A Model for Automated Construction Materials Tracking

by

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners. I understand that my thesis may be made electronically available to the public.

Abstract

Materials management is a critical factor in construction project performance, particularly in the industrial sector. Research has shown that construction materials and installed equipment may constitute more than 50% of the total cost for a typical industrial project. Therefore the proper management of this single largest component can improve the productivity and cost efficiency of a project and help ensure its timely completion. One of the major problems associated with construction materials management is tracking materials in the supply chain and tracking their locations at job sites. Identification is integral to this process. Research projects conducted during the last decade to automate the identification and tracking of materials have concluded that such automation can increase productivity and cost efficiency as well as improve schedule performance, reduce the number of lost items, improve route and site optimization, and improve data entry. However, these technologies have been rapidly evolving, and knowledge concerning their implementation is sparse. One new approach enables locating of components within a few meters at a cost at least a magnitude lower than preceding technologies. It works by combining GPS located reads of RFID tags read at a rate of several thousand Hertz in order to estimate the location of these inexpensive tags which are attached to key construction materials. This technology was rapidly prototyped and deployed on two large industrial construction projects in 2007 and 2008. This thesis analyzes and synthesizes the data and experiences from these unique and large scale field trials as well as the literature in order to develop a general implementation model for automated construction materials tracking for industrial projects. It is concluded from the model that this new automated construction materials tracking technology is likely to be successful if implemented full scale on well selected future projects. This conclusion is supported by subsequent industry decisions.

Acknowledgements

First of all I would like to express my sincere thanks to Dr. Carl T. Haas, my supervisor. This thesis would not have been possible without his guidance. I appreciate his knowledge, patience, support and the encouragement he has provided to me in the completion of this task.

After my supervisor, I would also like to acknowledge the support of the industry people who made this thesis possible. First amongst them is Paul Murray, the site manager of SNC-Lavalin for the Portlands Energy Centre (PEC) project in Toronto. His support to implement the proposed research at the PEC site and allowing us to interact with his subcontractors has really helped in achieving the research objectives. I would also like to express my thanks to Scott Kerr, fabrication coordinator of W.S. Nicholls Industries Inc. for working together with us on this project.

I am also thankful to Identec Solutions for providing some of the software and hardware used in our field work at the PEC project in Toronto.

Besides the industry people, I would like to acknowledge and thank my fellow graduate students, Saiedeh Nawabzadi Razavi and Duncan A. Young for working together with me at the Portlands Energy Centre, and providing valuable advice.

Finally, I would thank my family members for supporting me to work on this thesis; my mother who had to sacrifice a lot for my absence, my wife for her support and encouragement, and my children for their love and affection.

Dedication

I would dedicate this thesis to my family.

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Chapter 1
Introduction

1.1 Background

The Construction Industry Institute (CII) (CII 1986) has defined materials management as "the planning and controlling of all necessary efforts to insure that the correct quality and quantity of materials and equipment are appropriately specified in a timely manner, are obtained at a reasonable cost, and are available when needed." Materials management is a system, not the organization responsible for performing these tasks (The Business Roundtable 1982). Construction materials management has also been recognized to include the integrated coordination of materials takeoff, purchasing, expediting, receiving, warehousing and distribution (Bell and Stukhart 1986). It is an indispensable part of the project management which can be integrated with engineering to provide an end product that meets the client's requirements and is cost effective (Kini 1999). Materials management extends beyond inventory management. It involves: the procurement of equipment and materials, inspection and delivery to the job site, inventory control and the disposal of surplus material at the time of project completion (Silver 1988). Figure 1.1 shows the organization chart for a typical engineer/procure/construct (EPC) project.

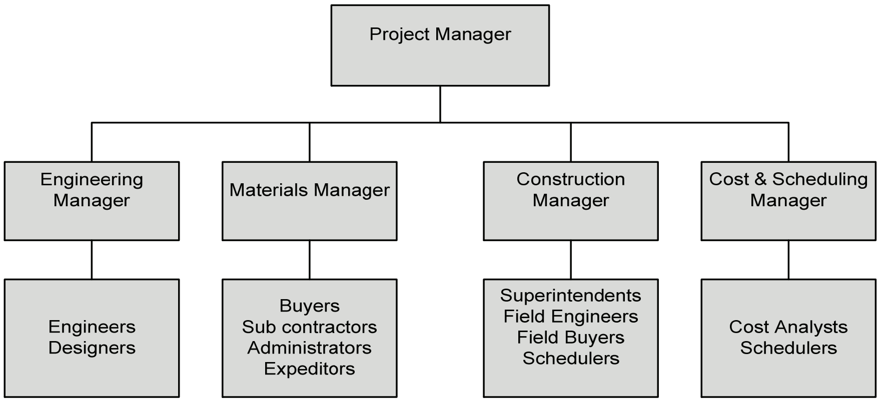

Figure 1.1: Organization chart for EPC project (Based on Kini 1999)

The project management team under the project manager consists of the engineering manager, the materials manager, the construction manager and the cost and scheduling manager (Kini 1999). For an integrated approach, within the project organization, the materials manager reports directly to the project manager and is at the same level as the engineering manager, construction manager, and cost and scheduling manager. This relationship is important to provide focus on materials management to the project team. The logical components of a materials management system are shown in Figure 1.2.

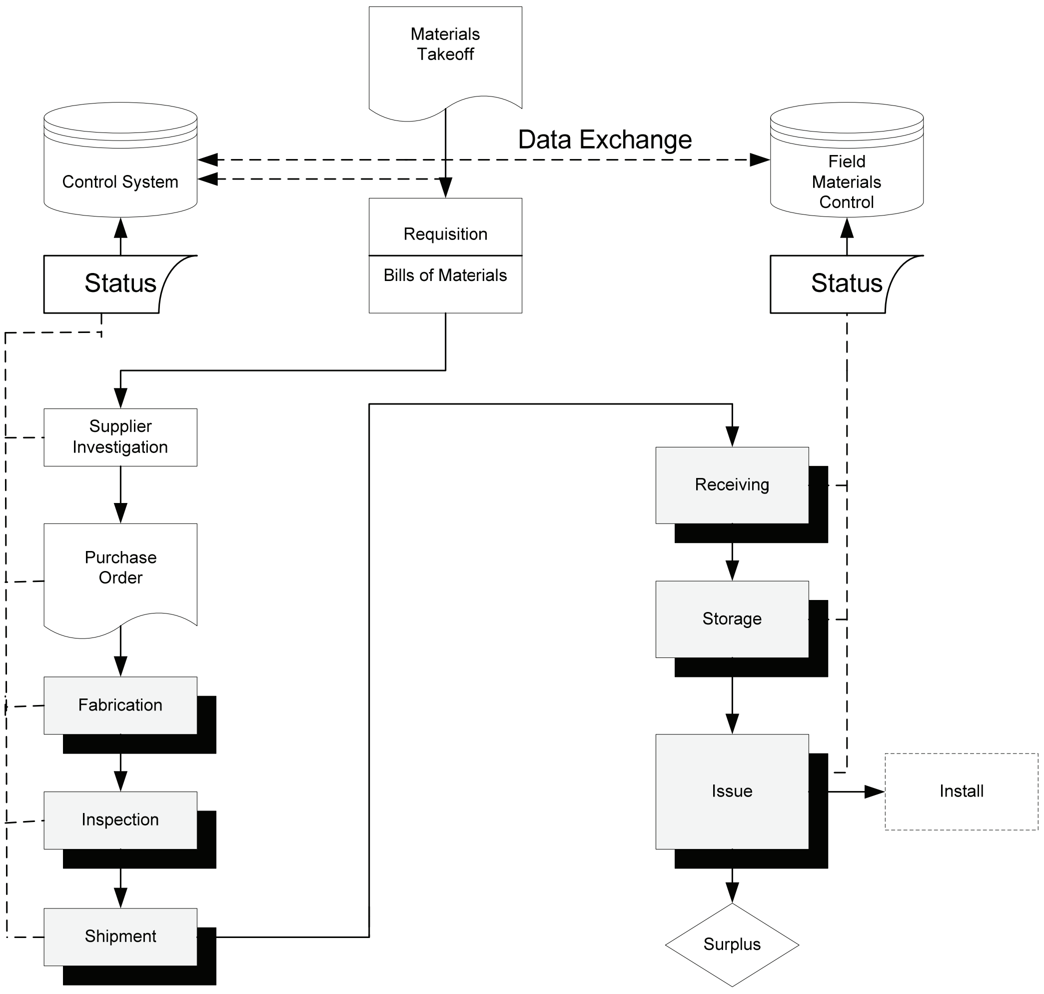

Figure 1.2: Flow chart of construction materials management (Based on Stukhart 1995)

The figure shows all the necessary processes in the supply chain of a typical materials management system starting from the materials takeoff to the installation and surplus. These processes will be described in more detail in the next chapters of the thesis. The shaded boxes represent the most important areas or processes of the materials management system which have the potential to improve craft labor productivity and optimize schedules. These shaded boxes also represent the materials locating and tracking processes. These processes are typically managed more or less in a manual or semi-automated way. The broader research project on which this thesis is based is motivated from the potential benefits that automating these processes would provide to the construction industry in terms of increasing craft labor productivity, optimizing schedules, and improving project performance.

1.2 Research Motivation

Many researchers have cited the need for investing in and automating materials management and control. Construction materials management can make a significant contribution to the cost effectiveness of a construction project. The Business Roundtable 1982, Construction Industry Cost Effectiveness (CICE) Report titled "Modern Management Systems" stated "the construction industry lags far behind the manufacturing industry in applying the concepts of materials management." The report further stated that "senior management of firms in the construction industry has not always recognized the significant contribution that materials management can make to the cost effectiveness of projects." The same situation exists today. The current materials management and control procedures on construction sites are mostly manual. Different studies have concluded that the materials management on construction sites is still the biggest problem and improving it can increase productivity (Thomas and Sanvido 2000; Saidi et al. 2003; Thomas et al. 2005; Song et al. 2006a; Caldas et al. 2006; Navon and Berkovich 2006; Ergen et al. 2007). For a typical industrial facility, the cost for engineering design is 10-15% of the total cost, whereas the construction materials and installed equipment account for 50-60% of the total cost (Kini 1999).

Industry in the US in general invests 1% of the production cost of products in materials management and control. The construction industry invests only 0.15% (Formoso and Revelo 1999). Many researchers have cited the need for investing in and automating materials management and control. In addition, the participants of a workshop on “Data Exchange Standards at the Construction Job Site” sponsored by the National Institute of Standards and Technology (NIST), in cooperation with the Fully Integrated and Automated Technology (FIATECH) consortium, came to the conclusion that “materials tracking remains a very big problem on the current construction job site” (Saidi et al. 2003). In studies which involved 125 projects, the most frequently documented causes of disruption were problems associated with materials management (Thomas et al. 2005). Thomas and Sanvido (2000) in their research examined three case studies of subcontractor-fabricator relations. In two of the cases, there were work stoppages due to lack of materials. They calculated baseline productivity and the loss of labor efficiency in each case. Their research concluded that inefficient materials management could lead to an increase in the field labor hours of 50% or more.

As stated earlier, the most important processes in an integrated materials management system are materials locating and tracking (shaded boxes in Figure 1.2). Another perspective on how these processes fit into the overall construction project management process is presented in Figure 1.3.

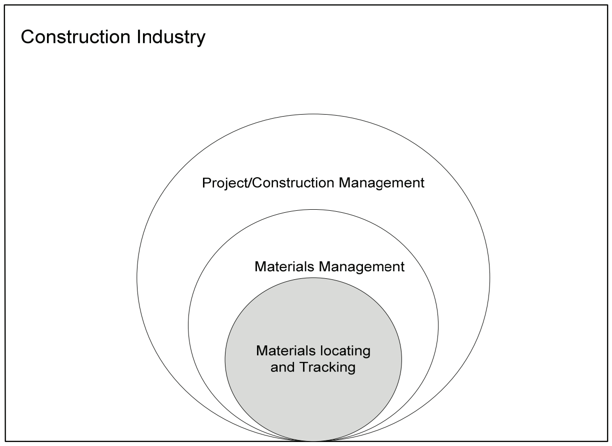

Figure 1.3: Materials locating & tracking and the construction industry

Materials locating and tracking are the core activities in the materials management process, which in turn is an integral part of the project/construction management.

The present approach to materials tracking processes mainly consists of manually intensive and semi-automated operations that are highly error prone. Further, in conditions such as heavy snow, sand, dirt, and heavy vegetation, it is often not possible to identify the materials using a manual approach. These conditions are often encountered on large industrial projects which have vast and scattered lay down yards; which are exposed to snow, sand, and heavy vegetation. One of the most effective strategies to improve the materials tracking process would be to automate the materials tracking operations. Promising technologies for doing this are rapidly evolving; however, knowledge about how best to combine, deploy and utilize them is sparse. In addition every construction project is different and has planning, design, execution and implementation arrangements which are to some extent almost always unique. Therefore each project needs an implementation plan designed for its specific needs. However, implementation guidelines for this new technology do not yet exist despite intense demand from the industry. If an implementation model or set of guidelines were developed, they might benefit the construction industry significantly.

Two recent, large scale prototyping and deployment experiments of this new technology provide the only field data that exists, but it provides a rich data and experience base that can be analyzed and synthesized with ongoing technical developments in order to develop some guidance for future implementation. These field trials were conducted in 2007 and 2008.

1.3 Research Objectives

The main objective of this thesis is to develop a model for automated tracking and locating of construction materials and equipment for increasing productivity and cost effectiveness. The model is focused on large and complex projects such as industrial, infrastructure, and large scale commercial. The scope of the research is further focused on the system architecture and management elements of the automated materials tracking system, not on the underlying aspects of the technology which is described in other publications (Song et al. 2005; Caron et al. 2006; Song et al. 2007; Caron et al. 2007). Pursuing the following sub-objectives helped in achieving the main objective of the research:

- Study the existing and emerging techniques of automated materials tracking systems and discuss their limitations.
- Describe and develop morphologies of these systems.
- Develop principles, methods and knowledge based on analysis of two large scale field trials to help develop processes for implementation of automated materials tracking systems on future projects.
- Identify and discuss integration issues with project information technology systems and materials management processes.
- Explore integration issues of automated materials tracking with the supply chain management process of the construction industry.
- Consider the impact on lean construction ideas, the just-in-time delivery concept, and reduction of multiple material moves.

1.4 Research Scope

The research presented in this thesis is part of a broader research program which consists of three distinct phases over the long term. These phases and their corresponding research objectives are shown in Figure 1.4. The research described in this thesis comes under phase III of the program. It is ahead of its originally planned date.

Phase I was focused on development and field demonstrations of: (1) basic portal methods for reading RFID tags on shipments of engineered materials such as steel pipe spools, and (2) basic proximity methods using GPS and RFID tag readers for estimating RFID tag location for a static field. Phase II overlaps in two parts. In part A, the objective is to identify the impact of utilizing technologies and location sensing methods for locating materials, equipment, tools and laborers to improve construction productivity. The results of this phase are very encouraging (CII 2008). Part B of phase II involves development of algorithms to track moved objects, development of decision support tools to exploit this data, and steps to implement and deploy the results in Canada and for the CII/FIATECH partners. Other graduate students are working on this part of the research program.

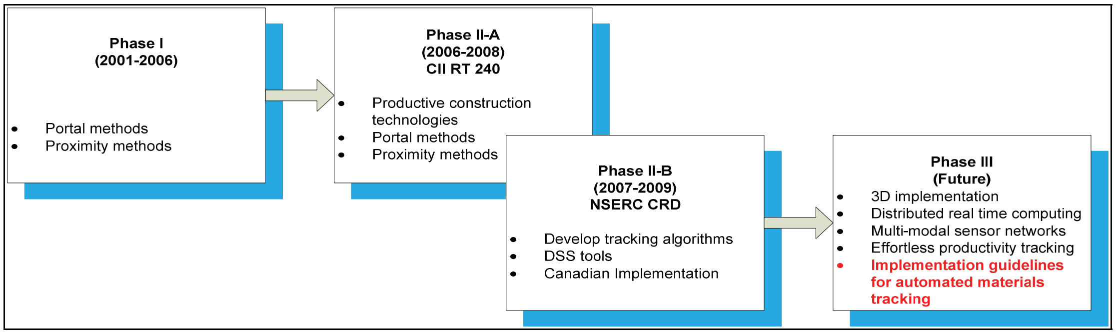

Figure 1.4: Research program for Developing Tracking Technologies in Construction

This thesis builds on the work performed earlier in the first two phases of the broader research work, in which the basic portal methods for reading the RFID tags were developed and the proximity methods and algorithms using the GPS and RFID tag readers for estimating the RFID tag locations were developed for a static field. The scope of this work is focused on the system architecture and its implementation process in large industrial sector construction environments. It provides guidelines for the implementation of an automated construction materials tracking system. This research program (2006-2009) has been supported by:

- the Construction Industry Institute (CII),
- FIATECH,
- the Natural Sciences and Engineering Research Council of Canada, Collaborative Research and Development Grant (NSERC CRD),
- SNC-Lavalin,
- Identec, and
- Ontario Power Generation Inc. (OPG).

The jointly funded CII and FIATECH research project entitled “Leveraging Technology to Improve Construction Productivity (RT 240)” should be described in enough detail to place this thesis in context. In phase II part A, the RT 240 project aims to identify the impact that changes in equipment, material, and information technologies have had on construction productivity. However, the largest part of the RT240 research effort was directed toward a field experiment with the application of the prototype combined GPS/RFID tracking system. The CII RT 240 team members are:

- Ron Bond, Tennessee Valley Authority Co-Chair
- Shrikant Dixit, Bechtel, Co-Chair
- Mike Alianza, Intel, Former Co-Chair
- Sergio Arantes, Petrobras
- Carlos Caldas, University of Texas
- Robert Chapman, NIST
- Steven Davis, WorleyParsons
- Paul Goodrum, University of Kentucky
- Carl Haas, University of Waterloo
- David Heaton, CCC Group
- Leandro Iglezias, Petrobras
- Ric Jackson (ex-officio) , FIATECH
- Sylvia Kendra, Smithsonian Institution
- Victor Puccio, Washington Group
- Sean Rooney, Fluor, Former Co-Chair
- Thomas Royster, J. Ray McDermott
- Kamel Saidi, NIST
- Brian Schmuecker, U.S. Dept of State
- Wayne Sykes, Aker Kvaerner
- George Stevenson, Bechtel
- Steve Thomas (ex-officio), CII
- Todd Vanderhaak, Nielsen-Wurster Group

The graduate and undergraduate students who are or have been involved in the research program for 2006-2009 are shown in Table 1.1.

Table 1.1: Graduate and undergraduate students location and research topics

Student	Status	Research Topic	Location
Laura Games	Co-op	Site support	Portlands Energy Centre, Toronto
David Grau	PhD	Location estimation algorithms and productivity	Rockdale, Texas, US and University of Texas at Austin
Jie Gong	PhD	Site support	Rockdale, Texas, US
Saiedeh Razavi	PhD	Data fusion algorithms	University of Waterloo and Portlands Energy Centre, Toronto

Hassan Nasir	M.A.Sc	Implementation model	University of Waterloo and Portlands Energy Centre, Toronto
Duncan Young	M.A.Sc	Supply chain management	University of Waterloo and Portlands Energy Centre, Toronto
Esteban Campion	Co-op	Site support	Portlands Energy Centre, Toronto
Victor Lam	Co-op	Site support	Portlands Energy Centre, Toronto

1.5 Research Methodology

To achieve the above research objectives in the context of two large evolving field trials, an iterative progression through the following steps was followed:

- Comprehensively review the existing literature on materials management and automated materials tracking and locating.
- Conduct field trials on two large industrial projects, on one of which the author was present for a significant amount of time.
- Define the various terms, technologies, and deployment architectures involved in materials management, and automated materials tracking and locating.
- Define the processes and functions for materials tracking such as receiving, invoicing, requesting (informing), locating, issuing and organizing space, etc.
- Analyze the different available automated materials tracking technologies in terms of their suitability for materials tracking under different circumstances.
- Synthesize and analyze the field trials data and the literature review.
- Develop an implementation process for automated materials tracking for key materials and for large construction projects, based on preceding synthesis and analysis.

Figure 1.4 explains the research methodology and the thesis writing process.

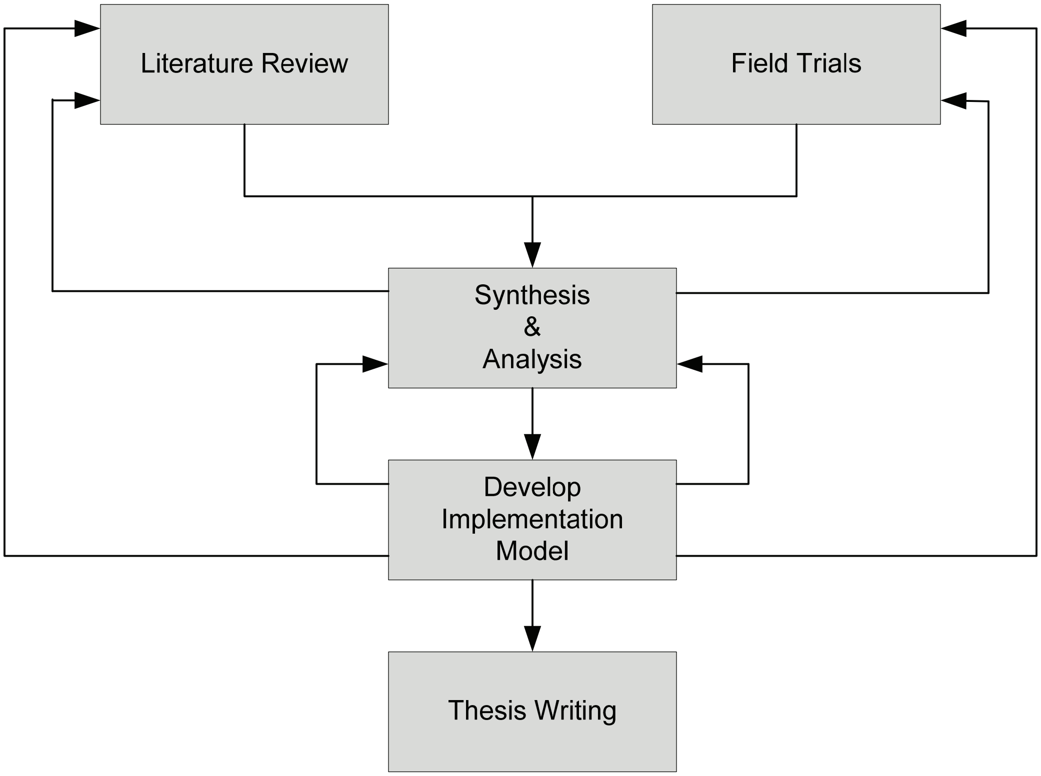

Figure 1.5: Research Methodology

1.6 Thesis Organization

This thesis is organized in six chapters. Chapter 1 gives an overview of materials management and materials tracking on construction projects and describes the motivation, objectives, scope, and methodology of the research.

Chapter 2 provides background and literature review. The literature review consists of two sections. In the first section of the literature review, construction materials are defined and a summary of past efforts on materials management in the construction industry is provided. This literature review provides insight about how materials management has been recognized as one of the most important factors for increasing productivity and decreasing costs and time. The second section of the literature review provides an overview of the past studies on the automation efforts made for materials management and tracking in the construction industry. The use of Automated Data Collection (ADC) technologies in construction is also provided in this section.

Chapter 3 describes the materials tracking and locating technologies directly related to the field trials and develops deployment architectures for automated construction materials tracking and locating systems. The first part discusses the materials tracking process and definition and explanations of the various steps in the tracking process. This is followed by the architectures for field deployment of the automated materials tracking and locating systems.

