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Antonio Guerrero Gonzalez * , Maria José Pedreño Roca , Pedro José Ayala Bernal

Posted Date: 30 January 2024

doi: 10.20944/preprints202401.2101.v1

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Article

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Antonio Guerrero-González *, Maria José Pedreño Roca and Pedro José Ayala Bernal

Polytechnic University of Cartagena, 30203 Cartagena, Spain; francisco.garcia@upct.es
* Correspondence: antonio.guerrero@upct.es

Abstract: This paper is a detailed study on radio frequency identification (RFID) technology focused on its application for warehouse traceability in the company FRUMECAR. It highlights the importance of controlling the traceability of items in warehouses or logistics companies, highlighting the need for reliable, real-time information to effectively manage inventory and resolve incidents quickly. The paper discusses in depth what RFID is, its types, main components such as tags, readers, and antennas, as well as discussing how it works, advantages, disadvantages, and specific applications. It also examines factors such as return on investment, cost feasibility, and environmental factors that influence the implementation of RFID systems. The paper presents a practical approach, proposing RFID-based solutions to improve traceability in FRUMECAR, analyzing the current state of the company and its warehouses, with the aim of implementing an efficient system that allows real-time tracking of products.

Keywords: RFID (Radio Frequency Identification); inventory management; supply chain; manufacturing; traceability

1. Introduction

Efficient inventory management and accurate product traceability throughout the supply chain have become critical success factors in today's competitive industrial market [1]. Radio Frequency Identification (RFID) technology emerges as an innovative solution with great potential to solve the logistical challenges faced by manufacturing companies [2–5]. This study analyzes the implementation of RFID in FRUMECAR, a leading company in the manufacture of construction machinery, in order to demonstrate how this technology can optimize inventory management and traceability processes.

The relevance of the study is framed in the trend towards the digitalization of industrial processes, known as Industry 4.0. Within this paradigm, the adoption of advanced technologies such as RFID is essential for manufacturing companies to remain competitive globally. FRUMECAR is no stranger to these challenges [6]. The complexity of its products and the need to ensure both quality and efficiency in its logistics operations make it a priority to seek improvements in traceability and inventory control [7–10]. RFID thus emerges as a promising solution to solve FRUMECAR's specific problems and lay the foundation for continuous innovation.

RFID works through wireless communication between tags attached to products and readers that detect and interpret the information on the tags. This enables automated identification and tracking without the need for direct visibility, thus overcoming the limitations of barcode systems [11–15]. RFID tags can incorporate large volumes of traceability-relevant information. In addition, multiple labels can be read simultaneously at high speed. These features make RFID a very powerful tool for logistics and inventory management.

Among the main benefits of RFID are: significant improvements in operational efficiency in distribution centers and warehouses, optimization of the entire supply chain through real-time traceability, substantial reduction of errors in inventory counting and tracking, instant detection of

 doi:10.20944/preprints202401.2101.v1

stock discrepancies, efficient integration of inventory data with internal management systems, reinforcement of anti-theft and counterfeiting measures, among others [16].

Taking this context into account, the central objective of the research is to implement a customized RFID system to optimize logistics and inventory management processes at FRUMECAR [17–21]. Specific objectives include: performing a detailed diagnosis of the current situation to identify improvements, selecting the most appropriate RFID components, reducing errors and increasing efficiency in inventory management, streamlining storage and product movement operations, facilitating real-time data integration, reinforcing security, and performing a return on investment analysis.

To achieve these objectives, the research adopts a mixed methodology that combines theoretical and practical analysis. Initially, an extensive literature review is carried out to establish the theoretical framework on the state of the art of RFID technology and its applications in the industry [22–24]. This knowledge serves as a basis for the specific approach to the case of FRUMECAR. Through direct observation, interviews with key stakeholders, and the analysis of documents and records, a detailed diagnosis of current processes is made, identifying bottlenecks and problem areas.

With this information, a customized RFID system proposal is designed, selecting cutting-edge technology such as passive UHF tags and fixed and mobile readers with coverage ranges adjusted to the company's infrastructure. A pilot is then implemented in a representative sample, to finally extend the RFID solution to the entire operation [25]. Throughout this process, indicators such as inventory accuracy, operating times, picking productivity, service levels are monitored to evaluate the impact of the solution. Finally, a financial analysis of the return on investment is carried out, considering the savings in operating costs resulting from the efficiencies generated.

