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Total Cost of Ownership of Real-Time Locating System (RTLS) Technologies in Factories

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Abstract

Real-Time Locating Systems (RTLS) have become an important supporting technology in manufacturing due to safety, logistical and managerial concerns. RTLS is a very wide term covering many different specific technologies. To increase the potential for implementation and better anticipate the costs associated, four different RTLS technologies have been evaluated according use case characteristics, maintenance costs, communication requirements. Data server capabilities, scalability, and integrability. The ability to analyze and determine such criteria are vital to support the selection of a specific technology (or mix of technologies) within manufacturing. The paper offers researchers and managers a reference comparison of the total costs surrounding the ownership of Ultra-wide band (UWB), Bluetooth Low Energy, Ultrasonic, and Optical RTLS technologies.

Keywords: Real-Time Locating System, RTLS, Indoor Wireless Positioning, Total Cost of Ownership

1. Introduction

In the face of increased competition, logistics complications, and production complexity the effective allocation and management of resources within companies is vital to industrial survivability and profitability [1]. Real-Time Locating Systems (RTLS) provide real-time visibility into the location and movement of critical assets, inventory, and personnel within manufacturing facilities. As an enabling factory technology, RTLS can be used to optimize production processes, reduce downtime, and improve safety and security. By having accurate and up-to-date information on the location of assets and personnel, manufacturers can quickly respond to disruptions, such as equipment breakdowns or supply chain delays, and make informed decisions to mitigate their impact. However, the ability to effectively leverage RTLS requires careful consideration of the effort and costs associated, that can be challenging to anticipate [2].

Typical methods to evaluate the costs of physical assets can provide some estimate to general costs, however they generally lack the ability to be easily modified and are not suitable for highly specific industry use case solutions [3]. In an effort to provide a common basis for making decisions, the operational effectiveness, organizational benefit (improved performance, enhanced capability), as well as Total Cost of Ownership (TCO) of new technological solutions should be considered [4]. To support the analysis of costs associated with RTLS, a study of different technologies and relevant factors has been conducted. This paper introduces a preliminary set of use case constraints, technological factors, and costs to evaluate and estimate RTLS TCO. The constraints and factors were analyzed to establish a reference comparison of the total costs surrounding the ownership of multiple RTLS technologies according to a considered use case.

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2. Theoretical Background

This section introduces TCO which has been exhaustively researched in literature, to establish the basis for evaluation. Additionally, the characteristics, of RTLS are presented, a more comprehensive comparison of the technologies referenced can be found in the following papers [8, 10].

2.1. Total Cost of Ownership

Originating in the United States in the 1990s as a result of a need to better evaluate large capital investments, TCO, focuses on the operator/user perspective of an asset and all the costs that occur during the course of ownership [5]. In practical terms this represents the sum of all costs associated with the research, procurement, deployment, personnel training, operation, logistical support and/or disposal of the technological asset over its full life. Including costs associated with purchasing the asset or service, as well as any related operational and maintenance expenses incurred during use. Additionally, TCO considers the physical and digital infrastructure, management expenses, licensing, operational costs, and ordering (transportation, receiving, inspection, rejection, replacement, downtime caused by failure, disposal costs) of the technology [6].

TCO has since the 1990's been utilized by numerous business organizations and individual evaluators giving rise to a number of approaches to evaluate suppliers based on price, or performance [7]. These can include Zero-Base Pricing, Cost-Based supplier Performance, Life-Cycle Costing, and TCO (Dollar-based, Value-based).

TCO provides an accurate and comprehensive prediction of a business's total cost of a product or service over a certain amount of time. Enabling the organizations to gain a better insight and understanding of their cost and identify areas where they can save or avoid costs [6-8]. This is especially useful for companies that are contemplating large capital investments, since TCO can help them determine if an investment is worth it or not. On this basis TCO is well suited to compare diverse options when considering capital investments, thus suited for evaluating RTLS technologies.

2.2. Real-Time Locating System

RTLS refers to a specific tracking system that combines hardware, software, and communication networks to identify, track, and monitor objects/assets or people in real-time. This is accomplished through the utilization of detection devices such as sensors, tags, or transponders that are placed on physical assets and transmit data to a computer or anchor (gateway) for real-time analysis or monitoring of motion (Figure 1).