Chapter 4 describes the field trials and prototyping activities for the automated tracking and locating technologies on the two large construction sites. It also describes the results of the field trials. These were unusual projects in the sense that some prototyping and process development occurred over the course of the trials due to the rapidly rising level of enthusiasm of the research partners from the industry during the trials.

Chapter 5 develops an implementation process for automated materials tracking. It includes the morphology or process overview of the system, the automated materials tracking project definition, the implementation evaluation criteria, the implementation options and evaluation of alternatives, the procurement and mobilization of the automated system, and the measurement and evaluation for next project implementation.

Chapter 6 provides the conclusions of the research and some recommendations for further research.

Chapter 2

Background and Literature Review

2.1 Introduction

The first significant research effort on materials management in the construction industry was initiated by the Business Roundtable in 1982. The Construction Industry Cost Effectiveness Committee (CICE) of the Business Roundtable (The Business Roundtable 1982), described materials management as a distinct management system that can make significant contributions to the cost effectiveness of construction projects. The Business Roundtable CICE report stated that cost of materials and equipment usually makes up 60% of the total project cost with construction labor cost contributing 25% to the total project cost. According to Kini (1999), for a typical industrial facility, the cost for engineering design is 10% to 15% of the total cost and the cost for equipment and materials is 50% to 60% of the total cost. Studies by the CICE and the Construction Industry Institute (CII) confirmed that a basic materials management (MM) system can produce a 6% improvement in craft labor productivity (CII 1986). An additional 4-6 % in craft labor savings is expected when the craft uses the materials management system to plan their work around materials availability (CII 1986). This 10-12 % reduction in labor cost essentially originates from avoiding non productive idle time of the labor due to waiting or searching for materials.

In 1996, CII Implementation Team 96-2 was formed to update the "Project Materials Management Handbook" published in 1988. The CII team conducted a questionnaire survey asking its member firms to report benefits that can be attributed to the use of new concepts and technologies in materials management. The average percent improvements reported by the respondents were: reduced bulk surplus, 40%; reduced site storage and handling, 21%; improved supplier performance, 24%; improved craft labor productivity, 16%; improved project schedule, 16%; reduced management manpower, 15%; reduced risk, 5% (CII 1999).

This chapter reviews research efforts in materials management on construction projects. It starts with definitions of different types of construction materials. Then the results of research efforts made on construction materials management are synthesized. In the later part of this chapter the research efforts made in past on the use of ADC technologies in data collection, materials management, tracking and control are described.

2.2 Construction Materials

Stukhart (1995) defined material as "a substance or combination of substances forming components, parts, pieces, and equipment items." Construction of a facility is a process where materials and equipment are being installed by craft workers according to designs and specifications (Tommelein 1998). Materials and installed equipment for construction projects have been divided into three categories (Halpin et al. 1987): 1) Off-the-shelf, 2) long-lead bulks, and 3) engineered items. The different categories of materials and installed equipment vary in cost, delivery lead time, and interchangeability.

The Construction Industry Institute (CII 1999) has classified three broad categories of materials, each of which require different approaches to their management and control. These categories are: 1) Engineered materials, 2) Bulk materials, and 3) Prefabricated materials. These are explained below:

2.2.1 Engineered materials

These are the items of the materials which have a uniquely assigned number (or tag) so that they can be uniquely referred to and identified throughout the entire life of the facility. They have been further divided into:

Major Equipment: These are the items which are engineered and fabricated specially for the project (e.g., tanks, heat exchangers, pumps, major instrumentation systems)

Minor Equipment: These are the items that are manufactured to an industry specification and are often stocked by the manufacturer or the distributor. They are also uniquely tagged for identification purposes (e.g., minor instrumentation items, thermo wells, transmitters, specialty items).

Engineered materials are the most visible, costly, complex and quality critical. These are identified and ordered by the engineering staff of the owner; they usually direct the project schedule; and the lead times of major equipment influence the entire schedule (Stukhart 1995).

2.2.2 Bulk materials

These are items of materials which are manufactured to industry codes/standards, and are purchased in quantity. They do not have uniquely assigned identification numbers. These materials include items such as pipe, fittings, conduits, and cable.

They are more difficult in terms of planning as they are many in numbers, and quantities are never exactly known until the job is done. Design changes cause continual updating of the bulk materials requirements (Stukhart 1995).

2.2.3 Prefabricated materials

These are the items that are typically engineered and fabricated in compliance with engineering specifications at a fabrication shop or site which is separated from the construction site. Depending on the project strategies, the component materials which constitute the fabricated items may be quantified, procured and delivered to the fabricator by the engineer or constructor. These materials include modules and preassemblies (e.g., ladders/platforms, structural steel, pipe spools, large and small process modules, and control stations).

Each category of materials requires a different approach during the planning and execution stages of the project. Generally, engineered items are available at higher costs in smaller quantities and with more unique properties than long-lead bulk materials and off-the-shelf items, thus implying longer lead time and requiring more front end planning (Tommelein 1998). On the other hand, the availability of long lead-bulks and off-the shelf items is of concern to short-range planning and execution of the work at the crew level. The use of engineered materials have increased manifold during the last two decades. Many construction projects are executed on a fast-track basis today. These projects involve a significant amount of materials which are prefabricated and/or preassembled off-site in a factory or in shop manufacturing conditions on site. Pipe spools, precast concrete components and structural steel members are a few examples of these prefabricated and/or preassembled materials. These all fall into the engineered materials category. Research has found that the use of prefabrication and preassembly in industrial projects had almost doubled during the twenty years between 1979 and 1999 (Haas et al. 2000).

2.3 Materials Management in Construction

Bell and Stukhart (1986) identified the attributes of materials management systems. They presented their findings on the attributes of materials management systems on large and complex industrial construction projects to control the functions of quantity takeoff, vendor evaluation, purchasing, expediting, receiving, warehousing, and distribution. They concluded that when these functions are not managed properly, materials shortages, surpluses, and cash flow problems occur. Expensive labor delays occur when the required quantity or quality of materials are not present when needed. It was further pointed out that planning and communication is vital for the effective materials management system. Decisions which are made in the planning stages are critical to the overall success of the project.

Bell and Stukhart (1987) also quantified the costs and benefits of materials management systems. They quantified the savings in the areas of: 1) improved labor productivity, 2) reduced bulk materials surplus, 3) reduced materials management manpower, and 4) cash flow savings. Bell and Stukhart (1987) concluded that an effective materials management system could reduce bulk materials surplus from a range of 5-10% of bulk materials purchased to about 1-3% of the bulk materials purchased. Bell and Stukhart (1987) also concluded that efficient materials management can cause reduction in man hours needed for materials management. Their research showed that on projects where there is a lack/absence of a materials management system, craft foremen spend up to 20% of their time searching for materials and another 10% tracking purchase orders (POs) and expediting. This time could be devoted to supervising workers. Leaving the crews unsupervised has a negative effect on labor productivity.

Thomas et al. (1989) studied the impact of materials management on labor productivity. The objective of their case study was to quantify the adverse impacts of ineffective materials management practices. Their case study on medium sized commercial construction projects showed a benefit/cost ratio of 5.7, supporting greater attention to materials management. They determined the number of work hours that were wasted because of ineffective materials management practices. Adverse materials management conditions were identified which include: extensive multiple handling of materials, materials improperly sorted or marked, running out of materials, and crew slowdowns in anticipation of material shortages. These adverse material management practices affected 10 out of a total 37 workdays, and for those 10 days that were affected, an average of 58% of the work-hours were ineffectively used. The work-hour overrun was equal to 18%, and the time overrun was about 19%. This is much greater than that projected in the CII (1986) and Bell and Stukhart (1987) reports. Thomas and Smith (1992) again concluded that generally, for all types of materials management deficiencies, there is a reduction of about 40% in daily productivity.

Akintoye (1995) estimated potential increased productivity of 8%, due to an efficient materials management and control system. This increase in productivity is mainly attributed to the availability of the right materials prior to the commencement of work and the ability to plan the work activities due to availability of materials. Choo et al. (1999) found that the biggest problems faced by the field workers is dealing with discrepancies between the anticipated, actually needed, and available resources which includes materials. Research has showed that a reduction in cost of materials is possible due to the reduction in waste otherwise caused by manual and inefficient materials management and control. Waste of materials represents a large percentage of production costs (Formoso et al. 2002; Li et al. 2003; Poon et al. 2004; Li et al. 2005).

In summary, an efficient materials management system put in place on a construction project can increase productivity, avoid delays, reduce man hours needed for materials management, and reduce the cost of materials due to decrease in wastage. The productivity and efficiency numbers reported here are ten to fifteen years old; however, they are cited here to highlight the importance of good materials management in construction and the positive changes it can bring to the construction industry. While implementation continues to vary widely, there has been little interest since then in studying the impact of conventional materials management best practices. Attention has focused instead on automation. Site materials management using the best of the conventional methods, while significantly better than no materials management, leaves much room for improvement via automation.

2.4 Automated Data Collection (ADC) Technologies in Construction

In this section, the use of ADC technologies in construction is described. This description becomes important for understanding the architectures, field trials, and model developed in the following chapters.

The use of ADC technologies in materials management, tracking, identification, and control are discussed. Automatic identification or Auto ID is a general term used to describe a range of technologies that are used to identify objects through the use of machines. Automatic identification is often used together with Automatic Data Collection (ADC). These Auto ID and ADC technologies are used to identify items, capture information about them and than transfer the data into a computer without manually typing it. The main aim of the ADC technologies is to increase efficiency, reduce data entry errors caused by human transcription, and reduce labor costs. There are a number of technologies that come under the Auto ID or ADC technologies. These include bar codes, smart cards, voice recognition, optical character recognition (OCR), radio frequency identification (RFID), and global positioning systems (GPS). While some have been implemented in their most basic form, they are rapidly evolving and beginning to be combined in innovative new forms. In the next sections, those technologies which have the potential to be used in the construction industry and particularly in materials identification, tracking, and locating are discussed in detail.

Two decades ago, Bell and McCullouch (1988) suggested bar code applications in the construction industry. Their research, supported by the Construction Industry Institute (CII), aimed at the exploration of potential applications of the bar code technology and the associated cost-savings benefits of using bar codes in the construction industry. They also studied and recommended guidelines for the extensive use of bar codes in the construction industry and suggested industry-wide standards that are required for the implementation of bar codes. Their research studied the specific applications in the areas of quantity takeoff, field material control, warehouse inventory and maintenance, tool and consumable materials issue, timekeeping and cost engineering, purchasing and accounting, and document control and office operations. Their research also confirmed that bar codes use can improve the speed and accuracy of computer data entry and produce the same cost savings in the construction industry as seen in other industries.

Rasdorf and Herbert (1990) provided an introduction to automated identification systems with particular emphasis on the bar coding technology. They explained the automated identification system criteria used to rate the system performance. They identified read rate, substitution errors, durability, and weather resistance as the criteria of identification system performance. They explained and compared the automated data collection (ADC) technologies in terms of their systems performance in the construction industry. They explained and compared the technologies which included; bar codes, optical character recognition (OCR), magnetic stripe (MS), and radio frequency (RF). They identified the potential use of bar codes in the construction industry for: 1) job site material management; 2) project activities; 3) document control, purchase orders, requisitions and drawings; and 4) construction equipment management. Their research stated that the automated identification system technology for data collection can provide better information flow to all the levels of management. Therefore the management can make better informed decisions which have a positive effect on the project performance.

Bernold (1990) introduced a prototype system for tracking construction equipment and materials using a bar code driven technology. The aim of the research was to improve the accuracy and timeliness of the tracking information/data. The research was divided into two steps: 1) development and implementation of an automated tracking system and 2) checking the performance of bar code labels and adhesives in the construction environment. His research demonstrated how yard control systems could adapt the automated data collection technology of bar codes and utilize the advantages of the new system. The research also pointed out some of the important factors for the selection of labels and adhesives for use in the construction industry/environment.

Jaselskis et al. (1995) provided information on radio frequency identification (RFID) and its potential applications in the construction industry. They discussed the use of three applications of RFID technology in the construction industry; 1) concrete processing and handling, 2) cost coding for labor and equipment, and 3) materials control. They concluded that construction firms could potentially save time, money, and effort with the effective use of RFID technology for several operational procedures. However, RFID technology had not matured enough at the time of the study to be used in the field. One problem was that the read-rate was too poor for field deployment.

Navon and Berkovich (2005) developed a model based on automatic, or semi-automatic, data collection for materials management and control. Their proposed model would automatically generate and manage the ordering of the materials, based on the project plans. It would also monitor the actual flow of materials and report the status of materials on the construction site, would give warning when the specifications of the materials arriving at the site differs from those in the purchase order, and inform when the stock on the site is less than the desired minimum. The model was evaluated by comparing the existing/customary materials management and control procedures with that using the model. No field validation was done.

Song et al. (2006a) presented an approach to automatically identify and track materials on construction sites without adding any extra site operations. They tagged the materials with RFID technology. Their approach leveraged the automatic reading of tagged materials by field supervisors or materials handling equipment that were equipped with an RFID reader and a global positioning system (GPS) receiver. A mathematical model was developed to check the feasibility of their approach by representing the job site as a grid, and the location of the materials within the grid were determined by combining proximity reads from a discrete range. The results of their field experiments conducted using an off-the shelf

RFID system showed that the approximate 2D locations of materials can be determined without much cost using the proximity localization techniques. Their research findings of the automated tracking of the materials on the construction job sites demonstrated the potential for improvement of field materials management and for effortless derivation of project performance indicators for real time control of project management.

Song et al. (2006b) demonstrated the use of RFID technology to track uniquely identified materials through the supply chain as well. They conducted field tests of the current RFID technology for determining its technical feasibility for automatic identification and tracking of individual pipe spools in lay down yards in industrial projects. Through their field tests they determined that the RFID technology can function effectively on construction sites that may involve large metal objects and that require a considerably long read range. They also proved statistically that the then commercially available active RFID technology can automatically identify pipe spools with 100% accuracy and precision when they are moved/passed through portal gates equipped with four antennas at a slow speed of less than 2 mph. Their study also suggested the potential benefits of using the RFID technology in automated tracking of pipe spools, such as: 1) less time required to identify and locate pipe spools, 2) accurate and timely information for both materials availability and craft work planning, 3) reduced search time for misplaced pipes and potential improvement on the pipe fitting schedule.

Caldas et al. (2006) studied the potential benefits of using manually operated global positioning system (GPS) technology for the materials locating processes on industrial projects. The main focus of their research was to: 1) evaluate the technical feasibility, and 2) quantify the direct benefits in terms of time savings during the materials locating processes by the use of GPS devices. A field trial was conducted by using the GPS unit in combination with a handheld computer within existing pipe spools locating processes in lay down yards. They concluded that the average time spent for locating a pipe spool using the existing/current process was 6 min and 42 sec. The time for the same process was reduced to only 55 sec when a GPS unit combined with a hand held GIS interface was used. The time savings of 5 min and 47 sec was statistically validated. Their research also suggested other benefits, besides direct savings of time by using the GPS technology for tracking materials. These benefits include improvement in processes, reduction in number of lost items, making positive impacts on construction performance, standardization and automation of locating processes, optimization of route sequences and layout, and improved data entry. Industry practitioners have been reluctant to implement this approach however, citing potentially frequent undocumented materials moves between manual GPS locating, thus they have seen more potential with the Song approach.

Ergen et al. (2007) proposed an automated system using RFID technology combined with the GPS technology for the tracking but not locating of precast concrete components in a manufacturer's storage yard. Their research focused on the requirements and approaches needed to implement the proposed integration of RFID and GPS technologies for the automated identification and tracking of precast components in the storage yard which would require minimal human input. It was distinct from the Song et al. (2006b) approach in that the combination of technologies was not used to accurately estimate RFID location using multiple reads, but was used as a magnitudes cruder discrete gate location recorder. A prototype system was developed and tested in the field at a precast storage yard based on the identified requirements. Their research identified data collection as the main area/process for improvement using automated tracking technologies. They identified the high level requirements for an automated precast tracking system as: 1) no or minimal human input required for data collection, 2) the accuracy of identification and tracking of the materials should be higher than that with the existing systems, and 3) the proposed automated system should perform consistently under harsh construction conditions and in the presence of metal and concrete. Their research results concluded that the proposed automated tracking system worked satisfactorily, and the prototype system was successful in the data collection as well as semi-automated tracking and functioning under harsh conditions in the presence of metal and concrete.

Emerging technologies are also available to the Architectural-Engineering-Construction and Facility Management Industry, such as combinations of: 3D Computer-Aided Design (CAD) engines, 3D positioning technologies, and 3D laser scanners. Bosche and Haas (2008a; 2008b) and Bosche et al. (2008c) used these technologies to develop methods for automated retrieval of 3D CAD model objects in 3D laser scanner range images and 3D range point clouds. Their research showed that these new approaches can be used to perform automated defect detection for dimensional Quality Assessment/Quality Control (QA/QC). Their research on automated retrieval of 3D CAD objects in 3D images has other applications for construction industry such as: automated project progress tracking, productivity tracking, and 3D image database information retrieval.

In summary, the use of ADC technologies in construction has been found to have high potential. Research in the twenty years since Bell and McCulloch's (1988) work has proven that ADC technologies can be used for a number of applications on construction projects. These applications include quantity takeoff, field materials control, warehouse inventory and maintenance, timekeeping and cost engineering, purchasing and accounting, document control and office operations, easy and errorless data entry, construction materials and equipment management, and assisting management in making informed decisions. Efficient use of ADC technologies in construction can improve field materials management, materials identification and tracking of the construction resources and provide help for real time control of project management. As a result there are signs of an increase in construction productivity related to implementation of modern materials management systems. Reduction in cost of materials by reducing wastage and number of lost items, and time savings are also being observed.

In the next section, those ADC technologies which have the most potential for use in the automated materials tracking are further explained and discussed.

2.4.1 Bar codes

Bar codes are Auto ID technologies that have the potential to reduce errors, save time, enhance accountability, improve resource utilization, increase productivity, and reduce costs. Bar coding helps in providing real time materials status by providing easy access to its databases (Stukhart 1995). Bar codes have been defined by Burke (1984) as: "messages where information is encoded using widths of wide or narrow bars and spaces (i.e., unique wide or narrow combinations of black and white bars). They provide a means of creating labels which can be read by instruments."

In 1982 a major boost was given to the bar code technology, when the U.S. Department of Defense (DoD) started to require all suppliers to ship their goods with attached bar code labels. Since then, both the automotive and grocery industries increased their efforts requiring bar code labels on every item moved between plants and organizations (Bernold 1990). The construction industry lagged behind the automotive, retail grocery, and other industries in the widespread use of bar code technology. Other industries have developed uniform standards and achieved industry-wide vendor compliance through their respective industry action groups. Realizing the great potential for cost savings that is associated with the bar code technology, the Construction Industry Institute (CII) started a formal research project in 1987 to explore the potential applications and the resulting cost saving benefits of using bar codes in the construction industry (Bell and McCullouch 1988).

Bell and McCullouch (1988) identified some of the applications of bar codes in the construction industry. The areas they identified were; quantity takeoff, field materials control, warehouse inventory and maintenance, tool and consumable material issue, timekeeping and cost engineering, purchasing and accounting, and document control and office operations. Since then, bar codes have been used in many areas in the construction industry. Figure 2.1 shows some bar coding labels. Figure 2.1 (a) shows a sample bar code label, whereas Figure 2.1 (b) shows a bar code label attached to a steel item, and Figure 2.1 (c) shows the bar code applied on a piping component.

Figure (a) Figure (b) Figure (c)

Figure 2.1: a) Sample bar code, b) bar code on a steel component, c) bar code on a pipe

A typical bar coding system consists of some hardware, software and certain infrastructure which may be wired or wireless to connect the hardware to the database that stores and analyzes the data collected by the system. The hardware system basically consists of the bar code scanner and the computer. Figure 2.2 shows bar coding system hardware components. A basic bar code scanner consists of a scanner, a decoder, and a cable which connects the decoder to the computer. There are different types of scanners; however, the most useful are the laser scanners. Some of the scanners have the decoder function incorporated into a chip within the scanner, thus eliminating the need for a separate piece of hardware.

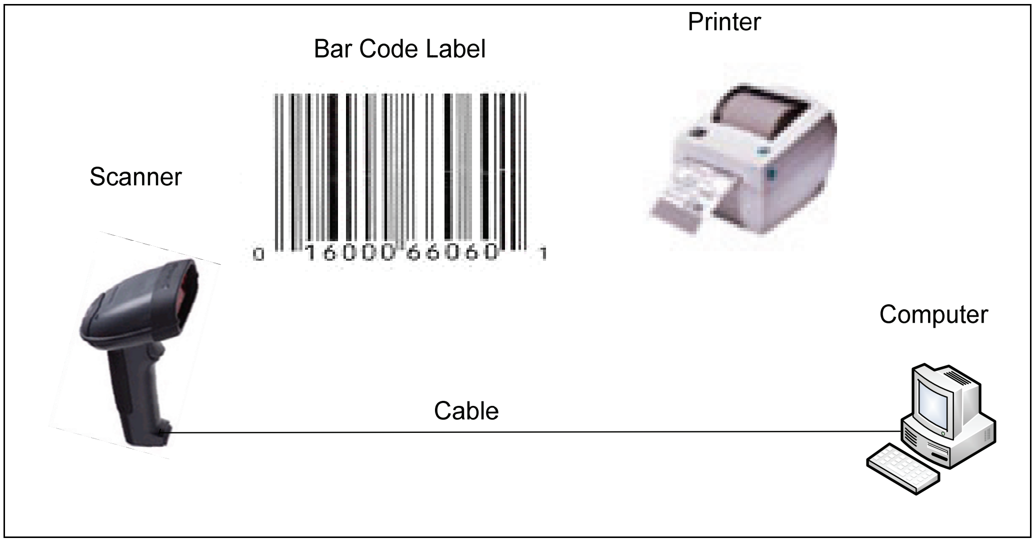

Figure 2.2: Bar coding hardware system components

The software system for bar coding technology consists of two essential software: bar code labeling software and bar code tracking software. Bar code labeling software are used for designing and printing quality labels, where as, the bar code tracking software are used to read and track the bar codes. A printer is also needed to print bar code labels. Bar code printers are specifically designed to produce high-quality labels.

Early research recommended many applications of bar codes in the construction industry, however due to limitations discussed later bar coding technology has been primarily used for the materials receiving and issuing functions in the industry. Using bar coding in the receiving and issuing functions covers most of its application such as improved materials control, increased accuracy of inventory data, labor savings, accurate data on shipping, receiving, and issuing, improved data on date and time of materials received and issued, and generating various reports. Figure 2.3 shows the information flow in a typical field receiving operation using bar coding.