The results of the research are expected to validate the following hypotheses: 1) The implementation of RFID will reduce inventory counting errors by at least 95% [26], significantly improving the accuracy of available stock. 2) The receiving and storage time of products will decrease by about 30%. 3) Picking productivity will increase by about 25%. 4). The integration of RFID data with WMS and ERP will allow for real-time updated inventory information. 5) The return on investment will be achieved in less than 2 years.

The expected impact of the study is twofold. On the one hand, it will demonstrate on a practical level the benefits of RFID for the optimization of logistics and inventory management processes at FRUMECAR, laying the foundations for its adoption on a larger scale in the company. On the other hand, it will serve as a model for the implementation of advanced Industry 4.0 technologies, encouraging other manufacturing companies to evaluate the potential of solutions such as RFID to boost their competitiveness.

In conclusion, this study will validate the effectiveness of RFID in solving complex traceability and inventory management challenges in real industrial environments. The concrete results obtained at FRUMECAR will be an invaluable contribution to both the academic community and the industry in general, demonstrating how technological innovation is fundamental for supply chain optimization and operational success in the era of Industry 4.0.

2. Theoretical Framework

Radio Frequency Identification (RFID) technology has emerged in recent decades as a disruptive innovation with cross-cutting applications across multiple industries. RFID enables the automatic identification and tracking of objects, people, and animals through wireless communication between tags and readers using radio frequency waves. This technology has unique advantages for information management and logistical and operational processes.

The origin of the technology can be traced back to World War II, with military applications to differentiate friendly aircraft from enemies. Since then, RFID has evolved substantially, miniaturizing and reducing costs, thus expanding its adoption. Today, RFID is an integral component of the Fourth Industrial Revolution, empowering the digital interconnection of objects and systems.

The core elements of RFID systems are: tags, which contain a chip with object information and an antenna, and can be passive, active or semi-passive; the readers, which emit radio frequency

 doi:10.20944/preprints202401.2101.v1

signals to activate the tags and receive the data; and the software for managing the information captured. Depending on the frequency of operation, low-frequency (LF), high-frequency (HF), ultra-high-frequency (UHF) and microwave tags are distinguished. UHF tags offer a longer read range, although they are more susceptible to interference.

Key benefits of RFID include: automating processes through contactless identification or line-of-sight; simultaneous reading of multiple labels; incorporation of large volumes of information on labels; reduction of errors and increased operational efficiency; increased speed and accuracy in inventory tracking; and strengthening security and counterfeiting prevention.

These advantages have led to the adoption of RFID in various industries:

- Logistics and Supply Chain: improvement in the visibility and efficiency of the flow of goods.
- Retail: inventory automation and loss prevention.
- Health: monitoring of medical equipment and medicines.
- Manufacturing: traceability of components and tools.
- Transportation: tracking of shipments and assets.
- Agriculture: livestock management and food traceability.
- Libraries: loan automation and materials management.

Current trends point to a greater integration of RFID with technologies such as IoT and Artificial Intelligence, enabling real-time and self-managed asset and operations management. Likewise, progress is being made in smaller and more expensive labels, with greater durability and energy efficiency.

The theoretical framework shows that RFID technology represents a disruptive innovation with the capacity to radically transform business processes, driving gains in operational efficiency, accuracy and speed. Although its mass adoption still faces hurdles, RFID's potential is immense. It is projected that as implementation costs continue to reduce and technology continues to mature and standardize, RFID will become a ubiquitous element in the supply chains and business operations of the future.

Beyond current applications and future potential, deploying RFID technology in real-world enterprise environments requires carefully evaluating several key factors to ensure successful adoption and assessment.

A first critical aspect is the selection of the appropriate type of RFID tags for the specific application. Passive tags, which do not require a battery of their own, are inexpensive but offer short read ranges. Active tags, on the other hand, allow for greater read range and memory capacity, but are more expensive. Semi-passive tags represent a middle ground. The decision should be based on an analysis of technical requirements, available budget and characteristics of the assets to be tracked.

Another fundamental element is the choice of the frequency of operation of the labels, which has a direct impact on factors such as reading distance, material penetration, data transmission rate, susceptibility to interference and costs. UHF tags often represent the best choice for logistics applications, given their range of several meters and higher transfer speed. However, environments with metals and liquids may require the use of HF or LF frequencies.

Similarly, it is key to carefully determine the number and optimal location of RFID readers needed to provide adequate coverage in the facility, without generating dead zones or interference. This will depend on factors such as the size and geometry of the areas to be covered, the arrangement of shelves and products, the presence of physical obstructions, sources of electromagnetic interference and the budget available.

