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# Inventory Control Modeling Using Radio Frequency Identification (RFID) Technologies

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### Abstract

It is critical to have high inventory accuracy for NASA astronauts in space. Previously, astronauts aboard the International Space Station (ISS) were informed from mission control that their outpost must be abandoned if a space flight that replenished consumables failed. Moreover, the flight crew was instructed to cut food intake by 5 to 10 percent to maximize existing consumable food inventory. It is estimated that a space flight costs $450 million, so emergency consumable inventory replenishments due to food supply shortage is costly. In this research, we investigate a "crew-free" inventory using the Automatic Data Capture technology Radio Frequency Identification. We investigate the impact that automatic data capture has in minimizing the aforementioned situations of poor inventory control. We build upon traditional inventory control planning methods; continuous and periodic review models such as EOQ, and (Q,r) models, respectively. This research conducted for NASA, describes an integrated system to eliminate daily logging of inventory while maintaining high inventory accuracy. Planned results of this research includes a system that allows astronauts minimized inventory counts and reduce excessive inventory weight for the space payloads.

**Keywords** Radio Frequency Identification, EOQ model and (Q, r) models

## 1.0 Introduction

The NASA Constellation Program has identified the need for a system that tracks inventory without requiring astronauts to perform daily logging activities. Currently, NASA tracks items such as crew clothing, office supplies, and hygienic supplies with barcodes at the bag level and not at the item level. Recently, NASA chose to evaluate Radio Frequency Identification (RFID) Automatic Data Capture (ADC) at the item level. This research investigates RFID ADC in conjunction with inventory control theory that can support better inventory control at NASA. Inventory control theory investigation includes traditional models such as the Economic Order Quantity (EOQ), and (Q,r) models.

This system will support improving previous NASA's inventory control problems. A recent example was in 2004 when astronauts aboard the International Space Shuttle (ISS) were instructed to cut daily food intake of 3000 calories by 5 to 10 percent to compensate for the food shortage aboard the space station. During this five-week period crewmember aboard the station rationed food inventory until a Russian cargo ship arrived with 440 pounds of food [2]. Additional fact that added to the situation is that an unsuccessful launch of the cargo ship would have left the crew only fourteen days of food [2].

This fact would have forced the astronauts to abandon the outpost and return to earth unsuccessfully completing the mission. When you consider that building a space shuttle for launch is an estimated 1.7 billion; an unsuccessful space mission is estimated as $450 million [7]. The combined cost of a space shuttle launch along with an unsuccessful completion of the planned mission is extremely high. To prevent this type of situation, investigating an improved inventory control system that is automated is justifiable. The background necessary for investigating inventory control theory and ADC is uniquely provided by Industrial Engineers and the research seeks to address NASA's concerns and highlight the abilities of IE's.

### 1.1 RFID Reliability Previous Research

Previously, a study of first generation RFID (Gen 1) technologies was tested for the NASA International Space Station (ISS) group at UNL's RfSCL Lab [8]. This study was conducted in 2005 by a team that included UNL, ISS, and Barrios Inc. The study included Gen 1 passive tags and readers, active tags, and other alternatives such as surface acoustic wave (SAW) tags and readers. SAW tags were investigated but not further tested at UNL due to production problems. Mandates (Wal-Mart, Department of Defense, Sam's club, etc.) have lead to the further development and standardization of the second generation (Gen 2) technology over the last few years. With the introduction of these Gen 2 tags, the research team investigated the performance of commercial off-the-shelf (COTS) Gen 2 RFID passive tags and readers. The project extended to Gen 2 technologies that became commercially available in 2008-2009. The results of the previous study, displayed below suggested that Gen 1 passive tags had limited success on consumable items within cargo transport bags (CTB's) and did not perform satisfactory on metals and water packaged items. In addition, the Gen 1 tags were determined unfeasible working with aluminum Russian containers. Active tags displayed a higher degree of success, measured by higher read capability but were not cost or weight effective; they were estimated to cost $25-$50 and weigh up to 200 grams per tag. Surrogated automated tags such as SAW tags, could not be validated due to lack of availability and is not considered industry standard. Recommendations from the study suggested implementing a portal type design for tracking inventory as it goes into designated areas, and tracing of consumed products. Other ideas suggested were to develop smart bags with a UNL SAT (sensor active tag) technology, and investigate how smart shelves could accommodate real time location of products using ranging technologies.

### 1.2 Relating RFID to EOQ

The previous research was carried out in two separate experiments. The objective of the first experiment was to evaluate the performance of Customer of the Shelf (COTS) RFID Gen 2 tags on a representative list of NASA and known RFID Gen 1 problematic items. The objective of the second experiment was to measure the performance of the best tags from the first experiment on NASA's consumable items inside a NASA Cargo Transport Bags (CTBs).