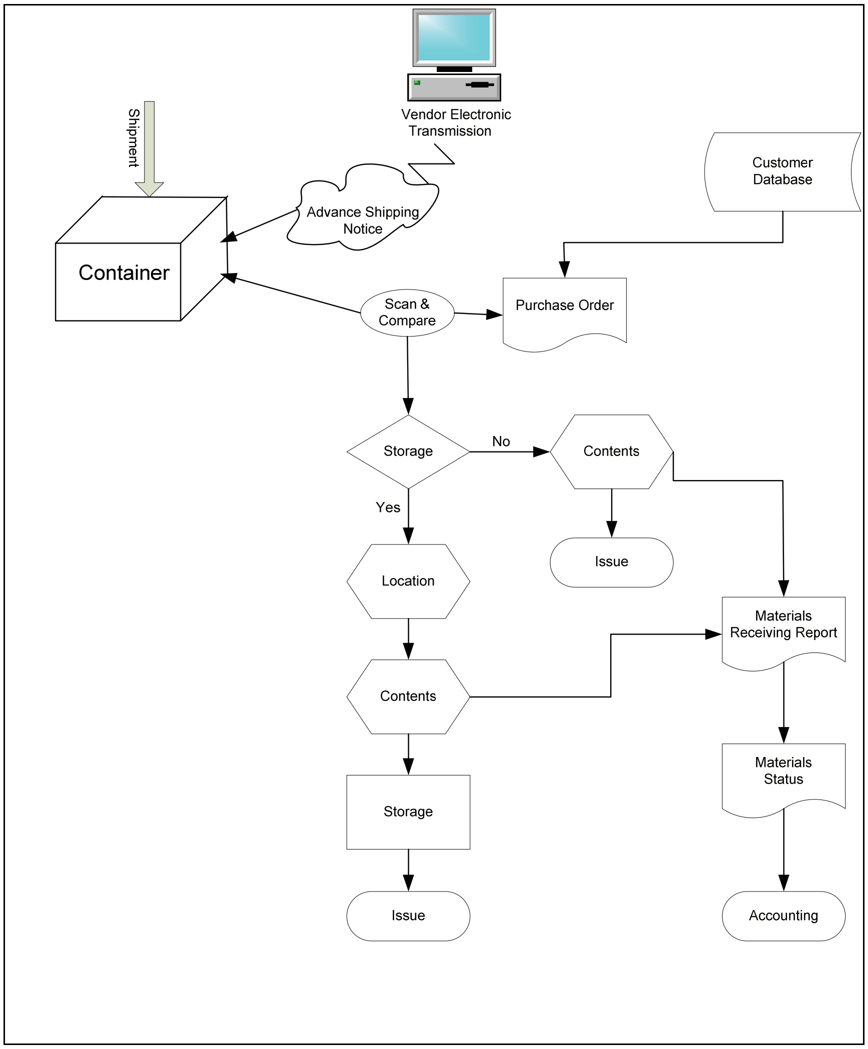

Figure 2.3: Receiving function using bar coding (Based on Stukhart 1995)

When a container is received at the site or gate, the constructor's authorized personnel matches its contents against a known purchase order and line item and takes decision whether the container should be opened or sent to storage without opening. This transaction information helps in deciding about the location of goods to be delivered and what handling equipment is required. The receiving workers record the transaction and quantities received on the materials receiving report, or directly into the database. A materials status report is generated and sent to accounting. In the case of storage, the information on the label is retained for future inventory and issue. The bar codes labels should be designed in such a manner so that important information such as item identification and quantity can be readily obtained.

Figure 2.4 shows the bar codes scanning procedure on a construction site. The crew physically goes near the item which has a bar code label attached to it, because the bar codes need a line of sight to be read by the scanner. The scanner reads the bar code and records the information about the material from the bar codes. The scanner data is then downloaded into the office computer and the database is updated with the materials status.

Figure 2.4: Bar codes equipment, scanning, and unloading information into a database

2.4.2 Stand Alone Radio Frequency Identification (RFID)

Stand alone radio frequency identification (RFID), like bar coding, is also an automated data collection (ADC) technology. The term “stand alone RFID” is used to distinguish this technology from that prototyped on the projects described in this thesis. RFID is a generic term used for technologies that use radio waves to automatically identify, locate, or track objects or assets and people. The most common method of identification is to store a serial number that identifies a person or object, and other information on an RFID transponder or an RFID tag. The RFID tag transmits the identification information to a reader. The reader converts the radio waves reflected back from the RFID tag into digital information that is then passed on to computers which make use of it and process the data.

RFID has been in use since the World War II. The patent for the first RFID tag was granted to Mario Cardullo on January 23, 1973 by the U.S. Patent Office. Until 2003, RFID tags were too expensive to be practical for use in commercial applications (Hedgepeth 2007). The increasing use of the RFID technology in the United States has been pushed onto the marketplace by two giant market and political forces: (1) Wal-Mart and (2) the Department of Defense (DoD). Both of them are the largest consumers of American goods and goods from overseas. Both have instructed that the small, passive RFID tag be put on pallets of goods by 2005 on most shipment of goods, if not on all. This is noteworthy when one considers that Wal-Mart has more than 10,000 suppliers and the DoD has around 42,000. Wal-Mart processes more than 250,000 trucks daily, unloading and loading goods from distribution centers and Wal-Mart stores (Hedgepeth 2007).

Jaselskis et al. (1995) introduced the potential for some of the RFID applications for use in the construction industry. Several years after their research, the construction industry began to focus on the use of stand alone RFID across a wide range of applications in the construction industry. These efforts gained momentum during the last five years and now research has indicated that RFID technology can be used effectively for increasing numbers of applications in the construction industry such as materials management and control, materials identification and tracking, tools tracking, and lay down yard management.

A typical stand alone RFID system consists of three principal components: (1) the transponder or tag, which is the component that is affixed or attached to the item that is to be tracked or identified within the supply chain by the RFID system; (2) the reader or interrogator, which has various responsibilities including reading data from the transponder, providing power to the transponder, identifying it, writing to it, and communicating with a data collection application; and (3) the data collection application (host computer), which receives data from the reader, enters the data into the database, and provides access to the data in a manner that is useful to the end user. These components are shown in Figure 2.5.

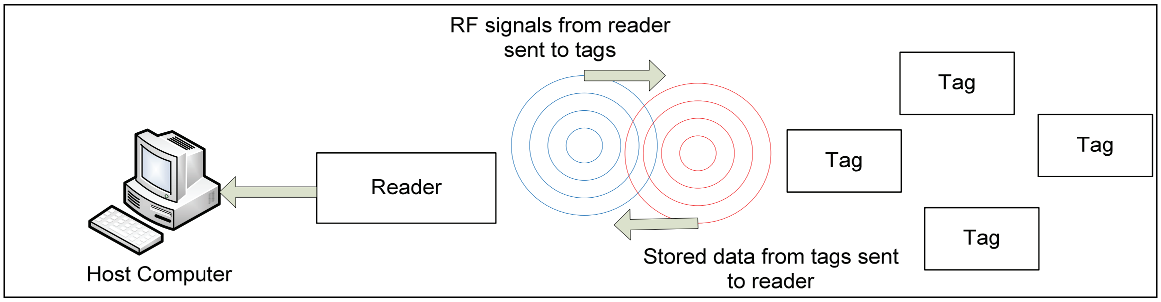

Figure 2.5: Typical RFID system components

Transponders

RFID tags come in a variety of forms and are often application specific. Different specifications include power source, carrier frequency, read rates and range, data storage capacity, memory type, size, operational life, temperature and corrosion resistance, and cost. A typical RFID tag is made up of a microchip with an antenna. “The chip and the antenna together are called an RFID transponder or an RFID tag,” (RFID Journal 2008). An RFID tag is a microchip attached to an antenna that is combined in a manner that it can be attached to an object. The transponders or tags receive signals from the reader and send signals back to it. The tag or microchips in the RFID tag can be read-write, read only or “write once, read many (WORM)”. In the read-write tags, information can be added to the tag or written over the existing information when the tag is within range of a reader. Read-write tags usually have a serial number which cannot be written over. Read-only tags have stored information on them which cannot be changed. This information is stored in them at the time of manufacturing and can be read only by the reader. WORM tags are those that can be written only once by the user; thereafter, it can only be read.

RFID tags can be active, passive or semi-passive depending on the manner in which they derive the operating power. Active RFID tags are those that have a transmitter and their own power source (a battery). The battery is used to run both the microchip's circuit and to send a signal to a reader. Passive tags have no batteries and have no power source of their own. They draw power from the reader, which sends out electromagnetic waves that induce a current in the tag's antenna. Semi-passive tags are those which have a battery to run the circuit in the microchip, but communicate with the reader by drawing power from it.

RFID tags operate at different frequencies. Tags operating at Ultra High Frequency (UHF) typically have longer read ranges than tags operating at low or high frequencies. Similarly, tags operating at high or ultra high frequencies have better read ranges and can transfer data faster than tags operating at low frequencies. Figure 2.6 shows a sample of different types of RFID tags.

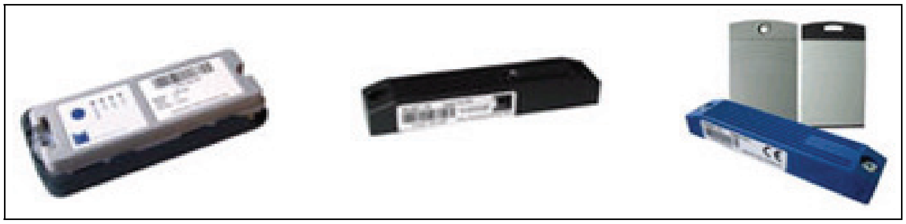

Figure 2.6: RFID tags samples (Identec solutions)

Reader

A reader is a fixed or mobile device that reads data from the tag. It also writes data to the tag through RF wireless communication when the tag comes within its read range. The read range of a reader varies and the RFID technology works from one inch to 100 feet or more. Figure 2.7 shows different types of RFID readers. Frequency of reads also varies. Typically, a reader can read thousands of tags per second.

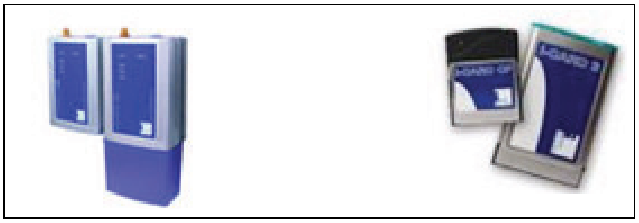

Figure 2.7: Different types of RFID readers (Identec solutions)

2.4.3 Stand Alone Global Positioning System (GPS)

The Global Positioning System (GPS) is a satellite-based navigation system formed by a network of 24 satellites placed into the orbit by the U.S. Department of Defense. The GPS was originally meant for military applications, but in the 1980s the government allowed civilian use of the system. Since then it is used extensively for a number of civilian purposes on land, at sea and in the air. Basically the GPS helps to record locations from places on the earth and helps in navigating to and from those locations (Garmin 2008). GPS is used in the air industry for navigation by general aviation and commercial aircraft; at sea it is mostly used for navigation by recreational boaters. The land-based applications of GPS are more diverse. Surveyors use GPS for much of their work, because it provides excellent accuracy and radical cost savings by reducing the setup time at the survey site. Basic survey units can provide accuracy down to one meter, whereas more expensive systems can provide accuracy within a centimeter. Today, GPS is extensively being used in automobiles for providing emergency road side assistance, determining the vehicle's position on an electronic map display, helping drivers to keep track of their position and look up street addresses, restaurants, hotels and other destinations. Modern systems automatically create a route and give turn-by-turn directions to designated locations (Garmin 2008).

GPS technology also provides a wide range of positioning solutions for the construction industry. Navigation (guidance from one location to another), tracking (monitoring the movement of people or assets), mapping (creating maps), and timing (precise timing) are some of the applications of GPS in the construction industry. Some of the GPS applications such as automation of processes and guidance of equipment are common in the construction industry, however, the potential of stand alone GPS to improve materials management on construction job sites has not been explored other than by Caldas et al. (2006).

However, GPS technology has drawn much attention from researchers attempting to find effective ways to automatically track the location of construction labor and equipment in outdoor environments and on construction sites (Peyret and Tasky 2002; Oloufa et al. 2003; Navon and Goldschmidt 2003; Sacks et al. 2003; and Navon et al. 2004). Navon and Goldschmidt (2003) showed that labors/workers locations can theoretically be automatically collected by the GPS and converted into the labor inputs based on a building project model developed by Sacks et al. (2003). This is an expensive application.

GPS technology has been identified as an accurate and robust technology for automated data collection for road construction control, however there are inaccuracies of GPS data collected which are caused by objects obstructing communication of the GPS receiver with satellites (Navon and Shpatnisky 2005).

The Navigation Satellite Timing and Ranging (NAVSTAR) system is the official U.S. Department of Defense name for GPS. The system consists of three segments: 1) space segment (the satellites), 2) control segment (the ground stations), and 3) user segments (the end users/GPS receivers).

Space Segment

The space segment which consists of a minimum of 24 satellites is the core of the system. These satellites operate at a high altitude of about 12,000 miles above the Earth's surface. The satellites are arranged in their orbits in a manner such that a GPS receiver on earth can always receive signals from at least four of them at any given time. Each satellite transmits low power radio signals on several frequencies. These signals require “line of sight”, which means that they can pass through clouds, glass and plastic, but cannot travel through most other solid objects such as buildings and mountains. The main purpose of these coded signals is to help in calculating the travel time (also called Time of Arrival) from the satellite to the GPS receiver on the earth. The travel time multiplied by the speed of light gives the satellite range, which is the distance from the satellite to the GPS receiver.

Control Segment

The control segment controls the GPS satellites by tracking them and providing them with corrected orbital and clock (time) information. There are five control stations located around the world, in which four are unmanned monitoring stations and one is the master control station. The four unmanned monitoring stations continuously receive data from the satellites and then send this information to the master control station. The master control station corrects the satellite data and then sends the corrected information to the GPS satellites.

User Segment

The user segment consists of the users and their GPS receivers. The users can be anyone who uses the GPS system and wants to know about their locations either for civilian or military purposes.

The GPS provides three-dimensional positions (latitude, longitude, altitude). For determining this three-dimensional position, the GPS uses triangulation from the satellites. To triangulate, the GPS receiver calculates the distances to at least four different satellites at any given time. The distances of the receiver from the satellites are calculated by measuring the travel time of coded radio signals from each one of these four satellites. The resulting position and its accuracy are influenced by the atmospheric conditions and the satellites’ location above the receiver. Very inexpensive GPS receivers are accurate to within 15 meters on average; however, modern state-of-the-art units can provide accuracy within a centimeter (Garmin 2008).

The accuracy of the GPS can be improved by combining the GPS receiver with a Differential GPS (DGPS) receiver, which can be operated from several possible sources to help reduce some of the errors. The DGPS systems works by putting a local GPS receiver, called a reference station at a known location. Examples of differential correctors for a GPS system include Ground Stations, Coast Guard Beacons, Wide Area Augmentation System (WAAS), OmniSTAR, and Real-time Kinematic GPS (RTK GPS) (Caldas 2006).

2.4.4 Geographic Information Systems (GIS)

A geographic information system (GIS) integrates hardware, software, and data for collecting, managing, analyzing, and showing all forms of geographically referenced information (GIS 2008). It is a computer-based system which can collect, store, integrate, manipulate, analyze, and display data in a spatially referenced environment. It helps to analyze data visually and look patterns, trends, and relationships that might not be visible in tabular or written form (EPA, 2008). A GIS is different from other information systems, because it integrates common database operations such as query and statistical analysis with the advantages of visual and geographic analysis through maps (EPA 2008). Figure 2.8 shows a well known layer based architecture, which is commonly employed in the traditional GIS. Each layer contains information/data about a particular kind of a feature.

Successful implementation of GIS has been found in areas such as civil engineering, transportation, facilities management, urban planning, waste management, natural resources management, environmental impact assessment and business analysis. GIS can be easily integrated with other automated data collection technologies and software. Cheng and Chen (2002), integrated bar codes and GIS for monitoring construction progress. They developed ArcSched; composed of GIS integrated with database management system, for controlling and monitoring the erection process in a real time basis and representation of the erection progress in graphics and colors. Li et al. (2003) proposed an internet-based GIS system for e-commerce applications in construction materials procurement. Li et al. (2005) introduced an integrated GIS and GPS approach for reducing construction waste and improving construction efficiency. These systems are all early prototypes.

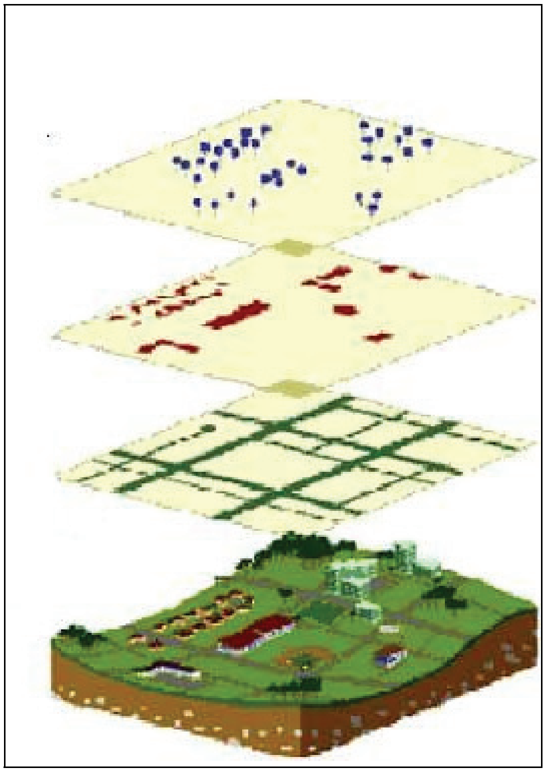

Figure 2.8: Typical layer based GIS architecture (EPA 2008)

2.4.5 Personal Digital Assistants/Handheld PC

Different types of mobile devices are used in the field on construction sites. The use of Personal Digital Assistants (PDAs) is increasing rapidly in the construction industry, because more powerful devices with wider ranges of applications are now available. Some of the main characteristics of the PDA are: use of calendar, address book, notes, and to-do lists; surfing the internet and web; GPS locating; maps and directions; coordinate or facilitate data transfer between PDAs and desktop PCs; and a platform for add-on software (McPherson 2000; Johnson and Broida 2000; Kimote et al. 2005; Tserng et al. 2005; Kim et al. 2008).

The advantages of using mobile computing devices in the construction industry have been well described (Baldwin et al. 1994; Fayek et al. 1998; McCulloch 1997; Saidi et al. 2002; Kimote et al. 2005). Mobile computing devices have been used in the construction industry for a number of specific applications such as: 1) to develop a field inspection support system for civil systems inspections (Sunkpho and Garrett 2003); 2) to develop a pen-based computer field application of an automated bridge inspection system (Elzarka and Bell 1997); 3) to provide collaborative and information sharing platforms (Pena-Mora and Dwivedi 2002); 4) to use mobile computers to capture data for piling works (Ward et al. 2003), and 5) to use PDAs in construction supply chain management systems (Tserng et al. 2005). Figure 2.9 shows a handheld PC or PDA.

Figure 2.9: Personal Digital Assistant/Handheld PC

2.5 Comparison of Bar Codes and RFID

Bar codes have been used in the construction industry for almost thirty years. They have been primarily used for automatic identification and data collection. Recently RFID technology has been introduced in the construction industry for automatic identification, data collection and assets/materials tracking. Table 2.2 compares bar codes with RFID, in terms of key performance measures. It is clear that as a result of these cost and performance differences, bar codes will continue to be used for inexpensive bulk materials. Stand-alone RFID and the new RFID/GPS combined technologies will be used for more critical materials such as key valves and assemblies.

Table 2.1: Comparison of Bar Codes and RFID

Characteristics/ Measure	Bar Codes	RFID
Line of sight	Requires line of sight. The scanner or reader has to see the bar codes.	Does not require line of sight. The reader can read the tags without seeing it.
Read range	Has limited read range. Read range measured in inches or fraction of an inch.	Has longer read range, and can be read from one inch to 100 feet.
Static Data Entry	The information written on tags is static; it cannot be modified once printed on a label. Bar code is read only.	RFID tags can be read-write type, on which new data or information can be entered through the reader.
Data Volume	Limited amount of data can be entered or stored on a bar code	RFID tags can store more data than bar codes
Identification of items	Bar codes identify only the product and not the unique items.	RFID tag identifies the product and item and much more on customer’s needs.
Simultaneous Data Capture	Only one bar code can be read at a time	RFID systems can simultaneously identify and capture data from multiple tags
Read rate	The scanner or reader has to read every bar code individually which is time consuming	RFID readers are capable of reading tag information at a rate of up to 1000 tags per second.
Environmental Durability	Bar codes cannot withstand harsh environments. If they get torn, ripped off or soiled by dirt or grease, they cannot be read.	RFID tags can be encased in hardened plastic coatings, which make them extremely durable and can perform in harsh construction environment.
Cost	Bar codes are considerably less expensive than RFID tags	RFID tags are expensive, however their cost can be reduced when purchased in large quantities and their prices are coming down with the passage of time and technology improvement.

Chapter 3

Automated Materials Tracking Process and Architecture for Field Deployment

3.1 Introduction

As explained and discussed in the previous chapters, research has proven that materials management in construction can make significant contributions to the cost effectiveness and timely completion of projects, besides having other benefits. Similarly, effective materials tracking and locating along the construction supply chain is the most important element of an effective materials management system. Studies have proved that timely and accurate information on materials availability for crew-level planning has the potential for improving labor performance and productivity.

Many industrial projects are executed on a fast track basis due to market forces. Therefore, the use of prefabrication and preassembly has increased tremendously during the last two decades, almost doubling in the two decades before the year 2000 (Haas et al. 2000). In an industrial project with a total installed cost in the range of \$200 to \$300 million, there can be around 10,000 pieces of individually tracked valves, fabricated steel components, pipe spools, and similar components (Song et al. 2004). Managing these large numbers of materials in the supply chain poses problems. Project managers may have little influence over suppliers and fabricators. Therefore, the materials managers, in order to avoid uncertainties, typically choose to accumulate large buffers of pipe spools on site so that they have flexibility in workable backlogs for pipe fitting crews. The managers try to have “at least 60 percent of all pipe on site when 20 percent of the pipe had been installed” (Howell and Ballard 1996). Some managers prefer the number to be 80%. This situation has not changed much and still in practice it can be found that the constructor’s lay down yard is full of pipe spools which are delivered to the site 5 to 6 months prior to their scheduled installation (Song et al. 2006b). This practice in industrial piping is the same as in the case with precast components which are usually stored in the precast storage yards for almost 6 months, until shipping to the construction site/erector (Akinci et al. 2002). Similar conditions exist for other categories of critical materials such as valves, electrical equipment, hangers, and others. (This situation was observed to a slightly lesser extent on the two projects studied as part of this thesis.) Therefore field materials management was identified as one of the areas which have the greatest potential for improvement and the greatest positive development impact on engineering construction work processes (Vorster and Lucko 2002).

The exact location or position of materials on a construction site or in supply chain is also very important. Just knowing or presuming to know based on faulty or out of date written records that the materials have arrived on the construction site or are available in the warehouse or lay down yard is not enough. Materials must be positively physically located. They must be tracked in the warehouse or lay down yard before they can be issued to the crew workers. Accurate and frequently updated tracking of the location of materials on construction sites can facilitate near real-time, on-site measurement of project performance indicators, such as schedule progress and labor productivity (Song et al. 2006a).

Unavailable, dislocated, or “not trackable” materials have a negative impact on the performance of continuous construction site operations. Accurate materials handling is necessary for effective logistics management. Certain techniques, such as, just-in-time (JIT) management on job sites can help to increase productivity levels (Pheng and Chuan 2001); and lean production techniques facilitate supply of the right amount of materials at the right time and in the right place (Tommelein and Li 1999). The JIT concept aspires to zero storage and no waiting or inspection times. This may seem unrealistic, but all these techniques can potentially be implemented if there is a reliable automated materials tracking and locating system on large industrial construction job sites.

In order to understand better the material tracking process, this chapter starts with the description of the existing or current materials tracking process. The necessary steps in the tracking process are defined and explained. There has been no site focussed automated locating process or technology until that deployed on the projects described in this thesis, so locating technology is described in a subsequent section. After explaining the materials tracking and locating process, as well as general system requirements, the architecture of an automated materials tracking system is defined. This is followed by an architecture that is developed for field deployment of the automated system.

3.2 Existing/Current Approach of Materials Tracking Process

Figure 3.1 is developed to describe in more detail the current approach of materials tracking process for the construction of a typical industrial project. The tracking process starts in the very first phase from the fabrication of the materials at the supplier/vendor's plant. This is followed by shipping or transportation to the job site. Further steps in the process include receiving and unloading at the construction job site, sorting, storing, recalling and flagging, picking up and loading and finally the installation. The figure explains the basic supply chain of the materials locating/tracking process.