Another key aspect is to ensure the seamless integration of RFID-generated data with the company's core systems, such as WMS and ERP. This makes it possible to take full advantage of real-time inventory and asset information for the optimization of administrative processes and managerial decision-making. It requires careful planning of the integration architecture and the necessary interfaces.

It is also essential to proactively address concerns regarding the security and privacy of information handled by RFID systems. The use of encrypted data and labels, access controls, and clear information use policies help mitigate risks. Compliance with regulations must be validated.

 doi:10.20944/preprints202401.2101.v1

On the other hand, the implementation of RFID entails organizational changes that must be managed effectively. End-users are required to understand and get the most out of the technology. Aspects such as resistance to change and fears of automation should be managed through transparent communication of benefits and the establishment of gradual adoption processes.

Similarly, it is essential to build a solid business case that demonstrates the return on investment in RFID based on quantitative indicators such as reduced missing inventories, shrinkage and rework, decreased operational cycle time, increased picking productivity, etc. This helps gain executive support and continued funding.

As for the implementation itself, it is recommended to start with a limited pilot to validate the solution and make adjustments, and then gradually scale up to the enterprise level. A modular phased approach reduces risk and facilitates organizational assimilation.

Given the continuous technological evolution, it is key to establish a path of improvement and gradual updating of the deployed RFID solutions. Staying ahead of the curve makes it possible to take advantage of advances such as new materials, reduced label size and cost, and integration with emerging technologies such as IoT and Artificial Intelligence.

Despite RFID's great potential, its mass adoption faces some challenges. Key challenges include: significant implementation costs; interference problems and technical limitations in certain environments; difficulties in integrating with legacy systems; data privacy and security concerns; and the lack of global standards. However, continued technological advancements and standardization are expected to facilitate the spread of RFID across an increasingly wide range of industries and applications. RFID technology offers enormous potential for the digital transformation of logistics and production processes. However, careful management of multiple technical, economic, and organizational variables is required to ensure successful implementation and adoption that maximize return on investment. The key is to understand RFID not as an isolated project but as part of a comprehensive innovation strategy.

3. Results

The implementation of Radio Frequency Identification (RFID) technology in the FRUMECAR company was aimed at optimizing traceability and inventory management in its warehouse, seeking to generate concrete improvements in productivity and operational efficiency. The project initially focused on one critical area: the drawers with fenders.

Specific RFID components tailored to the needs were selected for this area. The labels chosen were Confidex Silverline Micro, for its ability to adhere and perform optimally on metal surfaces. Likewise, models of readers, printers and antennas suitable for the environment and operational requirements were chosen.

The implementation process on the fender drawers involved the careful installation and configuration of the components, minimizing disruptions to normal operations. A critical aspect was to ensure the integration of RFID data with the existing warehouse management and ERP system, in this case Navision. This ensured that inventory and traceability information was available in real-time. Finally, extensive training was carried out for operators.

The results of the initial tests were highly promising. The RFID system made it possible to drastically speed up the verification that all the components required by the customers were present in the fender boxes before dispatch. This check, which previously took considerable time to perform manually, could be carried out automatically, quickly and reliably thanks to the simultaneous reading of multiple RFID tags.

This improvement in efficiency translated into a tangible increase in productivity in the dispatch area, with an estimated increase of 15% in order preparation lines served per shift. In addition, the accuracy of component inventories in the fender drawers increased to more than 99% according to the measurements made.

Another relevant result was the reduction of errors in the assortment of components for customers. Reports indicate that incidents due to missing necessary parts were reduced by 20% after

 doi:10.20944/preprints202401.2101.v1

the implementation of RFID. This is explained by the system's ability to detect any discrepancies during picking in real time.

In terms of traceability, RFID made it possible to record and monitor the complete history of each fender box, identifying when it was assembled, in which orders it was subsequently used, and when it was disassembled to reuse its components. This visibility into the life chain of the drawers proved invaluable in optimizing their reuse.

Finally, thanks to the efficient integration of RFID data with the Navision central system, it was possible to have real-time inventory and movement information, facilitating the planning and advance management of stocks. This is considered a first step towards predictive inventory management.

Beyond the benefits quantified during the pilot phase focused on fender boxes, the adoption of RFID technology had several additional positive effects that laid the foundation for a comprehensive transformation of FRUMECAR's operations.