The most commonly utilized technologies include Wi-Fi, Infrared, Optical, Ultra-wide band (UWB), Bluetooth, RFID, Ultrasonic, GPS, or a combination of technologies to track and monitor [8]. The different indoor positional technologies differ in reliability, confidentiality, robustness, positioning accuracy and other aspects. Each of the technologies presented have successfully been deployed in various contexts, including but not limited to tracking the location of medical equipment in a hospital, locating vehicles and store inventory, and facilitating warehouse efficiency. Within a controlled environment RTLS can monitor, collect, and communicate data related to the location of products, equipment or personal in real-time, allowing for enhanced security and automated management [2]. By being better able to know the speed of movement and location of people/assets/materials it is possible to shorten production cycles and provide workers more time to be productive. RTLS has demonstrated the ability to improve the conceptualization of inventory and asset tracking, simplifying the process of locating misplaced products or materials and calculating different process times (Inventory Management, Asset Tracking, Oder Tracking, Route Optimization, and Facility Planning/Improvement).

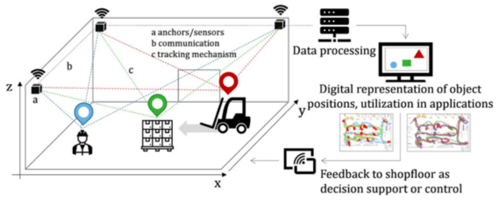

Figure 1: General principle of RTLS in factories [2]

Despite the general benefits of RTLS, accuracy challenges (signal and object interference), tag deployment, tag management (charging, placing, maintaining), network support and middleware licensing can add to the cost of the systems. These challenges can be further worsened when misaligned to novel/unprecedented use case requirements, as well as general boundary conditions (size and complexity of location, temperature, geometry, equipment) [9, 10].

3. Total Cost of RTLS Ownership

An RTLS system, including hardware and software, can cost anywhere from $1,000 to $50,000 (with complex systems exceeding $100,000). The TCO for RTLS solutions depends on several factors, including the type of system deployed, the size of the installation, the required accuracy and latency, the number of tracked items and the complexity of the environment being monitored maintenance costs. However, the TCO can be much more, depending on installation and maintenance costs, as well as any additional features such as analytics or reporting. Depending on the use case environment (facility requirements and characteristics) and operating specifications (Section 3.1), the technology involved (Section 3.2), the costs associated with the RTLS technology (Section 3.3) effect the TCO of RTLS.

3.1. Use Case Specifications (Evaluation and Criteria)

RTLS systems can be deployed in any environment where it is beneficial to monitor the movement of people and objects in real-time. This includes hospitals, factories, warehouses, office buildings, schools, retail stores, airports, and stadiums [9]. However, given the broad range of application areas it is critical to first consider the conditions (requirements, characteristics, capabilities) that the system will be required to perform within. The factors presented in Table 1 reflect the needs and limitations (*causal factors) that the system being evaluated will be constrained and/or designed for. This preliminary list is expected to increase depending on the complexity of the environment, however for the purpose of clarity only the most causal factors were included. In the table each factor is ranked as either being high or low, which is measured according to a defined metric.

The RTLS lifespan is principally determined by the tag type, typically replaceable lithium-ion or coin cell batteries that last for up to two years (used over an 8-hour cycle) are used (which increase the TOC of ownership when considering a period beyond 2-years). In contrast RFID tags can have a life span of 10-20 years depending on their environment. The metrics used (Table 1) can be measured using commonly available equipment, while Physical Interference Density can be estimated using an engineering reference guide (e.g., steel 7.85g/cm3, aluminum 2.70g/cm3, acrylic 1.185g/cm3). While the industrial RTLS technologies referenced in this paper have limited abilities to overcome physical interference the potential for leveraging Decentralized Object Location and Routing (DOLR) solutions exists and thus interference should be considered when evaluating RTLS.

Table 1. Use Case Criteria

Factor	Level	Description
Life Span (years of RTLS)	High	>2years
	Low	<2years
Size of Env. (sqm)	High	>200sqm
	Low	<200sqm
Assets (# of tags/devices)	High	>21 Tags
	Low	<20 Tags
Accuracy (root mean square error)	High	>1.1m
	Low	<1.0m
Latency (Mbps)	High	<50mbps
	Low	>51mbps
Physical Interference (# of physical objects in env.)	High	>9 objects (30*30*200cm)
	Low	<9 objects (30*30*200cm)
Physical Object Interference Density (g/cm3)	High	>1.2 g/cm3
	Low	0.0-1.2 g/cm3
Digital Interference (MHz)	High	3000-5000 MHz
	Low	13.56-250 MHz
Bandwidth (Mbps)	High	>50mbps
	Low	<3mbps
Network Scalability (Mbps)	High	>50mbps
	Low	<3mbps