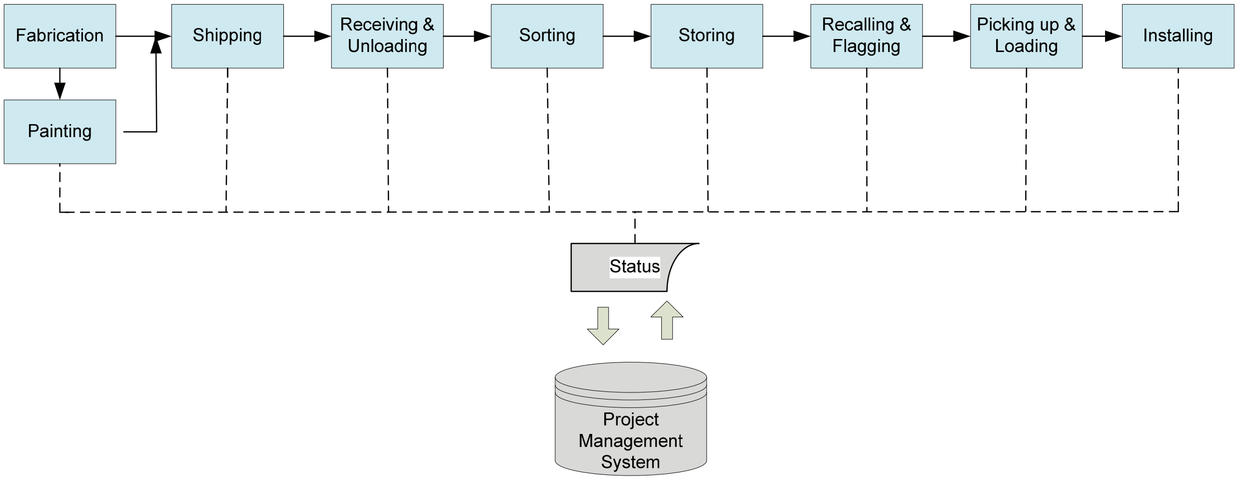

Figure 3.1: Materials tracking process for construction of an industrial facility

This process is typical for most of the construction projects of an industrial nature; however, there are variations for projects depending on specific circumstances.

3.2.1 Fabrication

Fabrication means to put together or combine basic materials or components to produce a finished part or more complicated part. Stukhart (1995, p.291) has defined fabricated materials as "an assembly of basic materials or component parts that are joined together to produce a finished part or a more complicated component, i.e., the building up of complicated shapes from simple stock materials, for example, a steel beam with holes, beam seats, and/or connected angles added."

Fabrication may be the first step in the supply chain of the construction materials identification, locating or tracking process. The fabricated materials are identified by the fabricator on the drawings. These materials are given a unique identification number or code (usually alphanumeric). It is common for many materials to include painting as a part of the fabrication process. Tracking from the fabricator through the paint shop can present practical and logistic challenges.

3.2.2 Shipping

After the construction materials are fabricated, the next step in the process is to ship them to the construction job site. Shipping means the transportation of the materials to the desired location either through road, air or water. Shipping includes all activities associated with transportation such as rate analysis, method of packaging, transit time, and security. The mode of transportation depends on the types of materials being shipped, their size, weight, and lead times. Usually engineered and prefabricated materials, which are made in the same country where the project exists, are shipped through rail system or flat bed trucks using the highways. Large modules or materials which are not available locally near the job site are often shipped through sea or inland waterways and are received at the port before they can be sent to the job site.

3.2.3 Receiving

The materials and construction components are received at the site by the on-site workers of the main contractor/owner or by the subcontractors. During the receiving process the materials are unloaded in the predefined areas before identifying or classifying them, which is either done during loading or immediately afterward. The materials are compared and identified with the packing list of materials. This unique identification code is usually alphanumeric. The received items are entered manually from the packing list into the project management system. The construction managers or foreman plan and execute the activities based on the received materials availability.

3.2.4 Sorting

After the materials are received on the site, they are sorted by the staff of the warehouse or workers of the contractor/sub contractor into grid marked areas by their physical characteristics and marked identifications codes. Typical area dimensions are 20m × 40m. Materials having similar physical characteristics are grouped together. During sorting, the materials are usually moved into the grid marked areas and are marked with colored tapes. Each material's identification, grid location, and color code are recorded manually on a sheet and then entered into the site management system.

3.2.5 Storing

After the materials are sorted, the next step in the process is the storing of these materials in appropriate places so that they are readily available and identifiable when needed, and to keep them safe from an environmental and security point of view. Usually, the materials are stored in lay down yards or warehouses, which are specifically planned and designed to meet the requirements of the project. The lay down yards are sometimes subdivided into multiple grid marked areas. The position of the materials in the lay down yards and warehouse is noted manually and then entered into the project management system for future reference. The materials usually remain in the same position during storage; however, they are often moved during retrieval of nearby items. Whenever, an item is moved to a new position, its identification code and the new position (grid number) should be recorded manually and updated into the project management system. This often fails to occur for various reasons.

3.2.6 Recalling and flagging

When the stored materials are required for a construction activity, a request is made by the foreman to the warehouse or lay down staff. The warehouse or lay down staff recall the grid locations, specific identifications, and color codes from the management system and a list is made. The workers try to visually locate the materials from the list in the lay down area. This takes time even if the materials are in their originally recorded grid areas. Sometimes, they may also need to make use of drawings and descriptions of materials to facilitate positive visual identification. Once an item is located, a flag or some other identification is attached to facilitate its quick identification during the issuing or pick up stage.

3.2.7 Issuing

After the requests from the foreman or subcontractors are processed and the materials are flagged, the materials are issued on a specified schedule. The materials are picked up and loaded into trucks and released to the contractors for installation.

3.2.8 Installation

When the materials or equipment are issued to the contractors, the last step in the process is the installation of these materials or equipment into the facility. Usually, in the construction of large industrial facilities, the materials and equipment have to pass through the staging process, where they are staged before finally installed into the facility. The staging area is the area next to the exterior of the facility or next to the work face. It is from this area that the materials are lifted into the facility or into position. Materials that are off-loaded directly into the facility also use this area.

On construction projects, the materials have to pass through the various phases of design, fabrication, interim processing, delivery and storage prior to scheduled installation. Planning by crews may involve the responsible foreman or field engineer identifying complete resource requirements for each task and verifying the availability of those resources (Choo et al. 1999). When the crew foreman makes requisitions for certain materials, the constructor’s warehouse/lay down yard personnel locate, identify and issue and/or stage them at the crew’s work area. This approach is often called “work packaging”, “work face planning”, and/or “short interval planning”. This approach is seldom achieved perfectly in practice.

3.3 General Requirements of a Materials Tracking System

An efficient materials tracking system must have the ability and flexibility to integrate easily with the overall materials management system and at the same time have the capability to effectively track and identify the materials and equipment.

Plemmons and Bell (1995) identified key measures to evaluate the effectiveness of materials management processes within the industrial construction industry sector. They identified six attributes of performance for the materials management process. These attributes or effectiveness categories are accuracy, quality, quantity, cost, timeliness, and availability. They based their research on a survey conducted among 56 construction industry professionals, who represented 42 construction related companies. Their questionnaire listed 35 proposed materials management effectiveness measures. Based on that survey the top 10 ranked key effectiveness measures are shown in the Table 3.1.

An efficient automated materials tracking system should automatically identify and track the materials effectively while performing well with respect to the effectiveness measures as stated in Table 3.1. Besides having the key attributes of a materials management system identified in the literature, the automated materials tracking system should also have additional characteristics of improved asset visibility, reduction in shrinkage and waste, increased service levels with lower inventory carrying costs, and reduced time to locate assets. In order to successfully integrate with the field construction materials and other project management systems, the automated materials tracking system must be flexible in terms of its implementation, have minimum infrastructure requirements for setting up the system, be easy to mobilize, be simple and user friendly in its operations, and be rugged enough to withstand the harsh construction environment.

Table 3.1: Key Measures of Materials Management Effectiveness (Plemmons and Bell 1995)

Rank	Measure
1	Material Availability
2	Construction Time Lost
3	Commodity Vendor Timeliness
4	Material Receipt Problems
5	Procurement Lead Time
6	Jobsite Rejections of Tagged Equipment
7	Purchase Order (PO) to Material Receipt Duration
8	Warehouse Inventory Accuracy
9	Commodity Timeliness
10	Total Surplus

3.4 Location Estimation Principles and Techniques

Triangulation and scene analysis are the two principal techniques typically used individually or in combination, for location sensing system implementation to locate materials, equipment, and people (Hightower and Borriello 2001). However, proximity or "constraint set" techniques were developed by (Simic and Sastry 2002; Song et al. 2005; and Caron et al. 2005) in the last few years. Each approach has its relative merits, which are described below.

3.4.1 Triangulation

Triangulation computes the position of an object by measuring its distance from multiple reference points with known locations. Triangulation is divisible into lateration and angulation, depending on whether ranges or angles relative to reference points are being inferred. The lateration technique is similar to the angulation technique, except ranges are used instead of angles for estimating the position of an object. Figure 3.2 shows 2D lateration, which requires three distance measurements/ranges between the object being located and three reference points. Figure 3.2 also shows 2D angulation which requires two angle measurements and one length measurement such as the distance between the reference points (Hightower and Borriello 2001).

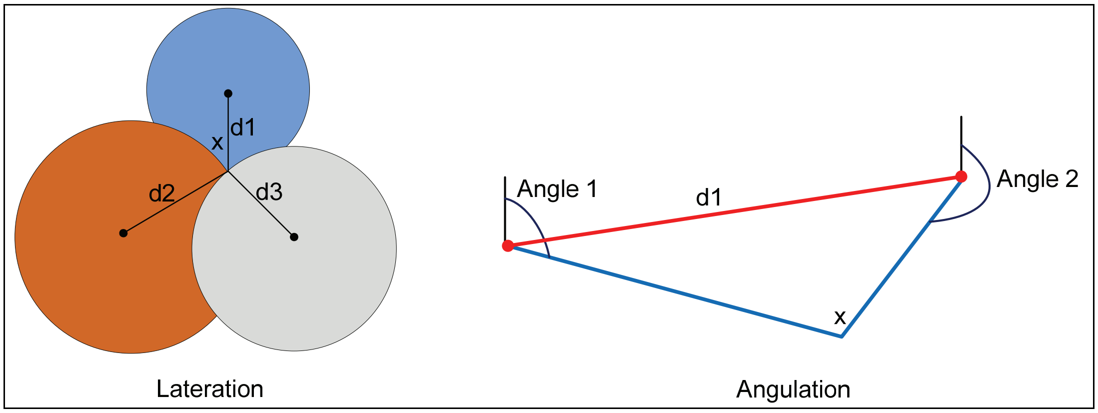

Figure 3.2: Lateration and Angulation

Lateration can be further categorized into the time-of-flight (TOF) and received signal strength (RSS) methods, where the ranges to references points are inferred from time of flight and signal strength of the communication signal, respectively. These techniques are difficult or impossible to implement with inexpensive RFID tags and reader hardware, but may be implemented with expensive system of fixed and calibrated readers and active tags communicating based on the IEEE 802.11x standards.

3.4.2 Scene Analysis

In this technique, the location of the object is computed using features of a “scene” constituted of the electromagnetic signal characteristics map defined by the attenuation of a transmitted signal from multiple locations in the “field of view” for the scene. Therefore, there is an “RF signature” unique to a given location and combination of receivers (Bulusu et al. 2000; Hightower and Borriello 2001). The major disadvantage of this technique is the extensive effort required to generate the signal signature database and reconstruct an entirely new database due to significant transmission changes in the environment which typically occur on a large industrial construction project. Thus, this approach requires a fixed reader grid, a static signal transmission degradation map, and much recalibration when the transmission space changes. Commercial systems have emerged that use this approach to track item locations at a cost typically many times greater than the cost of the system developed and deployed as part of this study. They include AeroScout, Cisco Systems, and Ubisense.

3.4.3 Proximity Techniques

The proximity technique determines whether an object is near one or more known locations, by monitoring physical phenomena with limited range, such as physical contact and communication connectivity to the bar code scanner or access points in a wireless cellular network. This technique does not actually measure the object’s distance to reference points, but only determines its presence within a certain range. The method of constraints, accumulation arrays, Dempster-Shafer theory, and fuzzy logic are some of the approaches that can be used individually or in combination for proximity based localization models (Caron et al. 2007). A crude variation on this approach is the center of gravity (COG) analysis, where the COG of the reads of a tag is used to estimate its location. These techniques were developed immediately preceding and on the projects described in this thesis by the research team involved in this project.

3.4.3.1 Method of Constraints

Simic and Sastry (2002) presented a distributed algorithm for locating nodes in a discrete model of a random ad hoc communication network and presented a bounding model for algorithm complexity. Song et al. (2005) adapted this discrete framework, based on the concept that a field supervisor or piece of materials handling equipment is equipped with an RFID reader and a GPS receiver, and serves as a “rover” (a platform for effortless reading). The position of the reader at any time is known since the rover is equipped with a GPS receiver, and many reads can be generated by temporal sampling of a single rover moving around the site. If the reader reads an RFID tag fixed at an unknown location, then RF communications connectivity exists between the reader and the tag, contributing exactly one proximity constraint to the problem of estimating the tag location. As the rover comes into the communication range with the tag time and again, more reads form such proximity constraints for the tag. Combining these proximity constraints restricts the feasible region for the unknown position of the tag to the region in which the circles centered at the reads intersect with one another (Figure 3.3). Given that read ranges are grossly distorted in the field, the much more computationally tractable form of a square read range may be used with little degradation in practice of the final estimate of location of the tag.

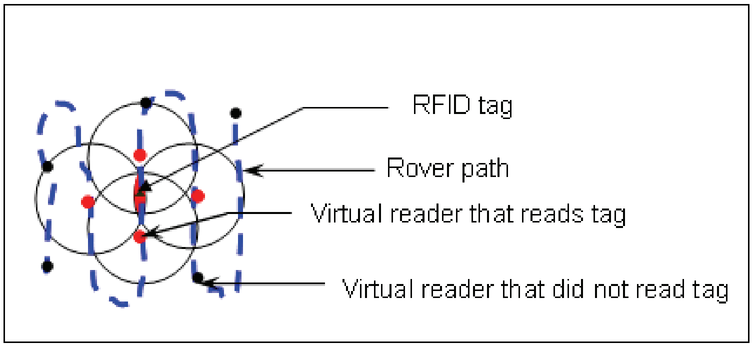

Figure 3.3: Combining proximity constraints from reader-tag connectivity

3.4.3.2 Method of Accumulation Arrays

Using accumulation arrays for discrete modeling of the working space is a conceptual variation for proximity localization based on the concept in Song et al. (2005). However, unlike the method of constraints, reads would simply be accumulated cell by cell for each tag (Figure 3.4). To handle moving and moved tags, cells for each tag would begin to erode after a fixed number of reads while cell value magnitudes are related to probability of tag location. This model has not been implemented yet, and its obvious drawbacks are its potentially slow response to moves, and its large data structure requirement.

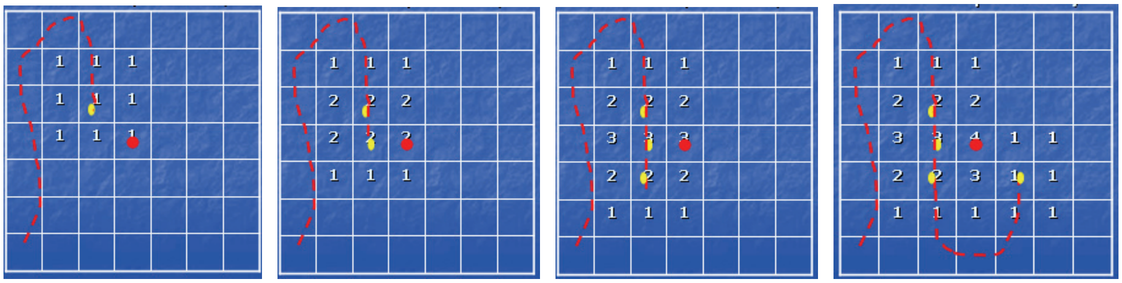

Figure 3.4: Accumulation of cell magnitude after each read in accumulation array method (with a discrete read range ρ =1)

3.4.3.3 Dempster-Shafer Method

The Dempster-Shafer method is another approach to proximity modeling which is based on Dempster-Shafer theory (Dempster 1968; Shafer 1976). Dempster-Shafer theory, also known as the theory of belief functions is a generalization of the Bayesian theory of subjective probability. While the Bayesian theory requires probabilities for each question of interest, belief functions allow us to base degree of belief for one question on probabilities for a related question (Shafer, 1992).

Caron et al. (2005) modeled each RFID tag read by a basic belief assignment which is fused to the past measurements, and implemented the Dempster-Shafer formulation in a simulation environment for application to materials tracking in construction. In this environment, when a reader which knows its own location reads a tag, it gets information about the position of this tag. This information, due to underlying imprecision and uncertainty, is modeled by a basic belief assignment under the belief theory framework. In this formulation, the probability of a tag lying in each cell is calculated using the pignistic transformation of this fused belief function, every time the fusion of a new read is made for the tag. Figure 3.5 is a simulation of the evolution of the pignistic probability of each cell as a function of new reads, and as the tag itself moves.

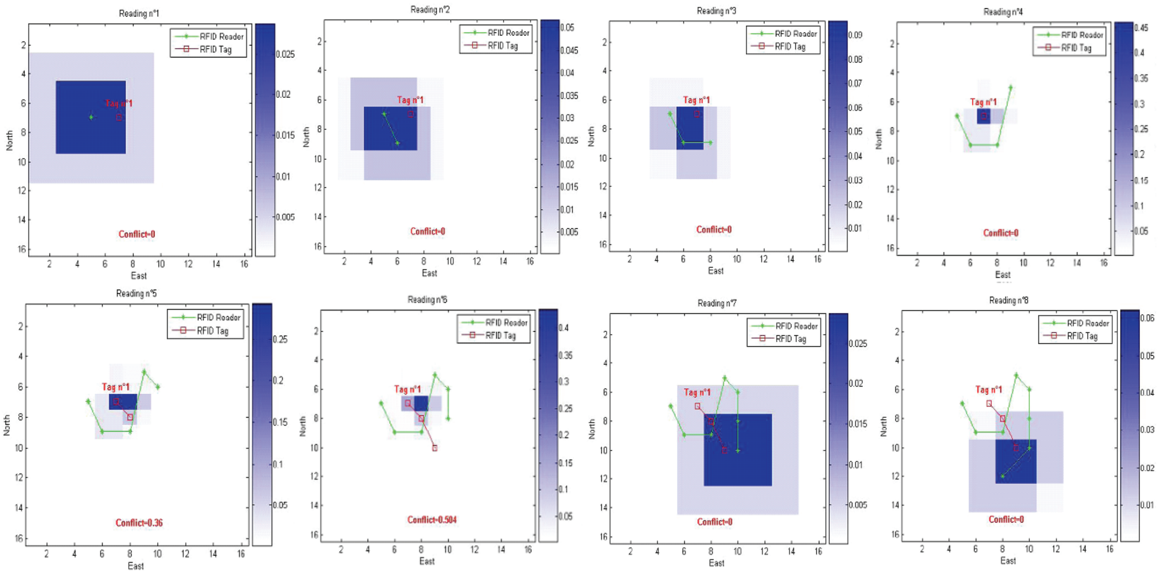

Figure 3.5: Evolution of the pignistic probability of each cell as a function of new reads

Generally, use of the Dempster-Shafer formulation increases integrity of localization of wireless communication nodes, because it can robustly deal with uncertainty and imprecision of anisotropic and time-varying communication regions. A key drawback of the formulation is that it increases complexity, although it is still computationally manageable.

3.4.3.4 Fuzzy Logic Method

This method of using proximity measurements for locating nodes would employ fuzzy logic instead of Dempster-Shafer theory in order to decrease the complexity associated with the Dempster-Shafer algorithm. While the fuzzy logic method builds on the insights gained through the Dempster-Shafer approach, it could consider the model to be continuous in some control variables such as moving tags or readers which are discretized in the other algorithms described earlier. This conceptual method is under development (Caron et al. 2007).

3.5 Information System Architecture for RFID Based Materials Tracking System

This section develops an ideal RFID-GPS based materials tracking technology's information system architecture based on what was learned over the course of this research project. The architecture is based on a number of hardware, software, and different service level applications. These components integrate with each other, and various software packages are required to run and operate this system. Commercial vendors for these components are emerging at the time this thesis was written, so details vary by vendor for each component. The schematic representation of this materials tracking information system architecture is shown in Figure 3.6.

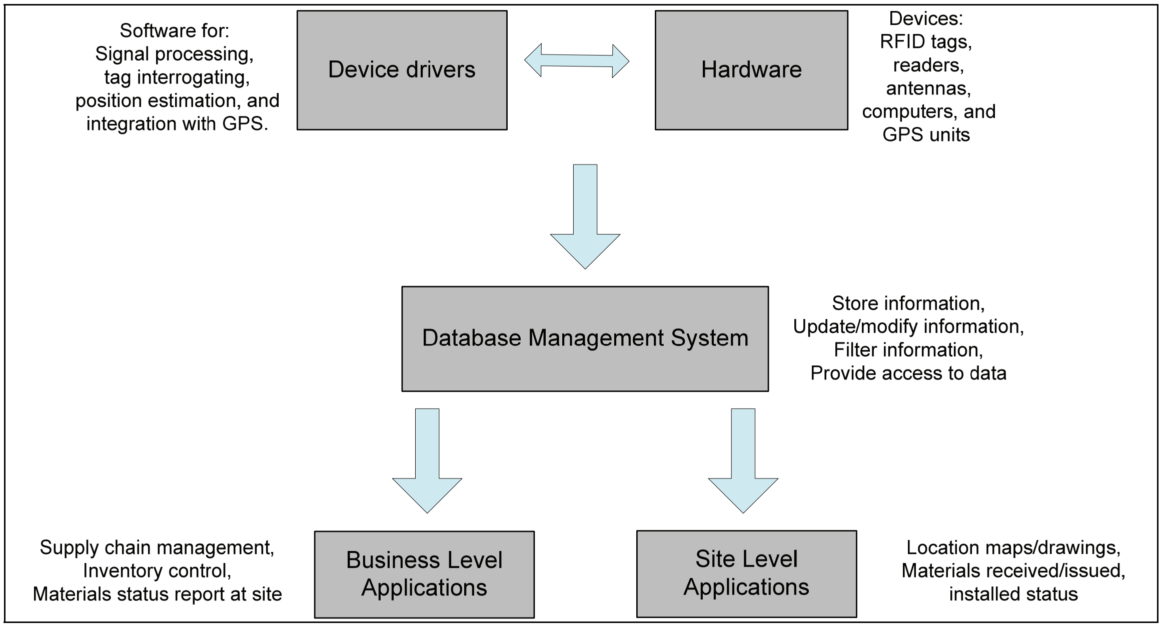

Figure 3.6: RFID based materials tracking information system architecture

The system's hardware devices include RFID tags, readers, antennas, computers, and GPS units. Some software/device drivers are required for the working and integration of these hardware components. These device drivers or software perform signal processing, position estimation, tags interrogation, and integration of hardware components including GPS. The hardware components collect data in the field about materials such as their unique identification number, estimated location, time and date of arrival at site. This data should be processed by the software and transferred to the database management system of the project. The database management system will use different software for storing, updating, modifying, and filtering this data.

This database should then be accessed for business level applications and site level applications. The business level applications will consist of supply chain management, inventory control, materials location information and other applications as required by the construction firms. The site level applications will mainly consist of issues related to materials such as their locations/drawings, received, issued, and installation status. The position of the materials in the supply chain is required for both the site and head office functions.