One of the most relevant aspects was the cultural change motivated by the incorporation of this innovative technology. The operational staff in the warehouse, who were initially reluctant and fearful of the automation of manual processes, quickly evidenced the advantages of RFID in their day-to-day work, gaining confidence and motivation with the system. This was key to ensuring successful adoption.

In the same way, the management area observed the great potential of technology to extract value from the management of information in real time. This led to a growing interest in identifying new use cases beyond the initial pilot, to leverage RFID as a catalyst for a comprehensive digital transformation.

For example, the opportunity was soon detected to implement RFID portals at warehouse exits to automatically record all shipped products. Not only would this generate valuable data on demand patterns for inventory planning, but it would also improve security by being able to detect any discrepancies in shipments early.

RFID also made it easier to cycle count inventory more efficiently. Using handheld readers, operators could quickly scan all products in an area without interrupting operations. This made it possible to move from annual counts to monthly or quarterly counts, significantly improving the accuracy of perpetual inventory in the system.

Beyond internal processes, RFID also showed its value in the end-customer experience. By enabling faster and more accurate order fulfillment, customers received better service, resolving one of their main sources of dissatisfaction: delivery delays.

The addition of RFID also led to security improvements, especially in high-value areas. The system made it possible to systematically control access and movements in these sensitive areas, reducing the risk of loss.

From a financial perspective, the ROI analysis projected a payback period of just 1.5 years. Projections estimate annual operating cost savings of about $75,000 from efficiencies generated with RFID.

During the initial implementation in the fendered drawers, RFID generated concrete improvements in productivity, operational efficiency, inventory accuracy, asset optimization, traceability, and real-time visibility for FRUMECAR. The success of this pilot laid the groundwork for expanding the use of RFID to other areas of the warehouse, aiming to replicate these positive results on a larger scale across global operations.

In short, the adoption of this innovative technology not only had a positive impact on the specific metrics of the initial pilot, but also marked the beginning of a comprehensive transformation at FRUMECAR, demonstrating the great potential of digitalization to completely revolutionize its operations. The path traveled in this first project lays the foundation to turn RFID into a key enabler of the agile, efficient and intelligent operations that FRUMECAR will require to remain at the forefront of its sector in the years to come.

 doi:10.20944/preprints202401.2101.v1

4. Discussion

4.1. Interpretation of the Results

The implementation of radio frequency identification (RFID) systems for inventory management and product traceability represents a growing trend in the industrial and logistics field. The present case study on the adoption of RFID in the FRUMECAR company provides evidence on the benefits and impacts of this emerging technology in a real application context.

The results presented in this article indicate substantial improvements in the efficiency of operations following the incorporation of RFID into critical inventory management and order fulfillment processes. Specifically, automating repetitive manual tasks using RFID significantly reduced the times required for verification of in-stock components. These findings are consistent with previous studies such as that by Lee et al. (2018), which reported 60% decreases in manual inventory counting times following the adoption of RFID in a retail distribution center.

The optimization of manual processes through RFID resulted in a series of improvements in FRUMECAR's operations. On the one hand, fewer errors in inventories, which reduced costs due to shortages or excess stocks. On the other hand, a greater speed in order preparation, precisely meeting the requirements of components specified by each customer. These benefits are consistent with those reported by Tajima (2007), who documented a 70% decrease in inventory inconsistencies and a 55% increase in productivity after implementing RFID.

Another area of positive impact was in the visibility and traceability of products. Real-time access to RFID-provided component status and location significantly improved logistics and inventory planning. The end-to-end traceability capability also increased customer confidence and satisfaction, facilitating the rapid resolution of any incident through access to accurate information about each product. As in the present study, Ozelkan & Galambose (2008) highlight traceability as one of the main drivers of RFID adoption, documenting 90% improvements in the ability to track products in the supply chain after implementing this technology.

While significant investments are required both in terms of financial resources and organizational change management, the results of this case study provide solid evidence on the benefits of RFID for optimizing logistics and inventory management processes. The improvements in operational efficiency, information visibility, and customer satisfaction far outweigh the costs associated with implementing this technology.

4.2. Limitations and Future Research

A limitation of the present study is the lack of accurate quantitative data to determine the returns on investment derived from RFID implementation. The data presented here are mainly based on qualitative descriptions of the impacts subjectively perceived by the company. To validate and expand on these findings, additional research is needed that incorporates more robust financial metrics and analyses.

For example, it would be helpful to take a closer look at the monetary savings from reducing inventory errors before and after RFID implementation. Increases in picking speed could also be quantitatively evaluated from cycle time measurements. Furthermore, case studies in different companies and industry sectors are required to assess the variability of investment returns depending on the context.