We describe the setup and high level results below. In the first experiment, we compared the performance of different varieties Gen 2 RIFD tags from different manufacturers. We utilized a 3 x 2 x 6 experimental design with the following metrics: material type (cardboard, metal, liquid), read distance (5 feet, 10 feet), and six tag orientations. The results from the experiment indicated that all four main factors (distance, tag type, material, and orientation) had a significant effect on the resulting read rate (using an alpha value of $p < 0.05$). In addition, two of the three 2-way interactions were found to be statistically significant. The conclusion for the analysis results are displayed in Table 1 and the main effects plot is shown in Figure 1.

**Table 1: Test statistics and p-values for F test**

| | F test | |
|---|---|---|
| Factor | Test Statistic | p-Value |
| Distance | 29.52 | < 0.01* |
| Tag | 6.04 | < 0.01* |
| Material | 96.18 | < 0.01* |
| Orientation | 3.87 | < 0.01* |

Note: *Significant at the 5% confidence level.

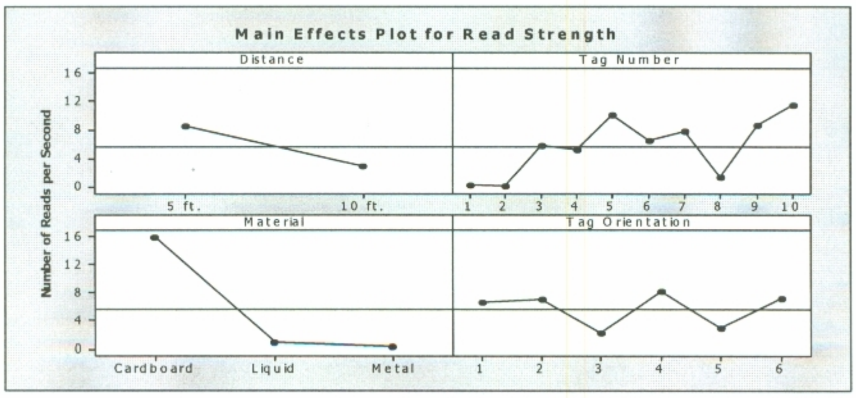


**Figure 1:** Main effects plot for factor analysis on the read strength of Gen 2 RFID tags.

In experiment 2 we used the best performing tags which met NASAs requirements to produce read rates greater than 99% on all material types within a distance of 5 feet inside the CTBs. Tagged items successfully read within the CTB's were documented while items that could not be read were modified by repositioning the RFID tag and/or adjusting the positioning within the CTB. This was necessary to ensure quality reads by not allowing variability to fluctuate between trials [8]. An analysis of the item level performance was conducted to evaluate the combination of tags, positioning, and antennas that provided the best results. **Results are shown below in Table 2.**

**Table 2: Results of item Level testing Using CTB**

| Trial Number | Distance (feet) | Number and Placement of Antennas | Movement of Items | Percentage of Tags Read B1 (Clothing) | B2 (Hygiene) | B3 (Office) | Total |
|---|---|---|---|---|---|---|---|
| 1 | 1 | 4 (2 per side) | None | 100% | 85% | 75% | 87% |
| 2 | 1 | 4 (2 per side) | None | 75% | 92% | 75% | 86% |
| 3 | 1 | 4 (2 per side) | None | 100% | 92% | 75% | 91% |
| 4 | 1 | 4 (2 per side) | Rotating | 100% | 100% | 100% | 100% |
| 5 | 1 | 4 (2 per side) | None | 100% | 100% | 100% | 100% |
| 6 | 3 | 4 (2 per side) | None | 75% | 92% | 75% | 86% |
| 7 | 3 | 4 (2 per side) | Rotating | 75% | 100% | 75% | 91% |
| 8 | 3 | 2 (same side) | None | 75% | 69% | 25% | 64% |
| 9 | 3 | 2 (same side) | None | 75% | 100% | 75% | 91% |
| 10 | 3 | 2 (same side) | None | 100% | 69% | 0% | 64% |
| 11 | 3 | 2 (same side) | None | 100% | 100% | 50% | 91% |
| 12 | 3 | 2 (1 per side) | Rotating | 100% | 100% | 75% | 95% |
| 13 | 1 | 2 (1 per side) | None | 100% | 92% | 75% | 91% |
| 14 | 1 | 2 (1 per side) | Rotating | 100% | 100% | 75% | 95% |
| 15 | 1 | 1 (one side) | None | 100% | 54% | 75% | 68% |
| 16 | 1 | 1 (one side) | Rotating | 100% | 100% | 75% | 95% |
| 17 | 3 | 1 (one side) | Rotating | 100% | 100% | 50% | 91% |

### 1.3 Previous Research on Inventory Control Models

Given our previous knowledge of RFID ADC we now must integrate the inventory control aspects. Several types of inventory models exist so to begin this research we begin with the most fundamental model, the Economic Order Quantity (EOQ) model. The EOQ should allow us to determine and prevent inventory shortages for NASA.