This information system architecture must be linked and harmonized with field deployment architectures. These may be site based only, or they may extend up the supply chain.

3.6 Architecture for Field Deployment of Automated Materials Tracking System

This section develops different options for the field deployment of an automated materials tracking system. How the system works and performs, what are the characteristics, advantages and disadvantages, and their fixed and variable costs under different approaches are described. The automated materials tracking system in the field can be deployed in combinations of primary subsystem architectural elements, including: mobile reader kits, fixed infrastructure, and/or portals or gates. These are explained in detail below.

3.6.1 Mobile Readers

This approach from an architectural or implementation point of view is characterized by mobile reader kits. In this system the RFID tags are attached to the materials being located or tracked. The position of each RFID reader is not fixed but is mobile. Readers can be mounted on people, materials handling equipment, and vehicles along with the GPS and handheld PC units. The RFID tags information is read by one or more readers, when they come into each reader's reading range, as the carrier moves or passes around the materials. The read rate is about 2000 reads per second. The GPS location of each read of each tag is recorded, and various algorithms exist (described in the previous section), using this information, to locate the tags within a few meters (based on triangulation, centre of gravity, constraint sets, etc.) (Caron et al. 2006; Caron et al. 2007). The schematic representation of this system is shown in Figure 3.7.

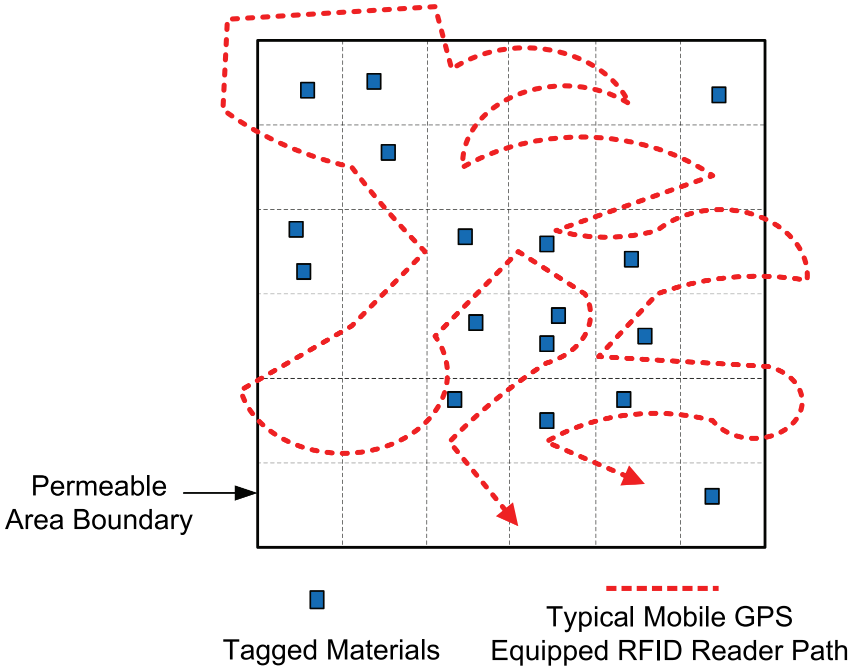

Figure 3.7: Schematic plan view representation of mobile reader system field architecture

The mobile reader can also move away or outside of the boundary of areas being logged as shown in the figure. This system is flexible and is most suitable for dynamic construction environments with less well defined boundaries and multiple satellite sites, and where the materials are frequently being moved around and between sites. If the materials are shifted or moved to new locations on the construction site or satellite sites, this system of field deployment can effectively track the location and movement of materials due to the travel flexibility of the readers.

Figure 3.8 is a schematic representation of a mobile reader field architecture for tracking the materials throughout satellite site areas. These areas may form a localized and less structured supply chain than a typical manufacturing supply chain.

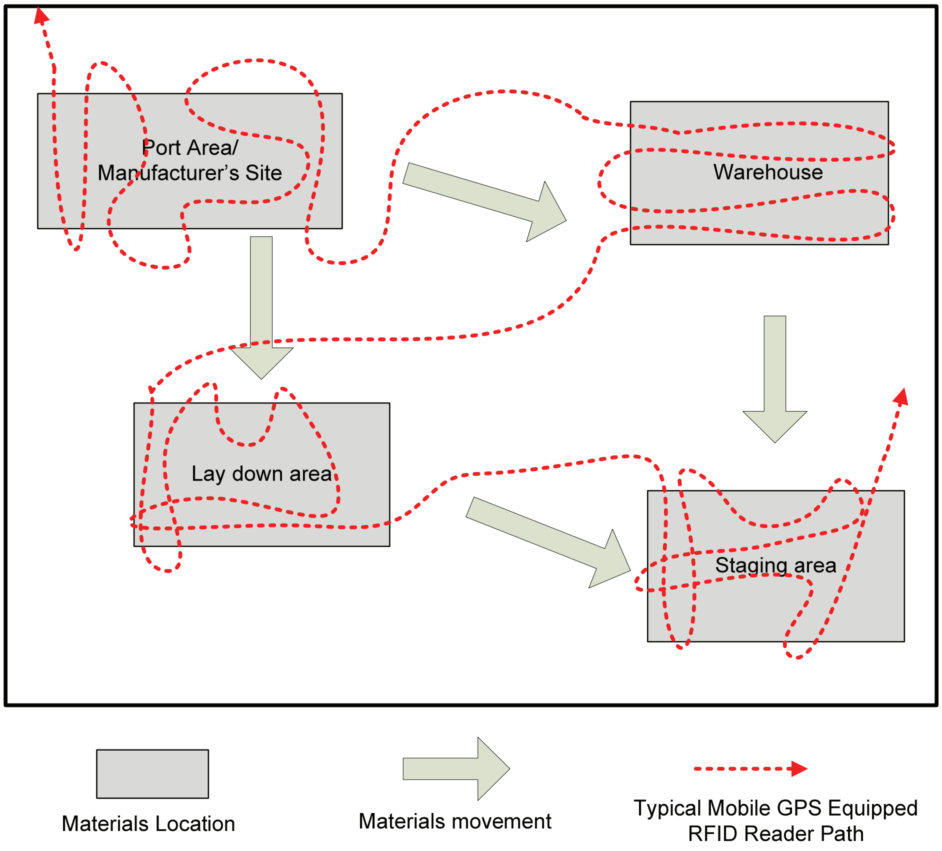

Figure 3.8: Schematic plan view representation of automated materials tracking by mobile reader throughout satellite site areas

In the first step, materials are identified and their information recorded where the materials are received; at the port, or at the manufacturer's yard. When materials are sent to the warehouse or lay down yards at the construction site, the same mobile reader system can track their location and movement. Similarly when materials are moved onward to the staging areas, the mobile reader system tracks their location in the same manner. Thus, this architecture of the field deployment of the automated materials tracking system has the flexibility of tracking the materials' locations at different places, without investing in additional fixed infrastructure. If there is only one reader, the disadvantage of this system is that someone has to carry the mobile reader to the locations where the materials are stored. Otherwise, multiple networked readers may be used.

The primary fixed costs of this system include the costs of mobile reader kits and the system software. A mobile reader kit consists of an RFID reader, antenna, GPS unit, handheld PC, and wireless connectivity. The variable cost of the system consists primarily of the cost of RFID tags attached to the materials. A partner on this research project which was partly funded by NSERC was Identec. Identec has now become a commercial vendor of this type of system and has added a software partner InSync. There are currently no other known commercial vendors of the technology developed on this research project.

3.6.2 Fixed Readers

This approach is characterized by a fixed infrastructure. The readers are fixed at certain known locations within the lay down yards and/or warehouses in the form of a grid layout. The readers are attached to the antennas and also to a host computer through a wired or a wireless network system. The position of these readers is known and recorded. When the tagged materials come into the reading range of multiple fixed readers, they are identified and their information and estimated locations are recorded. The approach is based on ultra-wide band communications technology and generally uses signal strength to multiple readers and scene analysis for location estimation (based on the IEEE 802.11x series of standards). This requires that the signal transmission and attenuation be mapped from every location to every reader. Obviously, this will work best in a fixed built environment such as an already erected building or warehouse but is not normally feasible where the transmission characteristics change as in a steel structure being constructed, or where large amounts of fabricated steel and piping are present. Figure 3.9 shows a schematic representation of the deployment of a fixed readers system. Commercial vendors of variations on these technologies have recently emerged and include Aeroscout, Cisco, Intelleflex, Siemens, and Ubisense, for example.

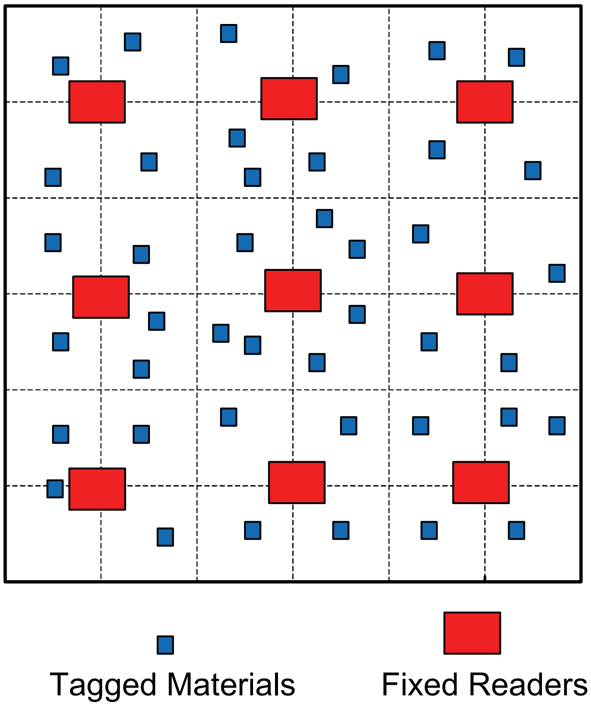

Figure 3.9: Schematic plan view representation of fixed readers system field architecture

This system has the advantage that as the RFID tagged materials come into the fixed boundaries of the lay down yard or warehouse for which these readers are programmed; they identify and locate the materials automatically, and transfer the materials position information to the host computer or database. It is most appropriate for bulk items warehouses and some types of fabricator yards, as well as existing plants where maintenance and outage work is being done.

One major drawback of this system is that it cannot identify and locate materials outside the read range of the fixed readers installed in the system. In other words, it means that the system can only track and locate materials if they are present in the predefined boundaries of the lay down yard or where the fixed readers system is installed. If the materials move away from these fixed boundaries, they can not be located or tracked in this system. Due to the dynamic nature of the construction site, this approach of field deployment is not suitable for construction sites, where there is a frequent movement and shifting of large materials items. Another major, and perhaps fatal, flaw of this system is that it must be re-calibrated every time the transmission space changes significantly, which may not be a problem on a lay down yard, but will likely be a problem on any vertical construction site.

The fixed cost of this system depends on the number of readers installed, which is governed by the area to be covered. The fixed cost also depends on the number of antennas used, the host computer, and the wired or wireless network system. The variable cost of this system is similar in structure to that of the mobile reader system, which is the cost, associated with the RFID tags; however the tags are typically several times more expensive than the tags used in the mobile reader system described in the previous section, since mobile reader systems can work with low power active tags and ultimately even with very low cost passive tags. Recalibrations will also be a variable cost.

3.6.3 Gates or Portal Structures

In this configuration of the field deployment of an automated materials tracking system, readers connected with antennas are attached and installed on the gates or portals erected on the in-gate and out-gate of the construction site, lay down yards, or warehouse. The schematic representation of this field deployment is shown in Figure 3.10. When the materials with RFID tags attached pass through these gates or portals, the reader records and identifies the materials. These readers then transfer the information to a computer through cables or wireless network, and the project database is updated with the materials status.

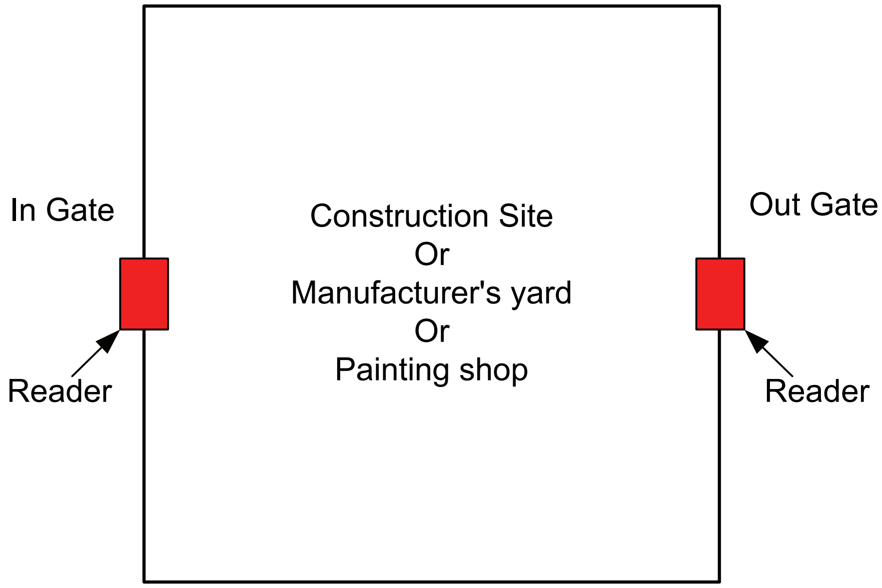

Figure 3.10: Schematic plan view representation of gate or portal system field architecture

This method of field deployment is most suitable for those construction projects or parts of projects where the materials identification is only required automatically at the time of their arrival and departure on site. Another advantage of this system could be the automated identification of materials received and issued in the warehouse at construction job sites or in the manufacturers' lay down yards or paint shops. When the tagged materials pass through the in-gate, they are automatically identified by the readers, and the information is passed on to the computers and the materials received status is updated in the project database. Similarly, when the materials are issued to the contractors from the warehouse, manufacturer's lay down yards or painting shops, this information is automatically recorded when they pass through the out-gate.

However, the major disadvantage of this architecture is that it does not identify, locate or track the materials beyond the gate or portal, nor does it estimate their location within the property. This makes it less suitable for some construction site environments, where the materials are frequently being moved around before their final installation, and where knowledge of location within a few meters, rather than mere presence in the yard somewhere or a grid area, is important.

3.6.4 Supply Chain Configurations

It is clear from the preceding discussion that one or all of the fundamental field architecture elements described in the previous three sections can be combined in a more comprehensive system architecture depending on the needs of the project and the level of sophistication of the supply chain. For example, portals may make most sense at small fabrication shops, while a large fabricator may wish to install a fixed grid system in its yard, and the site may wish to install portals for receiving in addition to mobile readers deployed throughout its lay down and staging areas.

Chapter 4

Implementation Field Trials

4.1 Introduction

Field trials were conducted on two construction sites. The author of this thesis was located on one of these sites. The field trials were intended to further prototype and assess the performance of the RFID/GPS technology described in the previous chapter. Based on the synthesis and analysis of the results of these field trials and the literature review, an implementation model for automated construction materials tracking is developed in the next chapter. The field trials were conducted concurrently on two industrial projects, one located in Toronto, Canada and the other in Rockdale, Texas, USA. The author worked on the project located in Toronto, whereas co-researchers worked on the USA project. Other Waterloo based researchers on the team visited and worked on the Rockdale site. This chapter describes the field trials held in Toronto. However, a brief description about the project in Rockdale, Texas and its results are also provided, because the results are critical for developing the implementation process for automated materials tracking described in the next chapter.

One construction site where the system was prototyped and where field trials were conducted is situated very near to downtown Toronto, Ontario, Canada. The project is known as the Portlands Energy Centre (PEC), a new state-of-the-art, natural gas fired, combined cycle generation facility in the Portlands area of Toronto's waterfront. PEC is now a 550 megawatts generating station. It is a 50-50 partnership of Ontario Power Generation Inc. and TransCanada Energy Ltd. The project was a challenging job, because it was forecasted that the city of Toronto would need an additional 250 megawatts of electricity by the summer of 2008; otherwise it might face blackouts. Toronto was already importing electricity for its ever increasing needs, and the only solution possible was to have its own power generating facility in operation by the summer of 2008 (PEC 2008). Figure 4.1 shows the pictures of the project obtained from its web site. The pictures provide a bird's eye view of the PEC, showing its location and important features.

The project is being executed on an Engineering-Procurement-Construction (EPC) basis. SNC-Lavalin is the main contractor of the project being constructed with union based labor. The main contractor is supported by a number of sub-contractors; each specialized in a particular area such as piping, electrical, and structures. Two identical units consisting of turbines, boilers, pipelines, and other components are used to operate the facility.

Figure 4.1: Portlands Energy Centre, Toronto, Canada (Photos, PEC web site)

The project had almost two identical sets of materials to support the construction of the two identical units. The facility required thousands of prefabricated and engineered components. These included pipe spools, safety valves, globe valves, control valves, steel members and pipe supports.

The next sections in this chapter explain the materials management procedure at the PEC and the problems associated with this approach. This is followed by the prototype automated materials tracking process, the lessons learned, and the results of the field trials.

4.2 Current/Existing Materials Management Procedure PEC

PEC is a state-of-the-art industrial project. The facility needed materials varying in different sizes and specifications. These included engineered materials, prefabricated materials and bulk materials. The materials used in the facility construction were supplied from different vendors. These materials came to the construction site from local areas, other communities in Ontario, Nova Scotia, and overseas. Most of the engineered materials and specialty materials in particular were to arrive from distant places including overseas via land and water (sea). Therefore the materials management process to identify and track the materials in the supply chain was challenging. The current or existing materials management process consisted of managing materials received at the Toronto port and materials received in the warehouse at the construction site.[1] Figure 4.2 shows the site and port location through a Google Earth image.

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[1] The materials management approach illustrated in Figure 4.3 to Figure 4.5 were developed in the early summer 2007, by the research team members in consultation with the materials managers of the main contractor and sub-contractors.

Figure 4.2: Google Earth image showing site and port locations

4.2.1 Materials Received and Stored At Port

The materials management procedure used for the materials already received and stored at the port of Toronto was documented by the research team and is shown in Figure 4.3. The process starts by submitting a requested materials pick up form from the subcontractor or contractor to the warehouse staff/manager. The warehouse staff confirms the arrival of the materials at the port and approves all the details of the pick up form, and then requests the items from the port. The work order form is filled for the checker/port dispatcher. The items are then searched, identified, located and loaded onto trucks at the port for onward delivery to the construction site. When the materials reach the site, they are distributed to the sub-contractors, who keep them in lay down areas for a long time before they finally get installed. The whole process of the materials identification and locating was done manually, and was time consuming and error prone.

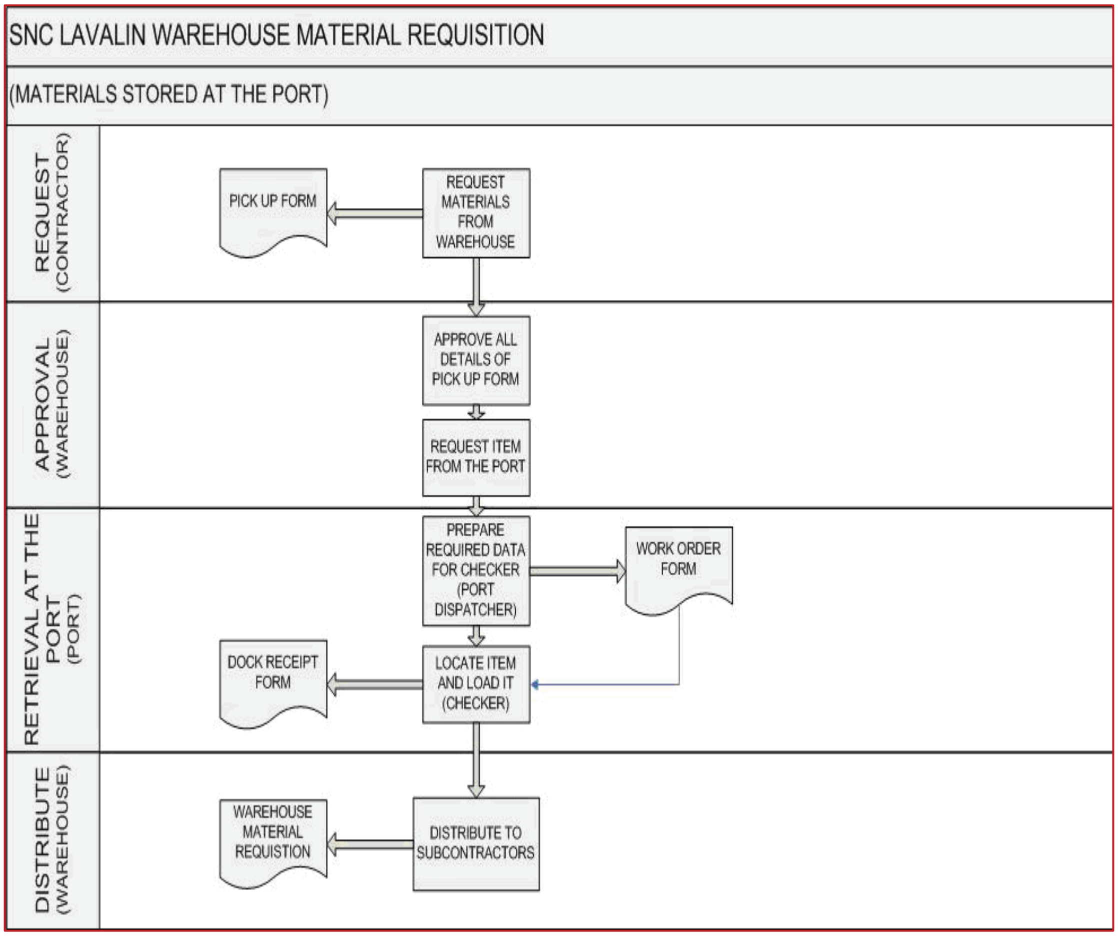


Figure 4.3: Materials management approach for materials stored at port

4.2.2 Materials Received and Stored In Warehouse/Site

The materials management process for materials received and stored in the warehouse and lay down yards at the construction site was documented by the research team and is shown in Figure 4.4. The process starts by the submission of a request form for materials by the subcontractors to the warehouse manager. The warehouse staff completes all of the details on the materials pick up form for approval. After that, the warehouse staff starts the materials locating/tracking process. They check the project database and find out about the stored location inside the warehouse or in the lay down areas. The crew searches for the materials in the lay down areas and identifies it by their physical appearance.