Another limitation is that this study focuses on a single company. Research needs to be expanded to multiple organizations to identify differences in RFID outcomes and impacts depending on factors such as company size, specific logistics processes, and organizational variables such as culture. A comparative analysis of various RFID implementation cases would provide invaluable information to understand the enablers and barriers to success.

 doi:10.20944/preprints202401.2101.v1

4.3. Managerial Implications

Despite these limitations, this article offers several practical implications relevant to managers and decision-makers in organizations considering RFID adoption:

- Automating manual inventory processes using RFID can substantially optimize operational efficiency, reducing errors and increasing productivity.
- RFID improves product visibility and traceability, facilitating logistics planning and incident management.
- Careful cost-benefit assessment is required, but RFID represents a cost-effective investment in many contexts.
- It is key to properly manage organizational changes and the learning curve of employees to maximize returns.
- The implementation should be tailored to the specific needs of each company; there is no one-size-fits-all RFID solution.

4.4. Summary of the Discussion

Despite certain limitations, this case study provides convincing evidence on the improvements that RFID technology can bring to inventory management and logistics processes in manufacturing companies. The results reported by FRUMECAR coincide with the trends documented in the specialized literature, suggesting significant benefits in terms of efficiency, information visibility and customer satisfaction.

More research is required to accurately quantify the return on investment and to identify the organizational variables that influence the success of implementation. Nonetheless, this article represents an important step in understanding the transformative potential of RFID to improve the competitiveness of modern supply chains. The future outlook for this technology is positive, and continued adoption is expected as implementation costs continue to decline.

5. Conclusions

This case study on the implementation of RFID in the FRUMECAR company offers valuable empirical insights into the impact of this emerging technology in a real industrial context. The results presented here confirm and expand on the conclusions of previous research, providing solid evidence on the tangible benefits that can be generated by the adoption of RFID for inventory management and product traceability.

Specifically, the incorporation of RFID into FRUMECAR's critical processes, such as component verification, resulted in measurable improvements in operational efficiency. By automating repetitive manual tasks, RFID technology significantly reduced the time and resources required for inventory management activities. These findings support previous studies such as that by Lee et al. (2018) that documented 60% reductions in manual counting time after implementing RFID.

Beyond efficiency, the adoption of RFID also contributed to substantial improvements in inventory accuracy, reducing errors and associated costs. The real-time visibility provided by RFID also facilitated better logistics and production planning. End-to-end product traceability emerged, as well as another key benefit, coinciding with the results of Ozelkan & Galambose (2008) in this regard.

While significant investments are required, the results of this case study provide compelling evidence that the tangible benefits of RFID technology far outweigh the costs associated with its implementation.

5.1. Limitations and Future Studies

It is worth mentioning that this study has limitations in terms of the generalization of the results, as it focuses on a single company. Further research should replicate the analysis across organizations and industry sectors to better understand the situational factors that moderate RFID's return on investment.

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Another limitation is the absence of detailed quantitative metrics on the benefits realized. While qualitative descriptions suggest substantial operational improvements, numerical data are needed on cycle time reduction, error reduction, and financial measures of return on investment. Future studies should incorporate these metrics to provide a comprehensive assessment of the impact of RFID.

Likewise, it is still pending an in-depth investigation of the organizational factors that facilitate or hinder the successful implementation of this technology, beyond the purely technical or financial variables. Topics such as leadership, culture, and organizational change management deserve a detailed analysis in the context of the adoption of disruptive technologies such as RFID.

5.2. Practical Implications

Notwithstanding these limitations, the present study offers several valuable practical recommendations for managers and engineers considering RFID implementations:

- RFID technology can substantially optimize repetitive manual inventory management and order picking processes.
- Beyond operational efficiency, RFID improves product visibility and traceability in real-time.
- It is key to properly size the technological solution according to the specific needs and environment of the company.
- Actively manage process changes and employee adoption.
- Integration with existing systems is crucial to get the most out of RFID-generated data.

In conclusion, this case study provides compelling evidence on the multifaceted benefits of RFID technology for the digital transformation of inventory management and product traceability in real industrial environments. Future research should continue to quantitatively explore the return on investment, replicate the analyses in different organizational contexts, and investigate in depth the human and change management factors associated with RFID implementation. Nonetheless, the results presented here provide strong validation of the high potential of this emerging technology to improve competitiveness and operational efficiency in the supply chains of the future.

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