Network scalability refers to the ability of the network to expand and adapt to an increasing number of nodes or an increase in traffic load. Bandwidth, on the other hand, refers to the amount of data the network can carry or transfer at any given point of time. Bandwidth plays a crucial role in ensuring network scalability, as a network must have sufficient capacity to accommodate all RTLS traffic. When network bandwidth is exhausted, scalability is hindered, and it becomes increasingly difficult to add new anchors. Therefore, it is essential to have sufficient bandwidth available to ensure that the network can adjust to the use case needs and increase its scalability.

3.2. RTLS Technology Evaluation

According to the environment (facility requirements and characteristics) and use case specifications the outcomes derived from Table 1, are used to identify a suitable/capable technology as shown in Table 2. Regarding the criteria in Table 2, performance above/beyond the necessary use case specifications is acceptable (enabling a scoring for each criterion and technology). While an increased capability may come with a cost, allowing for a technological comparison without factoring in cost prevents bias from being introduced and avoids a strict dollar-based assessment.

Table 2. RTLS Technologies Criteria Suitability [11-13]

Factor		Wi-Fi	Infrared	Optical	Bluetooth	RFID Passive	RFID Active	UWB	Ultrasonic
Life Span (years of RTLS)	High	x	x	x	x	x	x	x	x
	Low					x	x		
Size of Env. (sqm)	High	x	x	x	x			x	x
	Low		x	x		x	x		x
Assets (# of tags/devices)	High	x	x	x	x	x	x	x	
	Low								x
Accuracy (root mean square error)	High		x	x				x	x
	Low	x			x	x	x		
Latency (Mbps)	High		x	x				x	x
	Low	x			x	x	x		
Physical Interference (# of physical objects in env.)	High								
	Low	x	x	x	x	x	x	x	x
Physical Object Interference Density (g/cm3)	High	x			x				
	Low		x	x		x	x	x	x
Digital Interference (MHz)	High		x	x		x	x	x	x
	Low	x			x				
Bandwidth (Mbps)	High	x	x					x	
	Low			x	x	x	x		x
Network Scalability (Mbps)	High	x	x	x	x	x		x	
	Low						x		x

The technologies identified based on their capability to satisfy the use case specifications presents the first level of comparison between the RTLS technologies. By emphasizing capabilities over cost during this phase it is ensured that a short-sighted decision is not made that could have costly implications (maintenance costs, service cost, operational capability, system integrity and robustness).

3.3. RTLS Associated Costs

RTLS can be expensive to implement because it requires the use of sensors and antennas, software licensing, monitoring, and maintenance costs. Prices can range from a few hundred dollars for a basic system to hundreds of thousands of dollars for an advanced system with specialized sensors and extensive software. Figure 2 presents a simplified breakdown of the costs associated with RTLS throughout the systems lifespan.

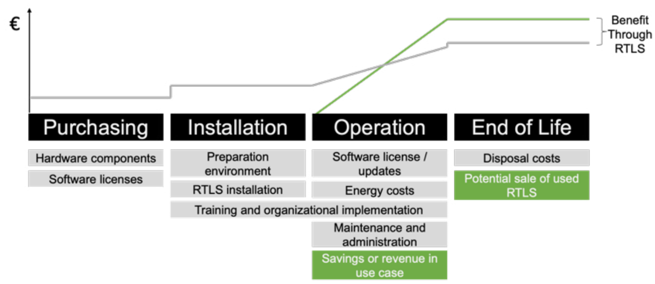

Figure 2: TCO Considerations and Benefits

3.3.1. Purchasing and Installation Associated RTLS Costs

The initial purchasing and installation costs (reference in Figure 2) includes all upfront capital expenses related to the purchase, installation, and configuration of the RTLS system. The initial cost of purchasing the equipment can range anywhere from tens of thousands to hundreds of thousands of dollars, depending on system parameters. While the cost of RTLS systems can vary depending on size and complexity, Table 3 introduces a set of costs that can be expected for each technology (outcome from Section 3.2) which is associated to the use case specifications (Section 3.1).