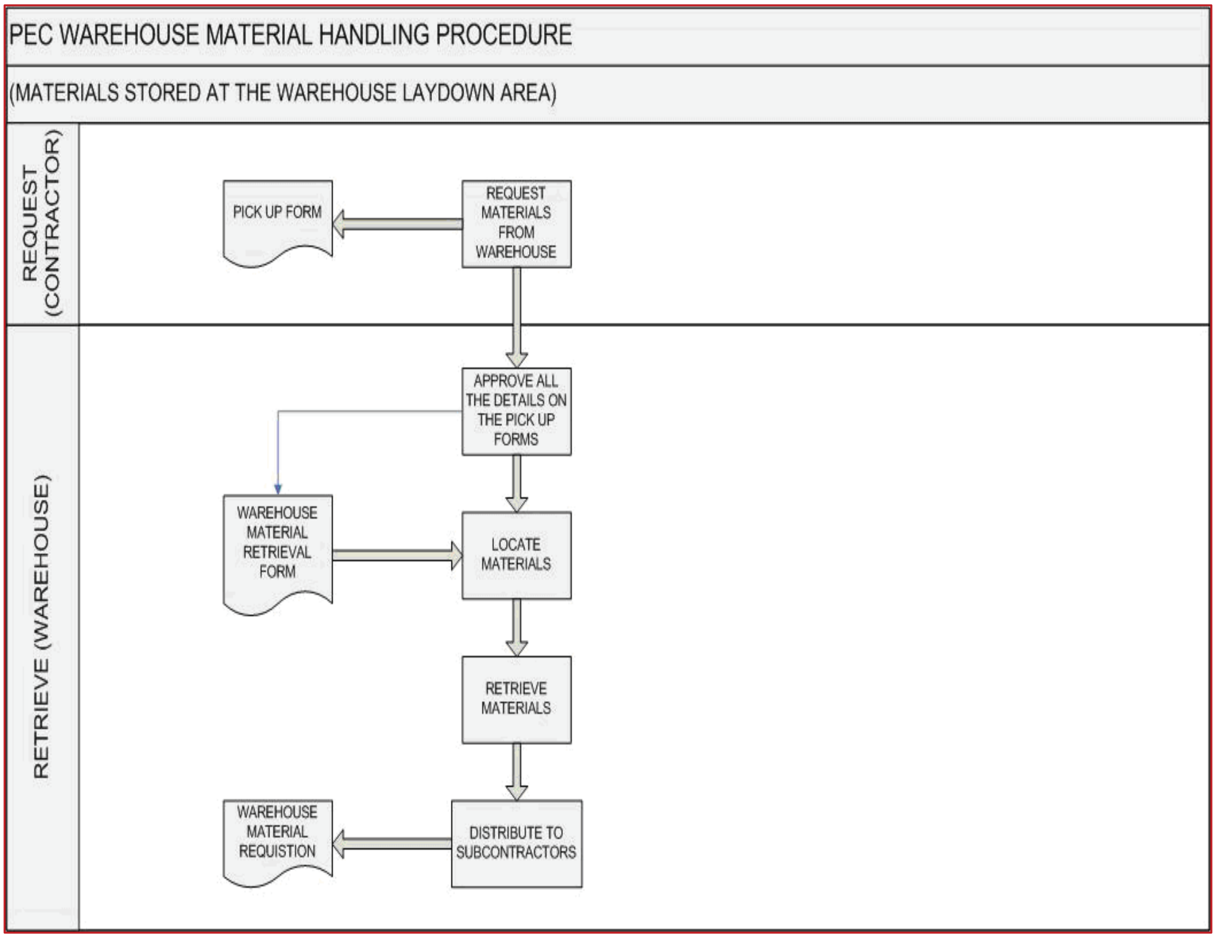


Figure 4.4: Materials management process for materials received at site

The materials thus identified, are compared with their unique identification number and their description in the purchase order and the materials pick up form. Once the materials are identified and located, they are flagged with different colors for issuing. The materials are then loaded and issued to the subcontractors. When the materials are issued to the subcontractors, they are again put in the staging/lay down areas before final installation. Sometimes, it takes months before the issued materials are finally installed into the facility. They are sometimes lost or returned to the warehouse in that period. They may be moved several times.

4.2.3 Materials Handling Process by Subcontractors

The materials handling process by subcontractors was documented by the research team and is shown in Figure 4.5. After receiving materials from the warehouse, the subcontractors bring the materials to their lay down yards or work areas, and spread them out.

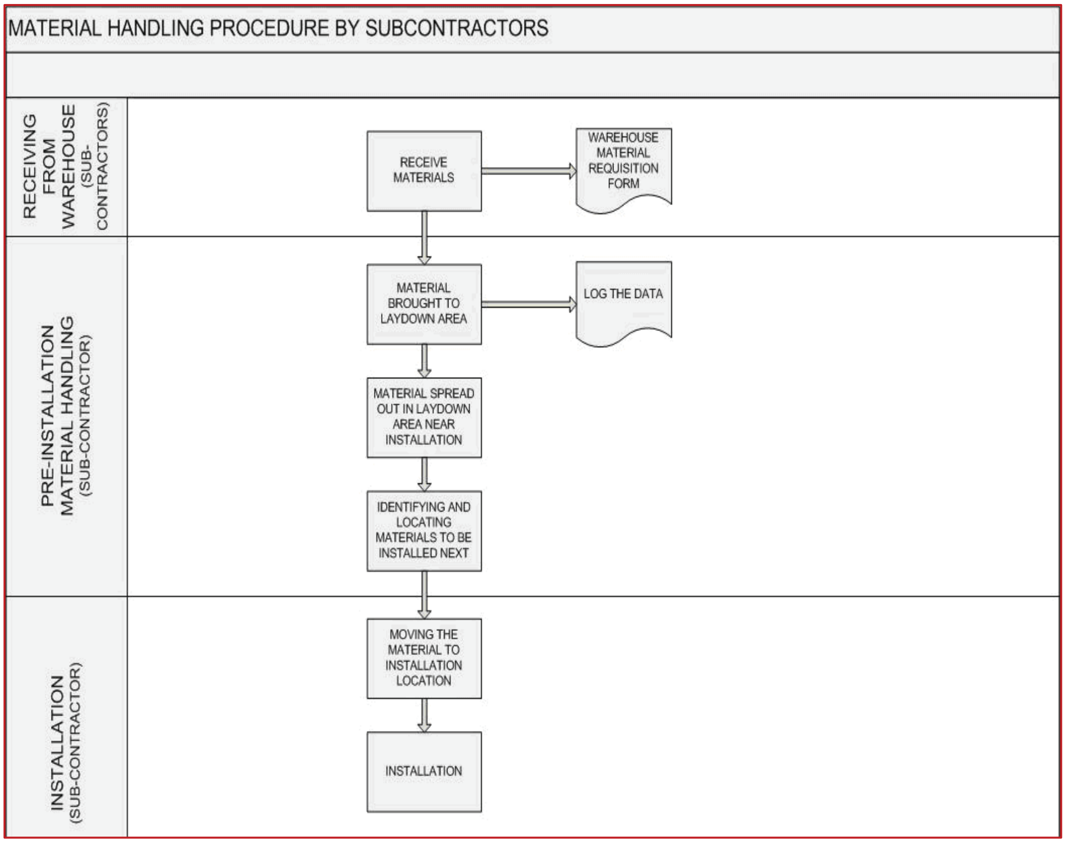


Figure 4.5: Materials handling procedure by subcontractors

Materials are usually stored before they are actually installed to avoid uncertainty on the availability of materials when needed. Materials keep coming to the lay down and work areas of the subcontractors, and they are moved multiple times before their installation. When the materials are actually needed, they have to search and locate them in the same way as was done earlier by the warehouse staff. They locate and flag the materials and then move them to the installation areas.

4.3 Problems with the Existing Materials Management and Tracking Approach

The existing field materials management and tracking process consisted of mostly manual operations documented with computer spread sheets. As a result it is time consuming, error prone, and often not reliable. The materials are stored in large lay down areas. These lay down areas are usually divided into small grids. However, when a big supply of materials is received, it is not sometimes possible to off-load the materials into the proper grids. Similarly when a number of project activities are going simultaneously in parallel with each other, the number of incoming materials is huge in number (surges), and therefore it is not possible to store them in the proper grids in the lay down areas. As a result the materials are scattered all over the lay down areas, and sometimes the materials are stored on top of each other, hiding the materials located at the bottom. Further, in conditions such as heavy snow, sand, dirt, and heavy vegetation, it is often simply not possible to identify the materials using a manual approach.

Figure 4.6 shows some examples of the materials storage at the Portlands Energy Centre site. From these pictures it is very clear that it would be very difficult to identify/track materials without the support of automated data collection and tracking technology. Also, due to the dynamic nature of construction site operations, it is not possible to keep the materials static for a long time. The materials are being moved around a number of times before they are finally issued for the final installation. This is particularly true in the case of prefabricated pipe spools. The prefabricated materials arrive at site much before their installation, sometimes even 6-7 months ahead of their scheduled installation. Therefore, the materials are handled multiple times, each move requiring a considerable amount of time and money. Sometimes this multiple handling caused the loss or unavailability of materials when needed. Therefore, to identify and track the materials using manual approaches would consume a large amount of time, and still it would not be possible to ensure the availability of the right materials at the right time.

Figure 4.6: Examples of materials storage at Portland Energy Centre site

4.4 Automated Materials Tracking Process Based on RFID/GPS Technology

The management of the main contractors at Rockdale and Portlands decided to allow field trials of the innovative approach to the materials tracking process described in the previous chapter. Initial meetings were held at Rockdale and Portlands that included the research team headed by Dr. Carl Haas, from the University of Waterloo. At Portlands, meetings were held with SNC-Lavalin, the main contractor of the project. The meetings were also attended by the representatives of the sub-contractors. The Portlands research team consisted of graduate and co-op students from the University of Waterloo. For Portlands, it was decided that only critical components would be automatically identified and tracked at both the materials receiving locations which include the port area and the warehouse at the construction site. Critical materials which were initially identified by the project management team to be tagged and tracked included 224 pipe spools for the unit 2 generator, 22 safety valves, and 100 globe valves. Later, it was also decided to automatically track and locate construction valves and pipe supports. Figure 4.7 shows examples of the critical items which were tagged with RFID tags for identification, locating, and tracking.

Pipe Spools Globe Valve

Safety Valves Pipe Supports

Figure 4.7: Examples of critical items attached with RFID tags

The decision to track only a subset of the critical components was based on a number of factors which included; limited number of RFID tags available for use, a new approach which needs field testing before full scale implementation, and lack of trained personnel. The critical components are those which have high cost, long procurement lead times, and are used in the critical path in the construction process. A list of these critical items was provided by the main contractor. These materials had caused crew delays and negatively affected project schedules on past projects.

Figure 4.8 shows the components used in the automated materials tracking and locating process. They included active RFID tags, a handheld PC, a GPS receiver enabled with Bluetooth technology, an RFID reader, and an Omni directional antenna. Back-up copies of all components were purchased or were donated by Identec. SNC-Lavalin also purchased several hundred tags.

Figure 4.8: Components used in the automated materials tracking process

Figure 4.9 shows the automated materials tracking and locating prototype process which required a combination of automated identification and data collection technologies. This process is explained in the following sections.

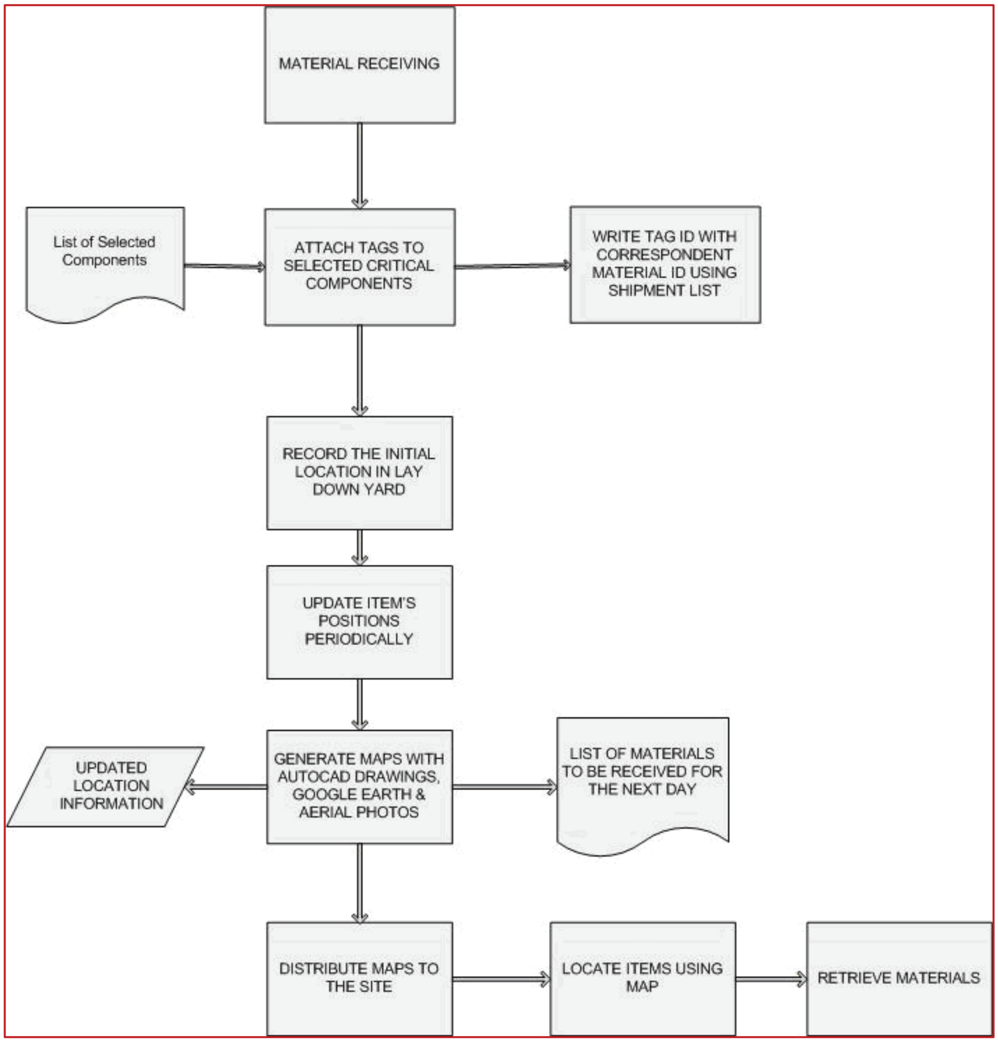


Figure 4.9: Automated materials tracking process used at PEC

4.4.1 Tagging of Materials

The process would start by tagging the selected components when they were received at the port and the construction site. Clearly, for a full scale deployment this would occur at the fabricator's shop, however a limited field trial was being conducted. When the list of critical items was received from the main contractor, it was compared with the shipment order and the materials were identified. When the materials were identified, an active RFID tag was attached to them through zip ties. Figure 4.10 shows some samples of RFID tags attached to pipe spools. Each RFID tag has a distinct number. The unique identification number of the item from the shipment list and the corresponding tag number were recorded in datasheets and then entered into the electronic format in excel spreadsheets in the office.

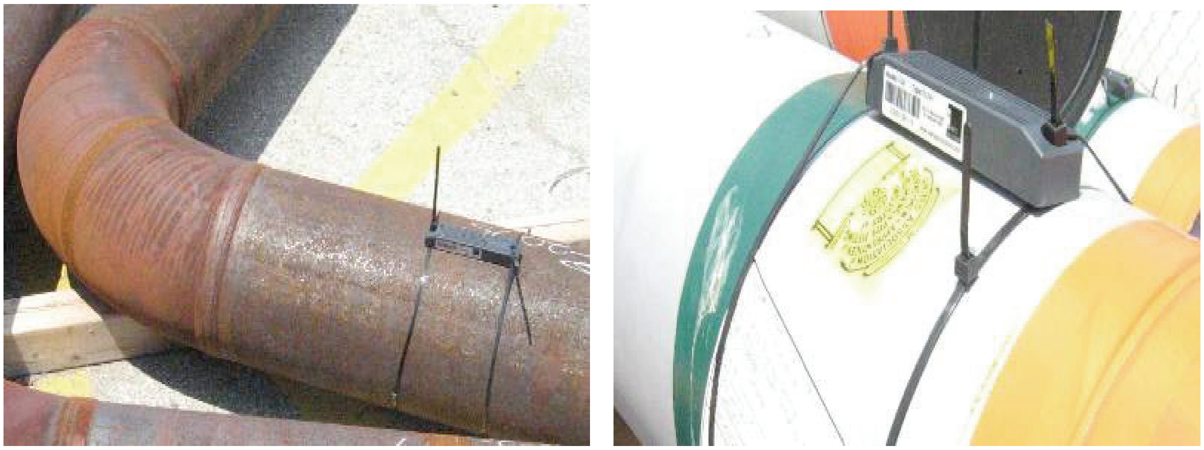
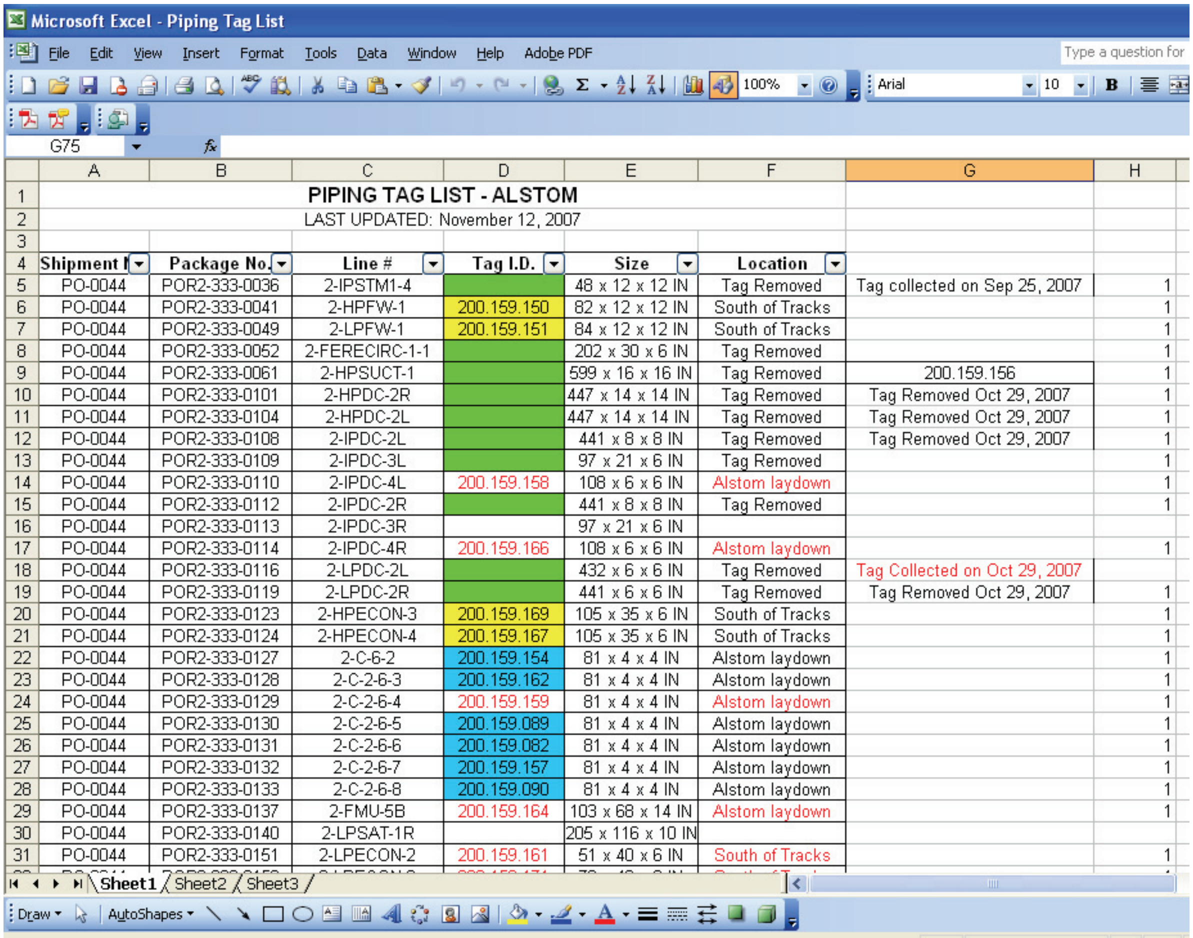


Figure 4.10: Samples of RFID tagged pipe spools

4.4.2 Data Collection and Materials Location Information

The initial locations of the materials were recorded for benchmarking purposes for subsequent analysis using the blue tooth enabled GPS. A worker (research team member in the case of this study) held the handheld PC and GPS, and walked around the materials in the lay down yard. The RFID reader along with the antenna was attached to the handheld PC. As the tags came into the reading range of the reader, they were identified by the reader and their information and corresponding reader location derived from the GPS receiver communicating with it in real-time was stored in the handheld PC. After the initial data was logged, the information recorded in the handheld PC was transferred to the computers in the warehouse office. After this data was processed to estimate tag locations, the project database was updated with the materials information including their locations. Figure 4.11 shows an example of the piping database, which was managed using an Excel spreadsheet. The spreadsheet contains all the necessary information such as the shipment number, package number, line number, size, and the corresponding RFID tag number for all materials items. The information about the location of materials in particular yards was also provided.



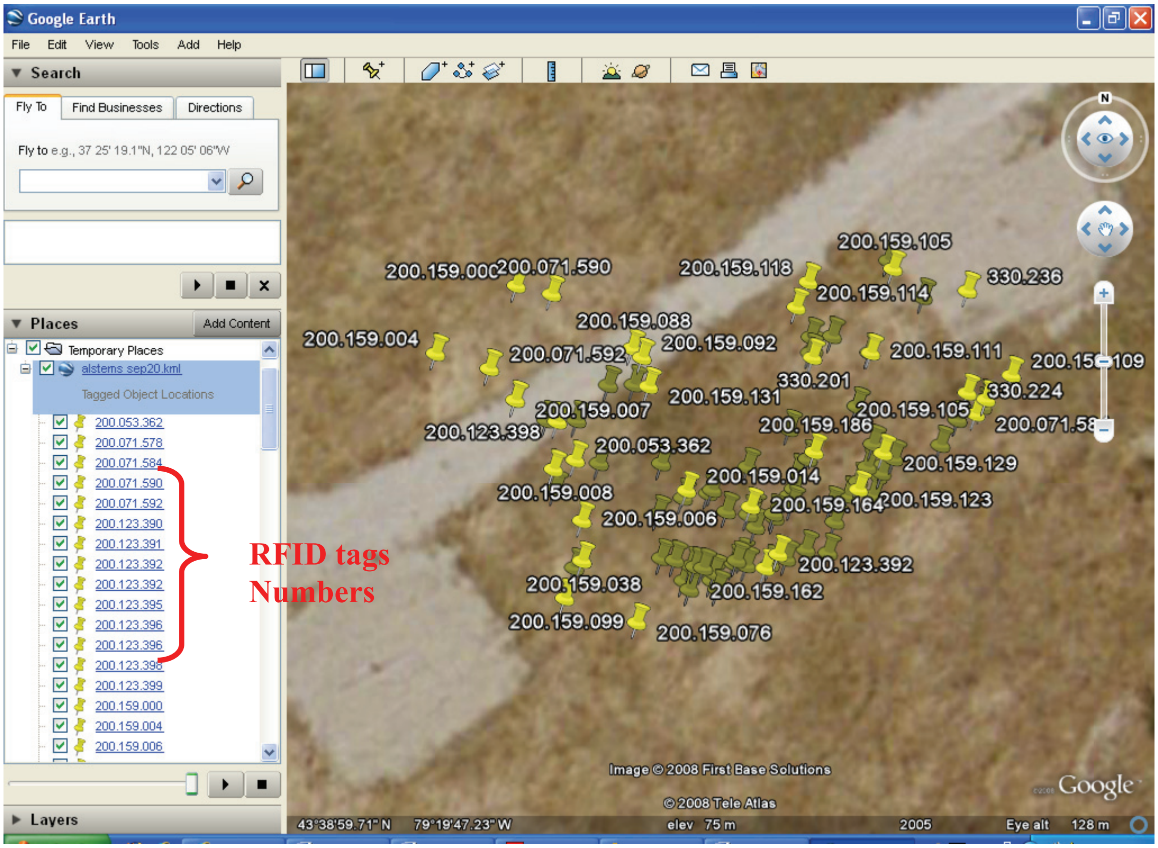
PIPING TAG LIST - ALSTOM

LAST UPDATED: November 12, 2007

Shipment	Package No.	Line #	Tag I.D.	Size	Location		
PO-0044	POR2-333-0036	2-IPSTM1-4	🟩	48 x 12 x 12 IN	Tag Removed	Tag collected on Sep 25, 2007	1
PO-0044	POR2-333-0041	2-HPFW-1	200.159.150	82 x 12 x 12 IN	South of Tracks		1
PO-0044	POR2-333-0049	2-LPFW-1	200.159.151	84 x 12 x 12 IN	South of Tracks		1
PO-0044	POR2-333-0052	2-FERECIRC-1-1	🟩	202 x 30 x 6 IN	Tag Removed		1
PO-0044	POR2-333-0061	2-HPSUCT-1	🟩	599 x 16 x 16 IN	Tag Removed	200.159.156	1
PO-0044	POR2-333-0101	2-HPDC-2R	🟩	447 x 14 x 14 IN	Tag Removed	Tag Removed Oct 29, 2007	1
PO-0044	POR2-333-0104	2-HPDC-2L	🟩	447 x 14 x 14 IN	Tag Removed	Tag Removed Oct 29, 2007	1
PO-0044	POR2-333-0108	2-IPDC-2L	🟩	441 x 8 x 8 IN	Tag Removed	Tag Removed Oct 29, 2007	1
PO-0044	POR2-333-0109	2-IPDC-3L	🟩	97 x 21 x 6 IN	Tag Removed		1
PO-0044	POR2-333-0110	2-IPDC-4L	200.159.158	108 x 6 x 6 IN	Alstom laydown		1
PO-0044	POR2-333-0112	2-IPDC-2R	🟩	441 x 8 x 8 IN	Tag Removed		1
PO-0044	POR2-333-0113	2-IPDC-3R		97 x 21 x 6 IN			
PO-0044	POR2-333-0114	2-IPDC-4R	200.159.166	108 x 6 x 6 IN	Alstom laydown		1
PO-0044	POR2-333-0116	2-LPDC-2L	🟩	432 x 6 x 6 IN	Tag Removed	Tag Collected on Oct 29, 2007	
PO-0044	POR2-333-0119	2-LPDC-2R	🟩	441 x 6 x 6 IN	Tag Removed	Tag Removed Oct 29, 2007	1
PO-0044	POR2-333-0123	2-HPECON-3	200.159.169	105 x 35 x 6 IN	South of Tracks		1
PO-0044	POR2-333-0124	2-HPECON-4	200.159.167	105 x 35 x 6 IN	South of Tracks		1
PO-0044	POR2-333-0127	2-C-6-2	200.159.154	81 x 4 x 4 IN	Alstom laydown		1
PO-0044	POR2-333-0128	2-C-2-6-3	200.159.162	81 x 4 x 4 IN	Alstom laydown		1
PO-0044	POR2-333-0129	2-C-2-6-4	200.159.159	81 x 4 x 4 IN	Alstom laydown		1
PO-0044	POR2-333-0130	2-C-2-6-5	200.159.089	81 x 4 x 4 IN	Alstom laydown		1
PO-0044	POR2-333-0131	2-C-2-6-6	200.159.082	81 x 4 x 4 IN	Alstom laydown		1
PO-0044	POR2-333-0132	2-C-2-6-7	200.159.157	81 x 4 x 4 IN	Alstom laydown		1
PO-0044	POR2-333-0133	2-C-2-6-8	200.159.090	81 x 4 x 4 IN	Alstom laydown		1
PO-0044	POR2-333-0137	2-FMU-5B	200.159.164	103 x 68 x 14 IN	Alstom laydown		1
PO-0044	POR2-333-0140	2-LPSAT-1R		205 x 116 x 10 IN			
PO-0044	POR2-333-0151	2-LPECON-2	200.159.161	51 x 40 x 6 IN	South of Tracks		1

Figure 4.11: Example of piping database

The estimated locations were also saved into a .Kml file, which was visualized using Google Earth. Figure 4.12 shows an example of a .Kml file opened in Google Earth.