The EOQ determines the number of units a company should add to inventory with each order to minimize the total costs of inventory [1]. The costs are associated into three different categories; holding costs, order costs, and shortage costs. The EOQ is utilized as part of a continuous review inventory system.
This system inventory status is monitored at all times with a fixed quantity that is ordered each time inventory levels reaches a unique reorder point.

The EOQ provides a model for calculating the appropriate reorder point and the optimal reorder quantity to ensure the instantaneous replenishment of inventory with no shortages. The EOQ model assumes certain measures, which the demand considers as being constant; also, inventory is decreased at a static rate until the value of zero is meant. At this point, a specific number of items return the inventory to its beginning level [1].

The EOQ model assumes instantaneous replenishment; there are no inventory deficiencies or no costs. Inventory cost, under the EOQ model utilizes a tradeoff between inventory holding costs (the cost of storage, as well as the cost of tying up capital in inventory rather than investing it or using it for other purposes) and order costs (any fees associated with placing orders, such as delivery charges) [4].

Prior research suggests that ordering a large amount at a given time will increase holding costs, while implementing more frequent orders of fewer items will minimize holding costs but increase order costs. The EOQ model has the ability to find the quantity that minimizes the sum of these costs. The EOQ formula is as follows:

$$TC = PD + \frac{HQ}{2} + \frac{SD}{Q} \tag{1}$$

TC = total inventory cost per year
PD = inventory purchase cost per year (P multiplied by D in units per year)
H = Holding cost
Q = Order Quantity
S = Order cost

The yearly holding cost of inventory can be determined by multiplying H by the average number of units in inventory. The model assumes that inventory is reduced at a uniform rate, with the average number of units equal to Q/2. The total order cost per year is distinguished by S and multiplied by the number of orders per year. This is also equal to annual demand divided by the number of orders or also known as D/Q [4]. Lastly, PD is constant and the order quantity has no effect on it. Equation 2 shows how the optimal order quantity is found:

$$\frac{HQ}{2} = \frac{SD}{Q} \text{ or } Q^* = \sqrt{\frac{2Ds}{H}} \tag{2}$$

Since the NASA shows a need for both the Q and R values to be independent decision variables, the research will also investigate the (Q,R) continuous review model with a periodic-review system. Theoretically, this research seeks to introduce RFID as a means of instantaneous replenishment (instantaneous information can be provided real-time information of RFID). The addition of instantaneous replenishment adds another layer of uncertainty in a (Q,R) model due to the known reliability rates of RFID technologies.

This research will use a model that integrates RFID reliability and the safety stock model created by Jones [6]. It is based from research that has introduced multiple sources of inventory inaccuracies that included theft, loss, and incorrect deliveries [10]. These ideas were expanded by Atali, Lee, and Ozer [12] using an analytical model that considers three sources of discrepancies (shrinkage, misplacement, and transactional errors) jointly. Lee and Ozer [9] expanded their model to include the effects of RFID on those three areas. A model that considers RFID in supply chain visibility is represented by Gaukler, Ozer, and Hausman [13].

They define the lead time $l$ of placing an emergency order $q$ given $q = \alpha Q$, with $a > 1$ at any time point $b \in \{1, 2, \ldots, N-1\}$ based on RFID real-time information. Their model defines the cost to place the emergent order as K($l$). The $l$ value is much less than the lead time of the regular order $(Q)$. Additionally, the probability that the emergent order will arrive before the regular order to be $P(l)$ if the regular order is already on its way and an emergent order is released anyway. Moreover, assume that the expected total cost associated with inventory position $IP$ and RFID reading point $b$ without releasing emergent order is $C_0(IP, b)$ and the according total cost with emergent order release is $C_e(IP, b)$:

$$C_e(IP,b) = K(l) + P(l) * C_0(IP,b) + (1 - P(l)) * C_0(IP + q, b) \tag{3}$$

The inventory manager can compare costs at the end of an ordering period and release an emergency order at $C_e(IP,b) \le C_0(IP,b)$, giving an optimal policy of: $\overline{IP} := \min\{IP : C_0(IP,b) \le C_e(IP,b)\}$ for all $b$ in subset $\{1, 2, \ldots, N-1\}$. Using a $(Q, R)$ policy and the RFID reading point status, a compound inventory policy can be created.