Table 3. RTLS Associated Equipment

Hardware and Software	Wi-Fi	Infrared	Optical	Bluetooth	RFID Pas.	RFID Act.	UWB	Ultrasonic
Access Point (anchor)	x	x		x	x	x	x	x
Receiver		x			x	x	x	x
Optical Sensor			x					
Equipment Mounts	x	x	x	x	x	x	x	x
Tag	x	x		x	x	x	x	x
Mobile Device (smartphone)	x			x				
IPV6	x	x	x	x	x	x	x	
Ethernet Cabling (Cat5, 6, 7)	x	x	x	x	x	x	x	x
Router				x			x	x
Server	x	x	x	x	x	x	x	x
Location Software License	x	x	x	x	x	x	x	x
Middleware	x	x	x	x	x	x	x	x
Wi-Fi Manager	x	x		x			x	x
POE Switch		x	x	x	x	x	x	x
Tag Battery/Charger	x			x			x	x

Installation costs can range from a few thousand dollars for a small single-room system to tens of thousands of dollars for large-scale applications. The installation costs for an RTLS system should include the equipment, labor, and associated services necessary to install the system correctly and securely. Based on Table 3, the associated costs can be interpreted as either fixed or variable and relate to the specification associated to the desired system (Table 4).

Table 4. RTLS Variable and Fixed Costs

Direct RTLS Costs		
Factor	Variable	Fixed
Size of Env.	Access Point (anchor), tags, receiver, optical sensor, equipment mount, ethernet cabling, router, server, POE switch	IPV6, server, Location Software License, Middleware
Network	Ethernet cabling, Router, Wi-Fi Manager, POE Switch, mobile devices	
Accuracy	Network (ethernet cabling, router, POE switch), Access Point (anchor), tags, mobile devices	
Latency	Network (ethernet cabling, router, POE switch), Access Point (anchor), tags, mobile devices	
Scalability	Network (ethernet cabling, router, POE switch), receiver, optical sensors, tags, mobile devices	
Assets	Access Point (anchor), tags, Network (ethernet cabling, router, POE switch),	
Physical Interference	Access Point (anchor), tags, latency,	
Physical Object Interference Density	Access Point (anchor), size, Network (ethernet cabling, router)	
Digital Interference	Access Point (anchor), size, Network (ethernet cabling, router)	

Cables, hardware, installation labor, and data networking equipment (connecting RTLS devices to the necessary networks, including purchasing IP addresses and additional networking components) must be considered during this phase.

3.3.2. Operation Associated RTLS Costs

The operational costs associated with RTLS (Figure 3) can critically affect the TCO. Considering such factors is critical for proper cost analysis. The most capital-intensive costs associated with RTLS are typically purchasing (Section 3.3), however additional product or service costs related to this life cycle phase including but not limited to:

- Maintenance and Support Costs: Costs associated with maintaining and supporting the RTLS can include, including any warranties, subscription fees, and/or repair costs. Maintenance costs vary depending on the size and complexity of the system, as well as the number of technologies, sensors and tags used in the system. Recurring costs can include hardware maintenance, software and firmware updates, tag replacement and service contracts. Additionally, IT specialists can be required to manage and troubleshoot the system.
- Training and Education Costs: The costs associated with training users on the RTLS and any associated educational activities to increase user proficiency. Costs can range from a few hundred dollars for basic training to several thousand dollars for customized training.
- Resources and Staffing Costs: This includes costs pertaining to personnel required to operate, monitor, and administer the system. A network system is necessary to provide the necessary computing power and communication infrastructure for RTLS data analysis, communication, and storage of the tracked assets and persons. Additionally, cyber security, servers, routers, switches, as well as edge computing devices, tablets or laptops can be necessary. These devices support the software and facilitates data collection and analysis.
- Integration, Upgrade and Migration Costs: When evaluating RTLS technologies, consider the costs associated with integrating, upgrading, or migrating to and from an existing or prospective system.

3.3.3. End of Life Associated RTLS Costs

The end-of-life costs RTLS depends on the specific components and any hazardous materials that are involved (lithium-ion battery's). Disposal of RTLS components (anchors, tags) can be compared to that of small household electronics such as tv remotes or electronic wall clocks. The costs associated with disposal can depending on the use case size can include transport and transfer fees, landfill and processing fees, and hazardous material fees.

4. Considered Use Case

The described cost model was applied to a representative use case which is a new 800m2 workplace that contains various manufacturing equipment and machines (Figure 3). The facility is a job shop whereby the activities involved focus on the basic conversion of raw material into a useful one-of-a-kind product (low volume, high variation). Therefore, the real-time location of the people, material, and equipment are vital for the effective workshop management and occupational safety of the operators, support staff, and various technicians.