RFID tags Numbers

Figure 4.12: A .Kml file opened in Google Earth

After gathering reads in order to estimate the initial locations of the materials, their positions were periodically re-estimated using the handheld PC, the reader, the GPS and the algorithms on the office computer once or twice a day depending on the site operations and movement of the materials. The project database was continuously updated with the new information.

4.4.3 Generation of Maps/Drawings

Once the positions of the materials became known, they were graphically represented by generating maps using Google Earth and AutoCAD drawings. Initially, Google Earth was used to generate maps showing the locations of tagged materials (Figure 4.13).

Figure 4.13: Maps showing materials locations using Google Earth

However, not enough up to date landmark information could be provided to the workers using these maps. Therefore, an AutoCAD drawing of the site layout plan was overlaid on the Google Earth aerial photo to provide more detailed information about the site landmarks. Figure 4.14 shows locations of the tagged materials on an AutoCAD drawing overlaid on the Google Earth image. These drawings or maps were then provided to the contractors. The crew workers used these maps in identifying and tracking the materials in the lay down yards. Maps or drawings were also generated if a request from contractors was received for the location of specific materials.

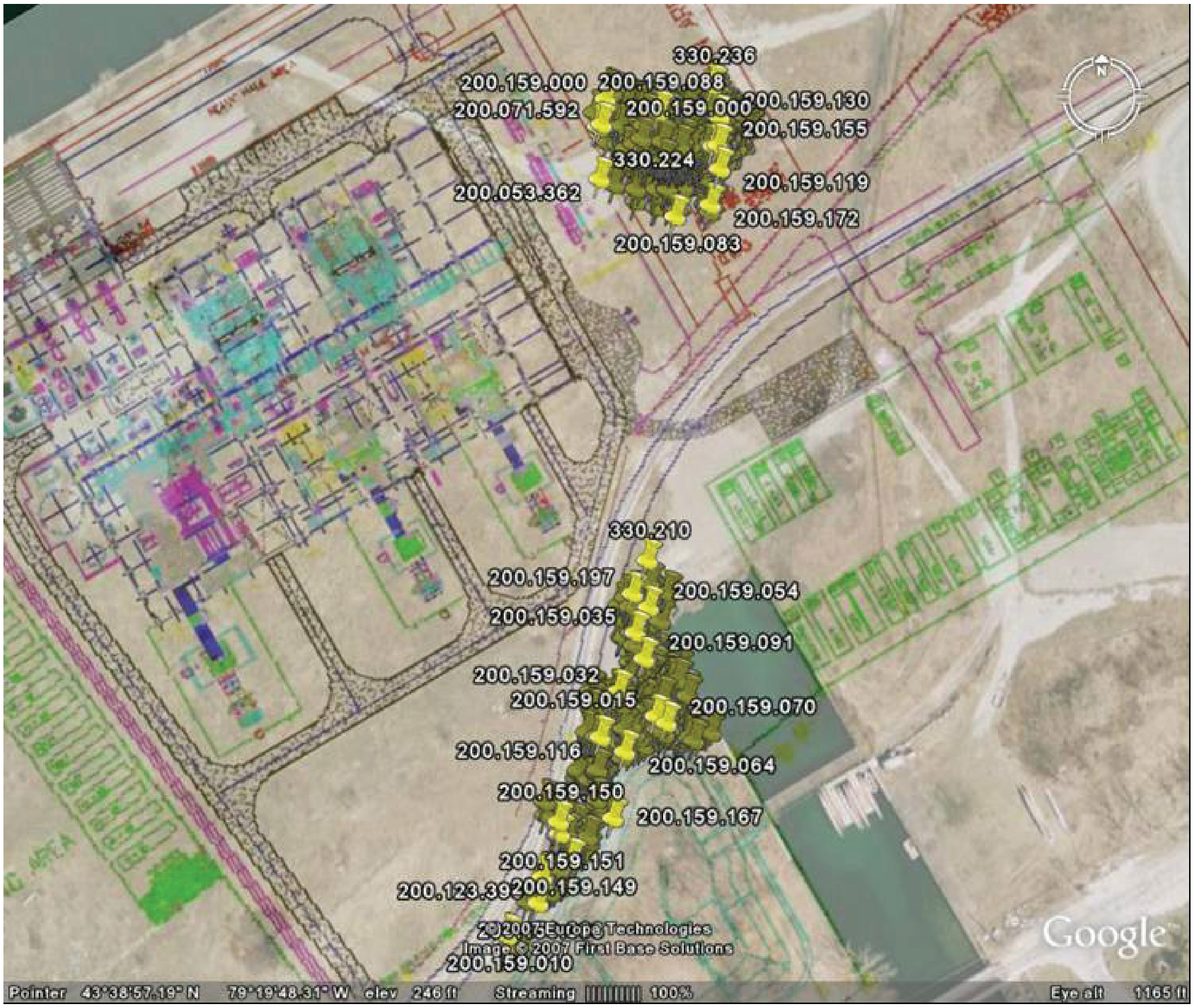


Figure 4.14: Location of all tagged materials on site using AutoCAD drawings and Google Earth

Maps were generated in different granularity and various scales to facilitate proper visualization by the field workers. Zooming in on a particular item was also possible. Figure 4.15 shows the locations of only two items which were requested by the contractor. The drawing was generated by selecting only the required items. The drawing shows the unique identification number of the materials instead of the RFID tag number. This made it more convenient for the workers to identify and locate the materials.

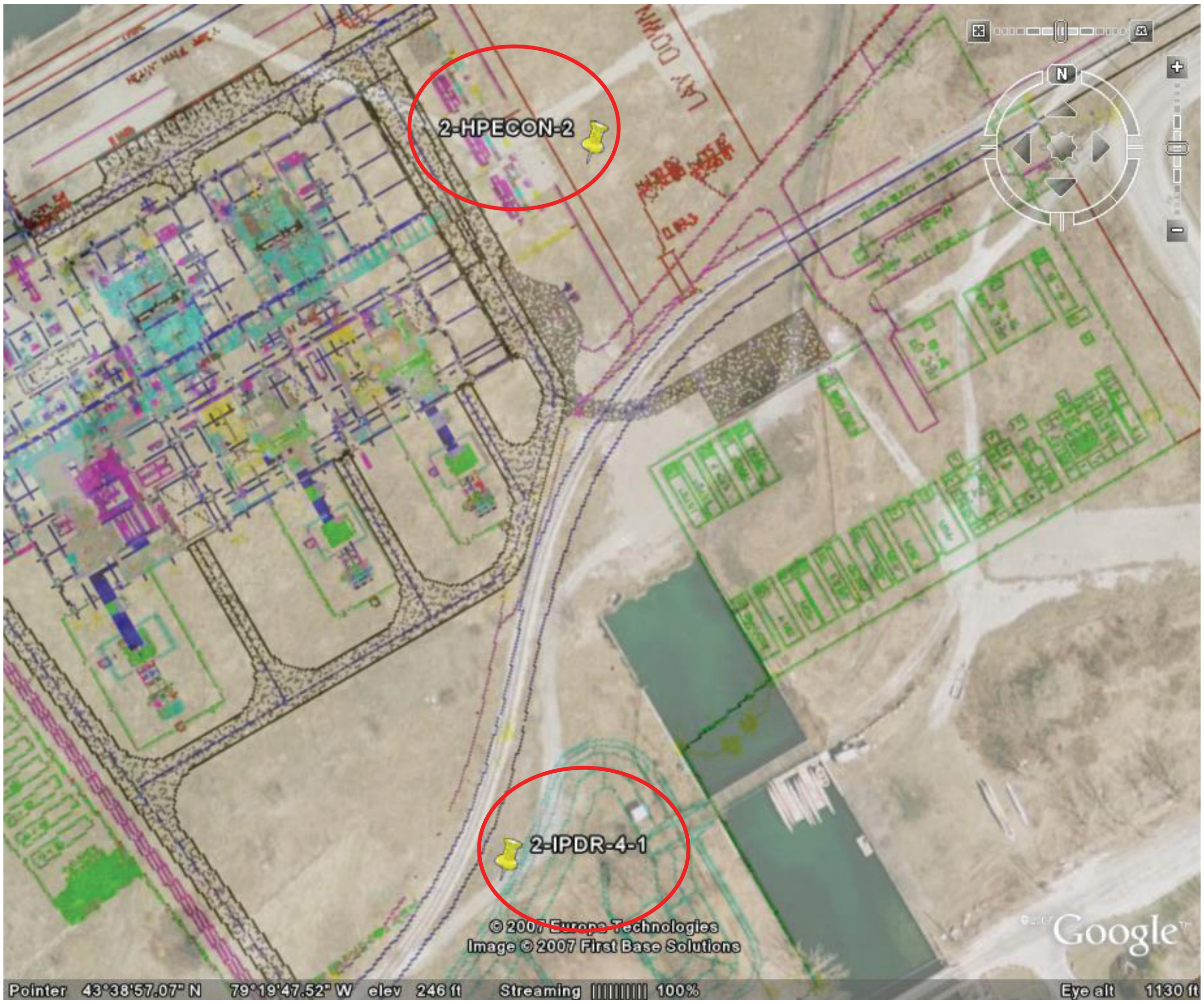


Figure 4.15: Drawing showing locations of two items in different lay down yards

Figure 4.16 shows another drawing, which was zoomed in on a specific item. This drawing shows the location of a pipe spool within a few meters. The surrounding landmarks of the site were also shown to make it more convenient for the field workers to locate the item.

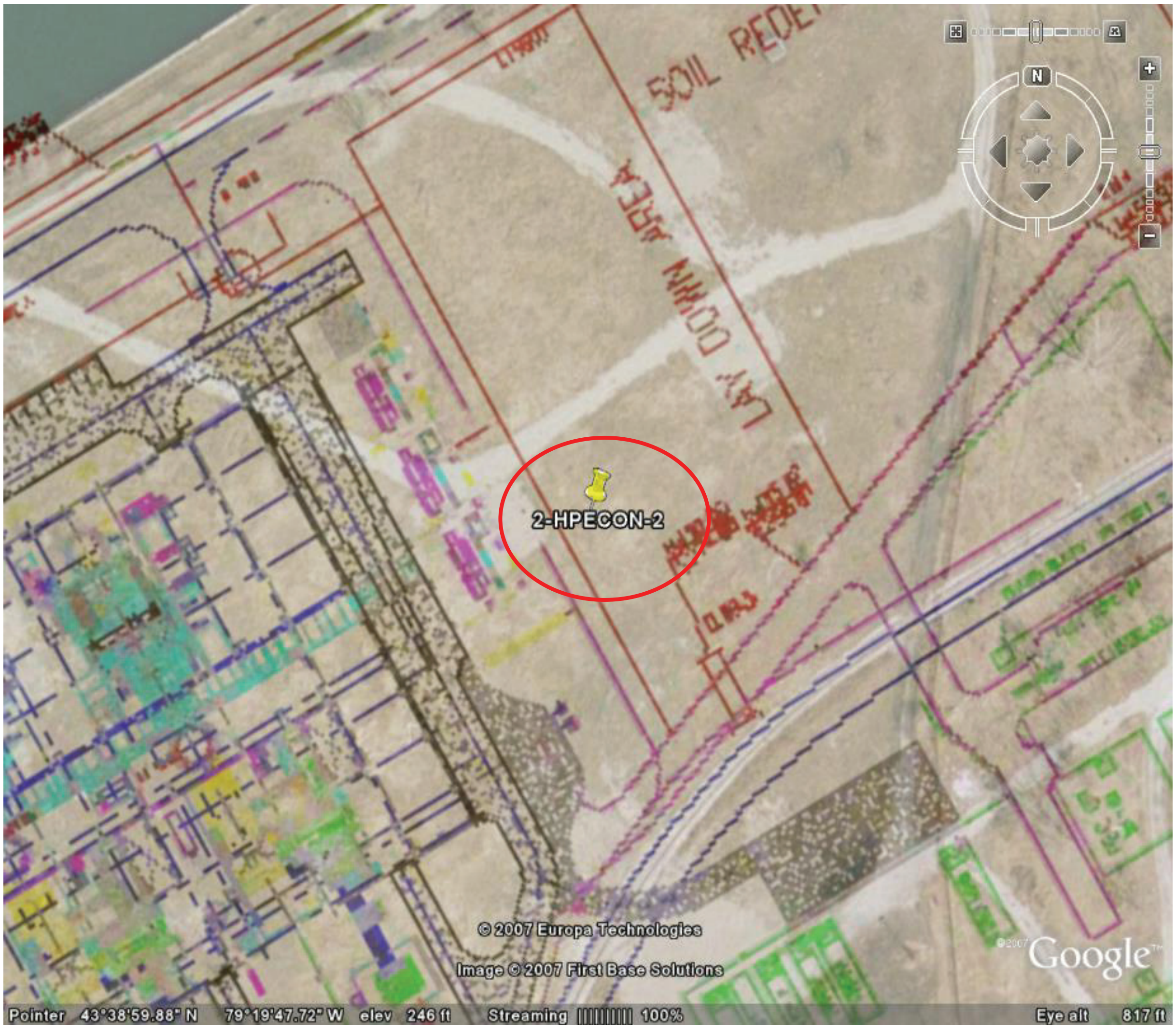


Figure 4.16: Drawing showing a close view (zoomed in) of a specific item

4.4.4 Retrieval and Issuing of Materials

Once the materials required for installation were identified and retrieved, they were issued by the subcontractors and their information recorded. When the materials were finally ready to be installed into the facility and it was confirmed that they would not be moved around further, the RFID tags attached to them were removed. The tags were returned back to the warehouse office, and the materials' list and the database was updated with the removed tags, codes. The tags collected were again used for other materials as they arrived on site.

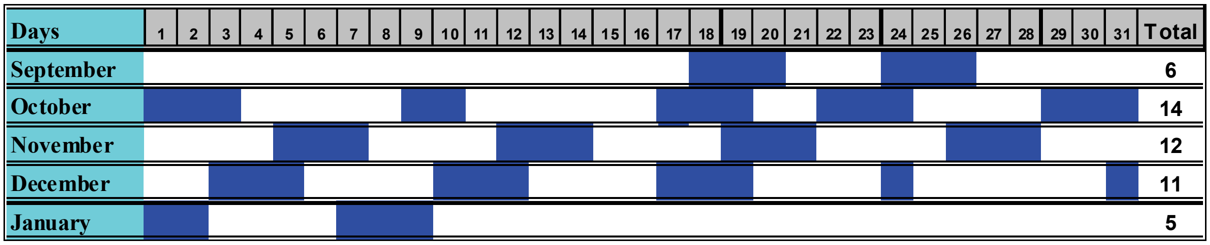
4.5 Duration of the Field Trials

The first meeting between SNC-Lavalin, the main contractor for the PEC, and the research team from University of Waterloo was held on May 29, 2007. It was decided that a graduate student from the University of Waterloo would be present on the site to set up the automated materials tracking system, attach tags to the selected components and collect data for research purposes. Pipe spools began arriving on the site via the port of Toronto in July, 2007 and by September 17, 2007 all of the pipe spools had been transferred from the port. The pipe spools were tagged at the port and this helped in tracking them from the port to the site and handled the cases of confusion during the delivery process. Several times, maps were produced of tagged items locations at the port, and at least once, items which were thought to be on site already were shown to be at the port instead by referencing the maps.

The second category of critical items identified for automated locating and tracking was safety valves. Twenty two safety valves were received at the port of Toronto on July 23, 2007. An RFID tag was attached to each valve and their location recorded using GPS. The safety valves were relocated to the project warehouse on July 27, 2007.The safety valves remained in the site warehouse for 6 weeks prior to being requisitioned by a contractor. The safety valves were relocated to an onsite work area in the week of September 21, 2007.

A graduate research student was present on the site from July 2007 on a full time basis; to tag the incoming materials, to perform the data logging for position estimating, to continue to implement changes to the prototype system, and to collect data for subsequent analysis. The author of the thesis joined the site on September 18, 2007. The author along with another graduate student from University of Waterloo, were present throughout the entire period from September 2007 to December 2007. Seeing the potential benefits of the automated materials tracking technologies and the system put in place by the research team, SNC-Lavalin decided to keep the project going from January to August 2008. Esteban

Campion, a co-op student from the University of Waterloo was hired to work on the project from January 2008 to April, 2008. The author worked on the site from September 18, 2007 to January 9, 2008. Figure 4.17 shows the details of the time the author spent on the PEC site in Toronto working on the research project and developing the implementation model. Another co-op student, Victor Lam from the University of Waterloo was hired by the main contractor to continue to manage the automated materials tracking system set up by the research team and to continue to collect data. He worked on the site from May 2008 to August 2008.



Days	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	Total
September																		■	■	■				■	■	■						6
October	■	■	■						■	■							■	■	■			■	■	■					■	■	■	14
November					■	■	■					■	■	■					■	■	■					■	■	■				12
December			■	■	■					■	■	■					■	■	■					■							■	11
January	■	■					■	■	■																							5

Figure 4.17: Time spent by Nasir on the PEC site, Toronto

After the initial tagging of the pipe spools and the safety valves, it was decided by the main contractors to expand the automated materials tracking project to other important materials. A list of construction valves and pipe supports was provided to be identified and tracked by the automated system. The pipe supports would be stored in the lay down yards in the winter season, and therefore, it was anticipated that they might be covered under heavy snow. The winter of 2008 saw one of the heaviest snows in the history of the province. However, the contractors faced no problems finding those pipe supports which were tagged with RFID tags, and their position estimated using the technology described here. It is important to mention here that the contractors faced severe problems in locating the materials in the heavy snow which were not tagged or tracked by the automated materials tracking system. A crew of five workers including the warehouse manager and the University of Waterloo student working on the site searched for two days unsuccessfully to locate the materials which were lost on the site due to snow. The contractor had to reorder some of these materials to avoid time delays.

The scope of the research was further expanded and it was decided to track the materials from the first step (fabrication) in the supply chain. A kick off meeting was held on January 24, 2008 between W.S. Nicholls Industries Inc. Cambridge, Ontario, who were fabricators and one of the subcontractors, and the research team from the University of Waterloo. The meeting was held in Cambridge, Ontario at the fabrication shop. The research team comprised of Professor Dr. Carl Haas, Hassan Nasir (the author), Saiedeh Razavi (PhD candidate), and Esteban Campion the intern student working at site. It was agreed to put RFID tags on the pipe spools to be used in "Area 5, Unit 1, Drain Piping" for one of the two identical boilers. Pipe spools were tagged at the fabrication shop of W.S. Nicholls Industries Cambridge, Ontario. The batch of pipe spools tagged at the fabrication shop consisted of 80 pieces of 2-inch diameter pipe from 6 feet to 40 feet lengths. After the fabrication shop these spools had to pass through the painting process in the painting shop. Therefore, the tags were put inside the pipes and fastened to flange holes with zip ties. In this way the RFID tags survived the harsh environment in the paint shop. Finally, the spools were transported to the PEC site by the fabricator with RFID tags already attached. When these pipe spools arrived at site, their identification and location was recorded automatically. Location information about these pipe spools were provided to the subcontractor. Some instances of when the contractor asked for the location of these spools are described in the case studies in Section 4.6.1.

The field trials which started in July 2007 were so successful that the main contractor decided to keep the automated materials tracking system on site. Therefore, from July 2007 to August 2008 a member of the research team or a co-op student from the University of Waterloo was present on site every day to manage the automated materials tracking system and assist the contractors in locating the tagged materials.

4.6 Results of the Field Tests

The purposes of the field trials were to: 1) assess the feasibility and to prototype the automated materials tracking system in a construction environment, 2) to assess the impact of materials tracking technology in tracking/identifying items, capturing flow of materials, and supporting crews, and 3) to develop an implementation model for automated construction materials tracking.

At the beginning of the project, most of the materials managers of the subcontractors were hesitant to utilize the automated materials tracking system. They were told a number of times by the site manager to provide a list of materials to be needed by them in the next few days, so that maps showing locations of the materials could be provided to them. They would not ask for the identification/location of the materials, until their crews were exhausted and not able to locate some of the materials. They would approach the research team when they would fail to manually locate the materials. On a number of occasions, the research team would quickly provide them with location maps through which the crew would easily locate the materials. Once the request to locate items was received; the research team would check its database and find out the corresponding RFID tag attached to those items, then the location of the materials using Google Earth and GPS readings would be obtained, and finally maps showing the location of items along with some adjacent/surrounding items would be printed for use by the crew.

