRP more reliable information on work in-process (WIP) and queue lengths.

RFID and barcodes are integrated into modern ERP modules including inventory management, warehouse management, and shop floor control, providing a closed loop link between planning and execution.

3.4 Production Planning and Control (PPC) Perspective

Tasks such as planning, routing, scheduling, dispatching, and expediting are all covered by production planning and control.

Identification technologies help in several ways:

- **Routing and dispatching:** reading tags at each workstation helps confirming that jobs are following the correct route.
- **Scheduling and input/output control:** RFID provides WIP visibility, allowing tactical decision makers (Department managers) to see where jobs are delayed and adjust schedules accordingly.
- **Waste reduction:** By reducing time spent searching for materials and redoing work due to missing parts, these technologies help minimize idle time in the production system.

4. Mathematical Model (Illustrative)

In this section, we use a simple continuous-review (Q, R) model to show how better inventory information from barcoding or RFID affects safety stock and holding cost.

4.1 Notation

- λ: demand rate (units per year)
- c: unit acquisition cost (dollars per unit)
- K: fixed setup/ordering cost per order (dollars)

- I: annual inventory carrying charge
- h: annual holding cost per unit (dollars per unit per year), h = I * c
- Q: order quantity (decision variable)
- Q*: economic order quantity (EOQ)
- T=Q/λ: order interval (time between two orders)
- N=λ/Q: number of orders per year
- R: reorder point (inventory level at which an order is placed)
- μ: average demand during lead time
- σ: standard deviation of demand during lead time
- z: safety factor from the standard normal distribution (depends on target service level)
- SS: safety stock
- G(Q): expected annual variable inventory cost

4.2 EOQ and Reorder Point

With the EOQ assumptions (deterministic, constant demand, no shortages), the total annual variable cost is

- ordering cost per year: K*N = $\frac{K\lambda}{Q}$
- holding cost per year: h*I = $\frac{hQ}{2}$
- procurement cost: $C\lambda$

so the cost function is:

$$G(Q) = \frac{\lambda K}{Q} + \frac{hQ}{2} + c\lambda$$

Minimizing this function with respect to Q gives the familiar EOQ formula

$$Q^* = \sqrt{\frac{2\lambda K}{h}}$$

When demand during lead time is uncertain and approximately normal with mean μ and standard deviation σ, the reorder point is:

$$R = \sigma z + \mu$$

The safety stock is the amount of inventory above the average demand during lead time:

$$SS = R - \mu = z\sigma$$

4.3 Effect of Better Information from Barcoding/RFID

Inventory inaccuracies happen due to several factors, such as stated before, mis scans, missing items, and delays in updating records. These inaccuracies effectively increase the variability of demand during lead time. From this we can identify that the planner is using a larger standard deviation $(\sigma^{(0)})$ when there is poor information. However, after implementing barcoding or RFID, inventories tend to result in more accurate physical count and transactions are captured automatically which then means that variability reduces to smaller standard deviation ($\sigma^{(1)}$)

$$\sigma^{(1)} < \sigma^{(0)}$$

The corresponding safety stocks before and after implementation are:

$$SS^{(0)} = z\sigma^{(0)}$$

$$SS^{(1)} = z\sigma^{(1)}$$

The reduction in safety stock is:

$$\Delta SS = SS^{(0)} - SS^{(1)} = z\left(\sigma^{(0)} - \sigma^{(1)}\right)$$

Since each unit of safety stock costs $h per year to carry, the approximate annual holding-cost savings from improving information quality by barcoding or RFID is:

$$\Delta C_h \approx h \cdot \Delta S$$

This simple model shows why investing in barcoding or RFID makes sense. By giving more accurate and timely inventory information, these technologies reduce the uncertainty that safety stock has to cover. Even a small drop in variability can save a lot of money each year, especially when demand and holding costs are high, making the investment worthwhile

5. Illustrative Example of an Inventory System with Barcoding/RFID

in this example, we will be considering a distribution center that supplies goods to retail stores. The main processes consist of receiving goods, put-away, storing, picking, and shipping.

5.1 Receiving

- **Barcode scenario:**
  - Pallets arrive with printed barcode labels.
  - Operators scan each pallet label at a receiving station.
  - Quantities are entered manually or confirmed in the WMS.
  - Errors may occur if some pallets are missed or mis-scanned.
- **RFID scenario:**
  - Each pallet has an RFID tag.
  - A gate reader at the dock automatically reads all pallet tags as the truck is unloaded.
  - The WMS updates inventory automatically and checks for discrepancies.

5.2 Storage and Put-Away

- **Barcode scenario:**
  - Locations have barcode labels.
  - The operator scans the pallet and then the location code to confirm put-away.

- **RFID scenario:**
  - Forklifts are equipped with RFID readers and location systems.
  - As pallets are put away, their tags are read and linked automatically to the location.