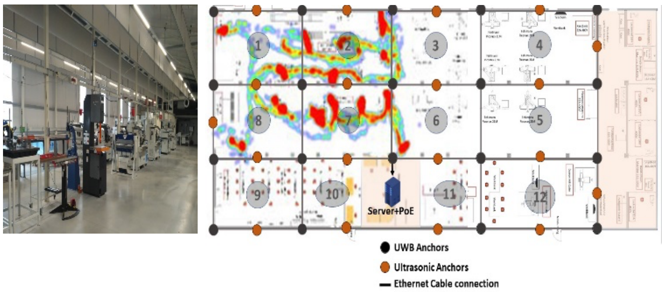

Figure 3: UWB and Ultrasonic RTLS Deployment

Raw material storage is located on the sides, and production equipment is located throughout the middle of the facility as shown in Figure 3. When materials are required, an operator requests a technician to retrieve the requested materials and transport them to the operator's working area. To ensure that the material, and volume, are transferred in the right sequence, at the right time, a technician should receive and record all the required information and manage the storage and material orders. This process is manual, prone to errors (incomplete or missing data), labor intensive, and unreliable. RTLS aims to replace manual tasks with automated, errorless, fully digital, real-time asset booking and tracking with the following aims:

- Provide the raw material and tools for the operators in the fastest way and highest accuracy.
- Identifying occupied and free machines for the operators.
- Improve work effort activities.
- Enable asset tracking to make the processes fully visible and transparent for all supporting staff.

4.1. Use Case Evaluation Criteria and Technology Selection

Based on the steps presented in Section 3, a set of suitable RTLS Technologies were evaluated (Table 5).

Table 5. Use Case Relevant Technology

Criteria	Use Case Requirements
Life Span (years)	High
Size (sqm)	High
Network (Mbps)	High
Accuracy (root mean square error)	High
Latency (Mbps)	High
Scalability (Mbps)	High
Assets (# of tags/devices)	High
Physical Interference (# of objects)	Low
Interference Density (g/cm3)	High
Digital Interference (MHz)	Low

Suitable RTLS Technologies Identified: Ultrasonic vs. UWB

Of the available RTLS technologies, UWB and Ultrasonic were selected due to their high use case criteria suitability for the facility. UWB RTLS is suitable for accurate and visible asset tracking and providing historical or real-time data related to the operator activities. On the other hand, Ultrasonic is suited for gathering information related to machine and equipment availabilities and identifying zones where there is the highest operator concentration for safety improvement (Figure 4).

4.2. RTLS Associated Costs

The costs were estimated according to the technology requirements and use case specifications. This analytical study allowed for the total costs experienced throughout the life of the system in the facility to be calculated.

Table 6. UWB & Ultrasonic RTLS

Life Cycle Phases	RTLS Technology Costs	
	UWB	Ultrasonic
Initial Purchase & Installation Costs	High	Low
Maintenance & Support Costs	High	Low
Training & Education Costs	low	Low
Resources & Staffing Costs	High	Very Low
Integration, Upgrade & Migration Costs	Very High	Very Low
Unforeseen Costs	High	Very Low
Disposal Costs	Very Low	Very Low

The results showed a high indirect cost for the entire life cycle phases for UWB. Based on the use case specifications and intended criteria, UWB is only suitable for RTLS technologies for long term deployment. In contrast, Ultrasonic has a significantly lower life cycle cost in comparison to UWB. Although its application in this use case can be limited to equipment detection and low-level field service management, it does so at a lower cost.

4.3. RTLS Use Case Total Costs

A one-year time frame was used to estimate the TCO for the UWB and Ultrasonic RTLS according to the size of the facility, the required accuracy and latency, and the number of items being tracked (Table 7). In the calculation the costs associated with the RTLS technology all associated costs (Section 3) were considered.