Introducing RFID technology into the inventory management system, adds a level of uncertainty to the previous model and a model to be used by NASA must take into account this uncertainty when creating an inventory policy for the ISS. The reliability of the RFID technology has an effect on these inventory models, and must be taken into account when creating a new inventory management policy. By expanding upon the emergency order policies for periodic review models, this research will add another element to provide a more accurate inventory policy for the NASA space station when compared to the (Q,R) models. An example of the effects of RFID is an "active tag" operating at 433 MHz with a battery that has a higher probability of transmitting signals than an EPC compliant RFID passive tag operating at 915 MHz without a battery in a highly metallic space shuttle environment. Unfortunately, the battery life of the active tag becomes problematic and the mean time between failures of the battery must be included in the transmission probability. This transmission probability can be described as the reliability of the RFID tag. Figure 2 depicts the effect reliability has on inventory control.

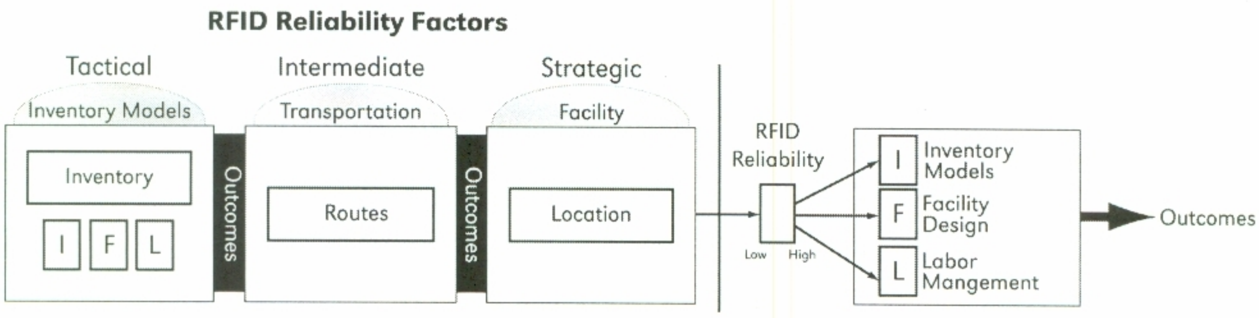


Figure 2: RFID Reliability Factors

In a white paper, Dr. Jones explored the inclusion of a RFID technology type factor ($RF_{tt}$), which is driven by reliability of the RFID technology considered, provides an impact on the inventory levels. The introduction of the reliability constant within a common (Q, R) model may lead to more accurate inventory policies in comparison to a simple EOQ model. Using the reliability information from previous research, we can build upon the previous Gaukler model and include a reliability factor $RF_{tt}$. This research introduces the influence of RFID technologies and their associated RFID reliability factors into the cost function, and evaluates their impacts on inventory, lead time, and customer service levels. Consider Equation 4, which expands Equation 3 described earlier:

$$C_{e(RF_{tt})}(IP, RF_{tt}, b) = K(l) + P(l) * C_0(IP, RF_{tt}, b) + (1 - P(l)) * C_0(IP + q, RF_{tt}, b) \tag{4}$$

In our model, the release of an emergency order at $C_e(IP,b) \le C_0(IP,b)$ gives the optimal policy of: $\overline{IP} := \min\{IP : C_0(IP, RF_{tt}, b) \le C_e(IP, RF_{tt}, b)\}$ for all $b$ in subset. Using a $(Q, R)$ policy and the RFID reading point status, a multi-level inventory policy can be created. This model can utilize previous research and can be evaluated against other $(Q, R)$ models without RFID, with RFID, and no technology factors for performance to determine the most accurate inventory management system. This new model can be used to help NASA determine the proper inventory policy which will minimize shortages and surpluses at the ISS. [6]

## 2.0 Methodology

The study will build on previous research of reliability and inventory models to evaluate the effects that the introduction of a reliability factor has on inventory policy accuracy. It will utilize the model theorized by Dr. Jones (seen in Equation 4). Comparisons will be made to simpler models to determine the effect the added reliability factor has on inventory ordering accuracy. Research will hopefully determine an accurate inventory model that will coincide with the launch schedules put forth by NASA.

## 3.0 Conclusion

RFID ADC inventory control system that integrates inventory models has the ability to improve NASA inventory efforts. Previous NASA RFID research show the opportunities and challenges with RFID reliability in studies by Jones [6,8]. The NASA Constellation Program has expressed the need for an improved mechanism to capture information automatically to reduce astronaut's need to spend time manually tracking inventory along with the need to correctly trigger replenishing or replacing consumed inventory. Our research for a system that provide both automated capture and better identification of when to replace critical life bearing inventory such as food utilizes core IE knowledge. Investigating RFID in conjunction with EOQ, and Q,R models will support an developing an effective system. This system will support NASA's concern pertaining to inventory control issues currently and in further space explorations.

## 4.0 Acknowledgements

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