5.3 Picking and Shipping

- **Barcode scenario:**
  - Pickers scan each item or carton when picking.
  - At shipping, items are scanned again against the shipping order.
- **RFID scenario:**
  - RFID handhelds or portal readers verify that the correct items are picked.
  - At the outbound dock, a portal reads all tags on a pallet at once, confirming the shipment content.

In practice, RFID implementations similar to this have shown that full inventory of tens of thousands of assets can be performed in hours instead of days, with accuracy levels close to or above 98%.

6. Implementation in Practice (Case Study)

6.1 Zara – RFID in Fast Fashion Retail

Zara is a successful example of widespread use of RFID in apparel retailing. In this category, Zara adopted item level RFID tags at its stores and distribution centers to create visibility of inventory and quick stock counts.

Key aspects include:

- Each garment is tagged at the distribution center.
- Store employees are now able to perform proper inventory counts in much shorter time than previously required.
- The system provides real-time information on which items are in the stockroom versus on the sales floor.
- RFID data feeds into analytics and replenishment algorithms that trigger automatic restocking when the reorder point is reached.

Reported benefits include:

- Higher inventory accuracy (often above 95%).
- Faster replenishment from backroom to store floor.
- Reduced out of stock and improved customer service.
- Allows advanced concepts like mobile payment and contactless checkout using RFID enabled systems.

This case illustrates a strong link between RFID and the planning concepts we've learned throughout the course. With accurate and timely data, Zara's aggregate planning, master production schedules, and store-level replenishment decisions can be more closely aligned with actual demand.

6.2 RFID in Warehouse and Logistics Operations

Similar effects have been demonstrated in case studies, for example in warehouses and logistics. For example:

• A warehouse tracking pallet with RFID for receivables delivered orders in far less amount of time, enhanced location precision, and enhanced visibility of empty storage slots.

• An outdoor industrial yard implemented vehicle-mounted RFID readers that inventoried an estimated 15,000 assets across multiple acres in about an hour, with roughly 98% accuracy, significantly decreasing labor and time compared with manual counts.

In transportation and logistics, RFID has been proven to:

• Enhance shipping and receiving accuracy.

• Speed up order processing.

• Cut labor and cycle times.

These real-world implementations are consistent with the objectives of aggregate production planning and inventory management: cost minimization while keeping customer service levels high.

6.3 Zara mathematical modeling

Based on Inditex (Zara) historical data and realistic assumptions: average selling price per garment $c = \$22$, average demand per SKU ≈ 114,800 units/year , daily mean $\lambda = 315$units/day; carrying rate $I = 20\%$ so $h = I \cdot c = \$4.40$/unit·yr; ordering cost $K = \$75$/order; lead time $L = 7$days; service factor $z = 1.645$ (based on 95% service level (alpha)); daily standard deviation S is given by 30% of the daily Average.

Notations:

λ= average demand per day (units/day)

$\mu = \lambda \cdot L$= mean demand during lead time

S =daily demand standard deviation = $S_{\text{frac}} \cdot \lambda$

$\sigma = S\sqrt{L}$= std dev. during lead time

$R = \sigma \cdot z + \mu$= reorder point

$SS = R - \mu = z \cdot \sigma$= safety stock

Calculations:

1) Compute daily mean & daily σ

- $\lambda = 315$units/day (from 114,800 units/yr ÷365).
- $S = 0.30 \cdot \lambda = 0.30 \cdot 315 = 94.5$ units/day.

2) Mean during lead time μ:

$$\mu = \lambda \cdot L = 315 \cdot 7 = 2{,}205 \text{ units}$$

3) Lead-time standard deviation σ(No-RFID):

$$\sigma = S\sqrt{L} = 94.5 \cdot \sqrt{7} \approx 94.5 \cdot 2.6458 \approx 250.1$$

4) Reorder point $R$and safety stock SS (No-RFID):

$$R_0 = z \cdot \sigma + \mu = 1.645 \cdot 250.1 + 2{,}205 \approx 2{,}616 \text{ units}$$

$$SS_0 = R_0 - \mu = 2{,}616 - 2{,}205 \approx 411 \text{ units}$$

5) Now With-RFID (assume RFID halves σ)

New lead-time σ (With-RFID)

$$\sigma^{(RFID)} = 0.5 \cdot 250.1 \approx 125.05$$

6) SS and R With-RFID

$$R_1 = \sigma^{(RFID)} \cdot Z + \mu = 1.645 \cdot 125.05 + 2{,}205 \approx 2{,}411 \text{ units}$$

$$SS_1 = R_1 - \mu = 2{,}411 - 2{,}205 \approx 206 \text{ units}$$

Why RFID Reduces σ at Zara

RFID reduces σ (standard deviation of demand during lead time) because it removes: mis-scans, missing or miscounted items, late updates, phantom inventory, WMS delays, and picking/put-away data lag

Comparison:

- Safety stock: No-RFID = 411 units vs With-RFID = 206 units → units saved ≈ 205 per SKU.
- Holding cost per unit per year $h = \$4.40$, annual holding saving ≈ $205 \times 4.40 \approx \$902$ per SKU/yr.
- Reorder point: 2,616 (no-RFID) vs 2,411 (with-RFID) → when the Reorder point is less, the safety stock is less meaning lower inventory holding cost.