Table 7. Use Case Total Cost Analysis (1-year)

	UWB			Ultrasonic		
	Quantity	Unit Cost (€)	Total (€)	Quantity	Unit Cost (€)	Total (€)
Anchors	19 piece	400-500	7600-9500	19 piece	80-100	1520-1900
Tags	30 piece	50-80	1500-2400	30 piece	70-90	2800-3600
Receiver	1 piece	30-100	30-100	1 piece	30-100	30-100
Mounting eqpt.	19 piece	10-20	190-380	19 piece	10-20	190-380
Ethernet cabling	950 Meter	0.2-0.3	190-285	-----	-----	-----
Data Server & License (Educational & Perpetual)	1 User	2000-4000	2000-4000	1 User	-----	-----
POE switch	1 piece	200-400	200-400	-----	-----	-----
POE injectors	19 piece	10-20	190-380	-----	-----	-----
Energy	1155 kWh/Annum	0.36-0.40	415-460	248 kWh/Annum	0.36-0.40	90-100
Installation	4 Days	500-1000	2000-4000	4 Days	500-600	2000-2400
Maintenance	1 Day/3 years	650-1700	650-1700	1 Day/3 years	650-1700	650-1700
	Total Cost		**15000-23600**	**Total Cost**		**6600-9300**

The direct costs for the RTLS systems, included hardware and software, ranging from €11,000-€15,000 for UWB and €4500-€5500 for Ultrasonic. However, as presented in Section 3 the TCO must consider additional factors relevant to the use case environment and technology requirements. One of the most critical costs resulting in a higher TCO for UWB is the requirements for networking and communication between the anchors and server. To achieve the highest accuracy with minimum latency, ethernet communication is preferred over Wi-Fi (allowing more reliable and faster data traffic). Due to the size of the environment and network communication demands, Power over Ethernet (PoE) and PoE injectors are required, which cost between €600-€1100. However, Ultrasonic does not require ethernet communication and PoEs due to its specification (offering comparable accuracy).

Additionally, the data server and licensing for UWB was greater due to deployment complexity, configuration specifications, positioning calculation scheme, filtration and synchronization methods required to obtain the location of each tag (Table 7). Based on the conducted evaluation UWB supporting companies providing the necessary data server do not allow for code modification or reuse and no source code with proprietary license. In contrast, the positioning calculation required for Ultrasonic can take advantage of simple requirements and utilize an open-source data server, reducing the costs for licensing and subscriptions.

Energy consumption is another additional factor considered within the TCO due to use case requirements. Based on technology demands a significant difference exists between the energy cost of UWB (Anchors, tags, and receiver) and Ultrasonic (main RTLS common hardware) due to the PoE network requirements of UWB. Based on the PoE switch and injector specifications, 17.9 watts per port was estimated to facilitate the communications and powering up the anchors.

The maintenance cost for both technologies was determined to minimal due to the availability of technical persons, and relative robustness of the chose technologies. The principal costs are associated with the cost of changing the rechargeable batteries for the RTLS tags. With both technologies requiring Li-pol 300mA batteries with a lifetime of two years (used over an 8-hour cycle). The overall maintenance cost includes the price for batteries for each of the tags and the required working hours for necessary technicians. While the TCO cost comparison was made over a one-year period, it should be acknowledged that after that time the tags require replacement batteries. Thus, it is not directly reflected in the first-year calculations, however, should be considered within the TCO to calculate long-term costs (time greater than 1-year).

5. Conclusion and Discussion

Based on the identified factors (Section 3) and tabulated use case costs (Section 4) the TCO for different RTLS technologies was calculated considering the purchasing, installation, operation, end of life (Figure 2). While the outcomes of the analysis (Section 4) demonstrated a positive outcome for the selection of the Ultrasonic RTLS, it must be acknowledged that this is attributed to the unique characteristics of the use case. Thus, it is important to note that the results may not be applicable to all situations, and there may be boundary conditions that make ultrasonic technology not feasible, such as limitations in the size of tags.

The factors identified and utilized to calculate RTLS TCO considered the entire life cycle of the systems under evaluation, but additional criteria may be required depending on the use case environment and deployment requirements. In addition to TCO, it is important to consider the ROI of RTLS before making selecting, purchasing, and deployment of the system. The ROI of RTLS is highly influenced by the business context and industry. For instance, improvements in inventory management, asset tracking, and personnel tracking have demonstrate an ROI of 18-23% [14] in general.

1. Inventory Management: inventory management where the improved visibility of assets in warehouses can reduce the need for safety stocks, freeing up cash and reducing warehouse space.
2. Asset Tracking: With an RTLS system, companies can track assets, ensuring that they are located where they should be, thereby improving business performance, reducing theft, and reducing losses due to misplaced assets.
3. Personnel Tracking: RTLS can track personnel, providing improved safety for employees, improved management of personnel, and improved productivity. By enabling quick location of personnel and automatic notification of critical events, employee performance can improve, and the need for manual check-ins can be eliminated.

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