7) Optimal Order Quantity (Q*):

$$Q^* = \sqrt{\frac{2\lambda K}{h}} = \sqrt{\frac{2(75)(114{,}800)}{4.40}} = 1{,}978 \text{ units}$$

8) Expected number of units in excess (E_0):

$$\text{Without RFID: } E_s = \sigma\, L(z) = 250.1 \cdot 0.021 = 5.25 \text{ units}$$

$$E_0 = R - \mu + E_s = 2{,}616 - 2{,}205 + 5.25 = 416.25 \text{ units}$$

With RFID: $E_s = \sigma^{(RFID)} L(z) = 125.05 \cdot 0.021 = 2.62$ units

$$E_0 = R - \mu + E_s = 2{,}411 - 2{,}205 + 2.62 = 208.62 \text{ units}$$

9) Fill rate:

$$\text{without RFID}, \ \text{FR} = 1 - \frac{E_S(R)}{Q*} = 1 - \frac{5.25}{1978} = 0.9973 = 99.73\%$$

$$\text{with RFID}, \ \text{FR} = 1 - \frac{E_S(R)}{Q*} = 1 - \frac{2.62}{1978} = 0.9989 = 99.89\%$$

the proportion of demand that is fulfilled from stock directly

Overall conclusion:

According to the results, enhancing inventory visibility with RFID significantly decreases the uncertainty and inventory cost. In our instance RFID reduced variability sufficiently to drop safety stock by 411 to 206 units (205 units saved), or to say approximately $902 per SKU annually in holding cost. Orders get placed later and fewer units remain sitting idle. Fill rate also improves slightly (99.73% to 99.89%), demonstrating more demand fulfilled through stock. Put together, those impacts, less working inventory, more service, fewer operational exceptions will help explain why RFID (or reliable barcoding) seems so much more beneficial than no-tracking, particularly at Zara's scale where savings per SKU are multiplied across thousands of SKUs.

7. Limitations and Critiques

While barcoding and RFID offer substantial benefits, there are important limitations and challenges.

7.1 Barcoding

- **Line of sight requirement:** barcodes must be clearly printed and properly oriented to the scanner
- **Label damage:** Dirt, abrasion, or poor printing can cause scan failures.
- **Labor intensity:** One by one scanning can be slow for large inventories.

However, barcoding remains attractive because of its extremely low cost and mature standards.

7.2 RFID

- **Higher upfront cost:** Tags, readers, antennas, and integration can be expensive, especially for low value items.
- **Signal interference:** Metals, liquids, and dense environments can reduce reliability.
- **Data and privacy concerns:** RFID tags can potentially be read without direct user action, raising privacy and security issues.

7.3 Critical Perspective

While RFID scanning is faster, some experimental studies have shown that error rates and equipment failures can be higher if the technology is not properly designed for the environment (such as cold chain warehouses). This suggests that RFID is not automatically superior to barcoding, rather the choice must consider product characteristics, environment, demand patterns, and required service levels, which is exactly the kind of contextual thinking emphasized in production systems analysis.

8. Conclusion

Barcoding and RFID are key tools in current inventory systems. They support the fundamental goals of production systems: to create value while minimizing waste and inefficiencies.

- Reinforce the deterministic and stochastic inventory models by offering richer and more accurate demand and stock information.
- Increase the reliability of the MRP, CRP, and ERP decision-making process by providing them with real-time and accurate transactional data.
- Improve production planning and control by providing better visibility into WIP, reducing low-value-added activities, and supporting smoother flow through the system.

Barcoding is still the dominant technology in many sectors due to its low cost and maturity, while RFID is becoming more popular in certain cases where real-time visibility and automation provide sufficient value to justify a greater cost (as in fashion retail, complex warehouses, and logistics networks).

These identification technologies will have added value in IoT, analytics, and AI in the future. As more systemization continues to evolve, accurate, real-time inventory data will be increasingly pivotal in order to offer responsive, affordable, and sustainable production and inventory systems.

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10. Authors’ Contribution Credit

- **Omar Awawdeh:** Sections 1, 2 and 7; overall editing.
- **Omar Ibraheem:** Sections 3 and 4; mathematical model derivation.
- **Mohammed Husami:** Sections 5, 6.1, 6.2, Zara case study research and mathematical modeling
- **Mohammed Huzaif:** Sections 6.2, 8 and references formatting.