4.6.1 Case Studies

A series of case studies are presented below which show the impact of automated materials tracking and locating technologies on the materials management at the construction site. These case studies represent recorded instances when the sub-contractors would approach the research team working on the automated materials tracking project to provide them with location information about the materials for which they had already searched and were unsuccessful. Unfortunately, many instances were left unrecorded, for various reasons. The information about the materials requested to be located were provided quickly to the sub-contractors on all occasions, and the items were immediately located without further waste of time. These cases are in addition to the snow cover incident.

4.6.1.1 Case Study 1

On August 27, 2007, one of the subcontractors after a manual search requested locating for three of the pipe spools. Two of the pipe spools were for generator Unit 1 and one was for Unit 2. As already explained the research team tagged only pipe spools for Unit 2. The pipe spool for Unit 2 was located through the RFID and GPS data within twenty (20) minutes. It was found that the item was located at the port of Toronto and was not transferred to the construction site. Therefore, after knowing its location, the foreman was able to transfer the pipe spool from the port to the site on the next load of materials. This was a unique spool on the project critical path, that if not found would have had to have been re-fabricated, which would have resulted in fabrications cost, crew delays costs, and most importantly, project delay costs.

It is important to mention here that the crew of at least two workers had already spent more than half a day in the search of these items, before they reported the situation to their foreman. The foreman redirected additional crew members to search for the items before requesting the research team to locate the materials. Further, the cost of redirecting other crew to other work tasks should also be taken into consideration.

4.6.1.2 Case Study 2

The same subcontractor as in case study 1 requested to locate one Unit 2 pipe spool on the morning of August 31, 2007. After checking the database of the automated materials tracking system, it was again found that the specific pipe spool was located at the port. Therefore the contractor was able to transfer the pipe spool to the site on the afternoon of the same day. In this case, the contractor was not required to invest any additional resources in locating the required pipe spool. This is a direct savings as compared to the expenditure of resources outlined in Case Study 1

4.6.1.3 Case Study 3

On September 20, 2007, five pipe spools were requested to be located for a contractor. Two pipe spools were for Unit 1 and three spools were for Unit 2. The automated materials tracking database was checked and two of the three pipe spools belonging to Unit 2 were identified and located through RFID and GPS data. It was found that the third spool for Unit 2 was not previously identified and tagged. Location maps were provided to the materials manager of the contractor.

The materials manager was asked about the feedback on a number of issues related to materials identification, search times, and location maps. Following is the feedback received from the materials manager:

- Approximately 15 – 30 minutes had been spent searching for each pipe spool (1.25 hrs– 2.5 hrs in total).
- The tagged pipe spools were able to be located within 5 minutes with the information provided.
- The untagged pipe spools (Unit 1) were able to be located within 10 minutes given that similar pipe spools for Units 1 & 2 are located in close proximity to each other.
- It was felt that the location information provided (e.g. maps) was accurate.
- The pipe spools were located within a 3m (10ft) radius of the map location indicated.

4.6.1.4 Case Study 4

On October 12, 2007, two pipe spools were requested to be located one each for Unit 1 and Unit 2, by the same contractor as in case study 3. Location maps showing the identification and location of the pipe spool for Unit 2 were provided to the contractor within ten minutes of the initial request.

The item was retrieved within five minutes using the information provided. It is important to note here that the item was a short spool, which was present inside a wooden crate and was covered by other materials from all sides. The other pipe spool belonging to Unit 1 was also located easily when the location maps were provided, because it was also located in the same crate. It is a common practice to store similar items in the same areas. The accuracy of the retrieval map was within three meters radius of the actual location.

4.6.1.5 Case Study 5

On April 18, 2008, the contractor working on the prefabricated pipe spools for Area 5, Unit 1, Drain Piping requested to locate six spools. It is important to mention here that these pipe spools were tagged at the fabrication shop before their arrival at PEC site. Drawings were generated for the contractor showing the location of these spools. It took only six minutes to locate the items through the automated materials tracking system. The foreman of the contractor informed us that this instance had saved at least 3 man hours for their firm. This time could have been more if the spools were not tagged at the fabrication shop and the foreman not confident that he can identify and track the materials automatically.

4.6.1.6 Case Study 6

On April 24, 2008, again the same contractor working on the prefabricated pipe spools already tagged at the fabrication shop requested for the drawings to locate two spools. The intern student working on the site checked the database in the office and generated maps which showed the locations of the pipe spools. The contractor’s crew took only three minutes to locate these spools. Their foreman reported that it had saved at least two man hours required for searching these materials.

4.6.1.7 Case Study 7

A request to locate two pipe spools was received from the contractor on April 28, 2008. When the record was checked by the intern student working on the automated materials tracking system, it was found that these two pipe spools were already issued and relocated to the installation area. These spools were also tagged at the fabrication shop. Therefore, the crew did not need to look for them in the lay down yard. Thus, another incident was avoided which would have caused a considerable amount of time searching for materials that was considered temporarily misplaced or lost.

This case study also demonstrates the performance of the automated system in the supply chain of the construction materials. These pipe spools were tagged at the fabrication shop. Their identification and location information was automatically recorded when these spools arrived at the construction site. Later on, their movement from the storage yard to the installation areas was also recorded automatically and their position estimates were updated in the office database.

Table 4.1 provides summary of the times spent on locating the pipe spools in case studies by workers of the contractors without using the automated materials locating system and time required locating the same spools using the automated system. The table illustrates the benefits of the automated system in terms of time savings in locating materials.

It becomes also clear by comparing the time difference in locating components in case study 1 with later case studies that the foremen realized the benefits of using the automated materials identification and tracking system. The foremen would not spend as much time on locating components as in the earlier cases, and would ask for the location maps after spending a few hours on manual search.

Table 4.1: Summary of time spent on locating pipe spools

Case Study No.	**Time spent on locating components without using automated system**	**Time spent on locating components using automated system**
Case Study 1	18 hrs	20 min
Case Study 2	The spool was present at port. Workers time was saved from searching on site.	05 min
Case Study 3	2 hrs	05 min
Case Study 4	1 hr	05 min
Case Study 5	3 hrs	06 min
Case Study 6	2 hrs	03 min
Case Study 7	The spools were issued for installation. Time was saved from searching in lay down area.	03 min

4.6.2 Cost Savings of Locating Temporarily Lost Materials

Based on the case studies described above and discussions with the materials managers, crew foremen, and project staff the following typical cost savings analysis is made for those materials which were lost temporarily (Table 4.2).

Table 4.2: Cost savings of locating temporarily lost materials

A-	Two workers searching for five (05) hours = 2×5×125 (rate/hour) = $1,250
B-	Cost of redirecting remaining crew members, eight (08) hours = 8×125 = $1,000
C-	Avoidance of expected further search and further disruptions, 16 hours = $2,000
D-	Risk of reordering the materials = $1,000
E-	Total cost for locating temporarily lost items (adding all of the above) = **$5,250**

In the above table, the cost savings in avoidance of expected further search and further disruptions has been assumed as equal to sixteen hours of crew work. This has been based on discussions with the materials managers at site keeping in view how much extra time would have been spent and inefficiencies caused on remaining crew because of imbalances due to absence of materials and workers. To estimate costs avoided due to reduced risk of reordering the lost materials from using the automated technology, we considered a typical scenario. Suppose that some components were lost which had an impact of $5000 on the cost of the project. This impact includes the price and the transportation charges associated with the components. These would be more than the normal costs, because the components would be expedited in order to avoid delays to the project. The impact also includes the costs associated to do the paper work, reissue purchase order, and make changes to the project management and contract documents.

A way of estimating the savings associated with reduced risk of lost materials is to take into account the percentage of reordering the materials on typical industrial projects. In a typical industrial project, there is a 1-2% probability of reordering materials due to lost items.

It was also recorded at the Rockdale site that approximately 10% of the components were not found immediately without using the automated system and 0.54% components were not found immediately using the automated system. It is assumed that items which need to be reordered will fall within this subset of the site's materials. The cost of a failure to locate a critical item at the right time in the project schedule can cause serious problems and even reprocurement. Therefore, it is assumed that the savings in the risk of reordering the materials should be based on the percentage of reordering the materials to the percentage of the materials not found immediately. The probability of reordering without automated system is 2% and with the automated system is assumed at 0.2%. Therefore in this case,

$$\text{Risk}_{\text{without system}} = \left(\frac{2\%}{10\%} \times \$5{,}000\right) = \$1{,}000$$

$$\text{Risk}_{\text{with system}} = \left(\frac{0.2\%}{10\%} \times \$5{,}000\right) = \$100$$

$$\text{Estimates savings} = \$900$$

However, the estimated cost savings in the risk of reordering the materials was rounded off to $1,000 in discussions with the members of the research team.

The analysis made, represents the worst case scenario. However, in normal circumstances, the savings in the form of cost avoidance would still be in the range of $2,000 to $3,000 per materials locating instance.

In summary, the automated materials tracking system was successfully prototyped for an extremely limited deployment of less than 400 tags at the field trials at the Portlands Energy Centre project. Over 10,000 items would have been tagged in a full scale deployment on a project of this size, with no more labor requirements and probably a net decrease given expected reduced work loads for materials management personnel. The following performance measures were achieved regarding the automated process/system prototype experiment.

- Successful in terms of automatic data collection
- Successful in the identification and tracking of materials
- Flexible and user friendly in the field operations
- Gave materials location accuracy within 5 meters radius
- 90% of the RFID tags survived the construction environment
- Helped in reducing the searching times of materials
- Provided a certainty to the field crew foremen in terms of materials location
- Helped in the short term work planning
- One general foreman was able to reduce initial crew size from 18 to 12 workers knowing that he would not have to allocate resources for locating and tracking materials
- Each location and retrieval of temporarily lost materials saved the project approximately between $4,000 to $5,000

Overall, performance of the system was extremely good in terms of materials identification and locating. Also, tracking of materials in the supply chain from the port and fabrication shop to the construction site and subsequent movements on the construction site was effectively captured by the system. The overall feedback received from the materials managers was very positive. According to the materials manager, automated materials tracking is a very good technology that could potentially save a significant amount of labor work-hours for locating and inventory-updating purposes. The general foreman opinion was that knowing which components are available for installation and their respective locations could be extremely helpful for planning purposes and allow for a more intensive focus on installation rather than on materials availability issues. Site workers repeatedly suggested tagging all the components in the lay down yard so that they could rapidly and confidently locate them and thus avoid site-wide types of searches.

As a result, the main contractor SNC-Lavalin has decided to implement the automated system on several upcoming projects (ENR 2008).

4.7 Rockdale Field Trials

These partner field trials were held at the Sandow Steam Electric Station Unit 5 project in Rockdale, Texas, USA. Bechtel was the contractor and Luminant Energy (formerly TXU) is the owner. The power plant project is a 565 megawatt circulating fluidized bed, lignite-fired power plant, which incorporates state of the art emissions control technologies and consists of 2 boilers, 2 bag houses, 1 stack, and 1 turbine. The project has two almost identical steel structures to support the steam generation processes. Both structures were composed of approximately 4,800 steel components and were divided in very similar sequences of installation. Each boiler structure (Figure 4.18) had its own assigned cranes, equipment, foreman, and installation crews. The field trials were conducted from August 1, 2007 to October 19, 2007.

Figure 4.18: Boiler structure, Rockdale, Texas, USA

The job site was divided into two main areas for the purpose of this study: the lay down yard and the installation area. The lay down yard stored the structural steel components in an area of 25 acres, while the installation area held the components retrieved from the lay down yard before their installation. The installation area was small and crowded with materials, equipment, and workers.

The same basic automated materials identification and tracking technology was used as described in the field trials at PEC, Toronto, with some minor variations. Materials were tagged with active RIFD tags on their arrival at the lay down yards, their position and location were estimated via GPS enabled reader's data, and maps/drawings were printed for crews to identify and locate materials.

4.7.1 Results of Rockdale Field Trials

Components of one boiler were tracked with the automated materials identification and locating system and the components of other boiler with the conventional materials locating process. For both boilers, 400 components from similar installation sequences were tracked during the trials and their respective productivity records were collected. Following are the results of these trials (CII 2008; ENR 2008):

- The average time required by labor for locating a component through the manual tracking approach was 36.8 minutes, whereas, to locate a component using the automated tracking system took only 4.6 minutes. This difference in labor times was statistically significant.
- The number of components not immediately found in the lay down yard was reduced by a ratio of 18 to 1 when using the automated process. This shows a percentage improvement from 9.52% to 0.54% in terms of components that were not immediately found.
- 19% of the tagged components were moved to a different location in the lay down yard more than one time during the two and a half months trial. This reinforced the perception that automated materials tracking could improve craft productivity and minimize the number of components not immediately found.
- In the installation area, the productivity rate associated with steel erection tasks was improved by 4.2% when using the automated process. This productivity data is based on the work hours required to unload, store, identify, and erect steel components in

the installation area. It does not include the effort needed to plumb, align, paint, and inspect these components because these activities remained unaffected by the way components were tracked.

Overall, these differences in productivity indicated that the automated process potentially improved the craft productivity of the activities involved.

Chapter 5

Proposed Implementation Process for Automated Materials Tracking

5.1 Introduction

As explained in the introduction and literature review in the first and second chapters, various research efforts have been conducted during the last 10-15 years to automate the identification, tracking, and locating of construction materials. Recent research including the project on which this thesis is mostly focused has also provided evidence that automating the tracking and locating of construction materials can increase productivity and cost efficiency besides improving the scheduling, number of lost items, route and site optimization, and improved data entry.

However, the research conducted so far has focused on automatic tracking and locating of only selected types of construction materials such as precast concrete components, fabricated pipe spools, valves, and tools. Moreover, these research efforts have been directed towards the utilization of a specific automation technology for certain specific scenarios, such as the use of bar codes, stand alone RFID, stand alone GPS and others for their specific usage in storage yards, materials management systems, job sites, and supply chain. The research presented in this thesis develops an implementation model for automated materials tracking. While deployment architectures and costs and benefits have been defined, an implementation process or procedure is required to complete the model. The process should suggest a methodology, principles, criteria, etc., for determining what type of technology combination and architecture should be used in different types of projects for different construction materials and equipment. The following process has been developed as a result of a synthesis and analysis of the literature review, the development of field deployment architectures for automated materials tracking and locating systems, and the extensive field trials at the Portlands Energy Centre, Toronto and Rockdale, Texas.

5.2 Process Overview

The process is illustrated in Figure 5.1. It starts with identifying the needs for the automated materials tracking. After the needs have been determined, the next step in the process is the project definition, followed by the generation and weighting of criteria for evaluating the design, the development of implementation options (alternative designs and configurations), evaluation of the options, deployment of the automated system, and then finally the measurement and evaluation of the implemented system for feedback and knowledge to guide the next implementation effort.

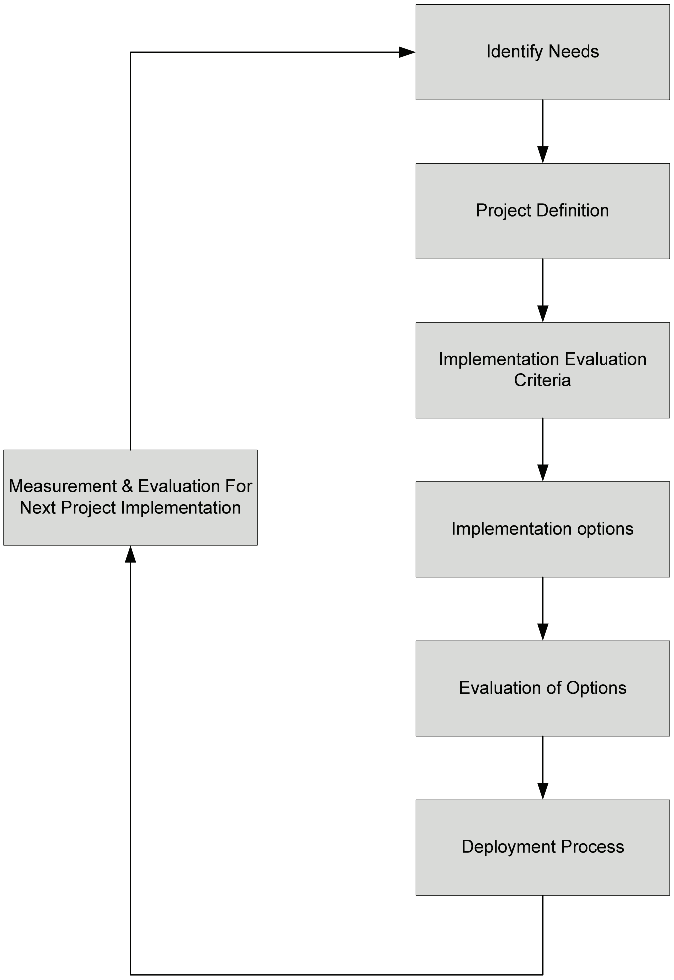


Figure 5.1: Implementation process for automated materials tracking

Typically a company would specify and implement an automated materials tracking system for each major project or for each maintenance program, thus the process described here is focused on project level implementation. For a few of the largest and most sophisticated constructors, corporate level information system integration will also be necessary, but discussion of this is outside the scope of this thesis, because the top ten North American constructors have unique information systems. Each step in the process is explained in detail in the following sections.

5.3 Identifying the Need for Automated Materials Tracking

The first step in the automated materials tracking model is to identify the needs for automated tracking. As explained previously, materials management is the key to the successful management of construction projects. There are certain types of projects which need extra efforts in the materials tracking process. Some of the examples of projects which would require an automated materials tracking system for their successful materials management are:

- Projects which involve a large number of high value engineered materials items (typically, more than 5,000).
- Projects which require unique materials.
- Projects which have a complex materials supply chain.
- Projects where the materials are difficult to track or locate due to environmental conditions such as snow, jungle, vegetation, or sand which might cover the materials during the implementation of the project.
- Projects which have large and scattered warehouse facilities, lay down yards, and staging areas.
- Projects which anticipate frequent movements of materials in the lay down yards or construction site, despite the fact that repeat handling is avoided if at all possible.

Naturally, these types of needs are mostly associated with large industrial projects and mining projects. Early adoption decisions by leading contractors and owners that have occurred while this thesis was being completed, have in fact all included industrial and mining projects.

5.4 Automated Materials Tracking Implementation Project Definition

The materials management plan should fit within the framework of the overall project plan and take into consideration the limitations, constraints, and overall project strategies. The materials management plan cannot be developed without knowing certain basic information about the project itself. General project information and parameters such as project type, size and location are required to define and develop the overall project plan. People responsible for materials management should be identified at this planning stage and should be actively involved in the development of different project strategies (CII, 1999).

A basic description of the facilities to be constructed is required in the initial stages of the project. Information about the major equipment, main buildings/structures, major piping and electrical systems, is essential for determining the quantities of engineered and bulk materials. Similarly the project location provides information about the site access planning, extent of preassembly and modularization, mode of transport, method of storage and disposal of materials, and local environment and climate conditions. Actual jobsite conditions also provide important information such as access to site, total area available for storage, conditions and layout of site roads. Having information about these project characteristics is essential for the planning and design of an efficient automated materials tracking system.

The characteristics of the project that are important to be considered for implementing an automated materials tracking system include: quantity of items to be located or tracked (i.e., a hundred items compared to thousands of items); number of types of different materials; number of items expected to be located per day; frequency of locating required; supply chain of the materials or network morphology; project governance boundaries and conditions; and site layout.

The role of subcontractors in the procurement of materials should be clearly defined. Subcontractors may be significantly involved in procurement or be responsible directly for fabrication of engineered components such as pipe spools. In such cases, appropriate contract language would need to be drafted requiring them to tag and track items in their chain of responsibility, and specifications for automated system components would have to be transmitted to them with appropriate lead time.

Automated materials tracking is for a select subset of materials in the overall materials management system. Some types of materials need more advanced and costly technology to be applied to them for their automated tracking and some need less advanced and less costly technology. Deciding what level of cost and sophistication is appropriate for each type of material depends on their strategic importance to the project, cost and lead times involved in their procurement. Table 5.1 lists the types of materials, and the recommended technology for their automated tracking. These recommendations are based on the preceding analyses and the consensus of the industry members of the CII Research Team 240 who are experts in materials management. Subsequent cost benefit analyses tend to reinforce these basic recommendations.

Table 5.1: Materials Types and Recommended Technologies for Automated Tracking

Types of materials	Examples	Cost Range	Technology recommended	Cost (approximately)
Strategic assets	Tanks, heat exchangers, pumps, turbines, major instrumentation systems.	High	GPS and sensor enabled tags	$1,000/tag
Critical items	Minor instrumentation items, transmitters, specialty items	Medium	Active RFID tags with GPS enabled readers	$20/tag
Common but valuable items	Structural steel, pipe spools, valves, ladders/platforms.	Low/Medium	Active/Passive RFID tags	$2-20/tag
Bulk materials	Pipes lengths, fittings, conduits, cables	Low	Bar codes	$0.10/label

The reasons and needs for automated materials tracking have been explained in Section 5.3. The use of automated materials tracking technology based on RFID and GPS should generally be considered for industrial projects which involve a large number of engineered materials. For general construction sites, such as buildings, parking garages and bridges etc., this automated materials tracking system may not be suitable due to certain reasons. The most important reason for not using the automated materials tracking system on general construction sites is that the materials on these sites are not moved frequently. These projects are repetitive in nature and have well defined materials supply chains, and small and well defined warehouses/lay down yards. The materials used in these projects tend not to be unique and easily identifiable. If certain materials on these general construction sites require tracking due to certain reasons, they can also be identified and tracked in the same manner as the engineered materials on industrial projects. However, the reader when operating on floors of a high rise, for example, would have to be location referenced with some system other than GPS, because GPS works poorly if at all inside structures. For bulk materials on general projects and industrial projects; such as reinforcing steel, post-tensioning hardware, expansion joint materials, railings/barriers, and finished materials such as doors, windows, flooring, etc., the use of bar coding technology is recommended due to its relatively lower cost. The use of bar coding in construction projects has been explained in Section 2.4.1.

5.5 Implementation Evaluation Criteria

After getting all the details about the project for which the automated materials tracking would be applied, the next step in the process is selection of the criteria for evaluating the system design. In this phase of development we have to determine how can the effectiveness or value of an automated materials tracking system be measured? What are the essential attributes/characteristics of a good materials tracking system? Table 5.2 lists the most important evaluation criteria for automated materials tracking systems based on the analysis of the literature, the field trials, and the input of the research team members.

Table 5.2: Evaluation criteria/Characteristics for automated materials tracking system

1	**Accuracy of location estimate** (ideally +/- 5 meters or better)
2	**Reduction in lost items, shrinkage and wastage** (for early implementers this will be based on estimates from other projects and studies)
3	**Reduced time to locate assets** (less time required for locating materials and equipment than manual searching; again, based on estimates from preceding studies)
4	**Improved assets visibility and automation** (the ability of the system to automatically collect information, identify and track the materials with minimum human input and make this information readily and easily available)
5	**Increased service levels with lower inventory carrying costs** (the ability of the system to keep minimum variable inventory such as tags, etc., by reusing them, without compromising the service level and performance of the system)
6	**Robustness with respect to dynamic transmission space** (e.g., fixed Wi-Fi systems must be recalibrated as objects are constructed in the receiver grid space, whereas the technology prototyped at Portlands and Rockdale is not constrained in this way)
7	**Ease of integration** (with other materials and project management systems)
8	**Set-up time and cost** (should take minimal time for initial set up and must have reasonable set-up cost)
9	**Cost of the tracking system** (fixed infrastructure cost such as gates/portals, readers and variable inventory cost such as tags, etc.)
10	**Ability to phase implementation** (the flexibility of the system to be implemented in different phases based on future circumstances)
11	**Ruggedness to harsh construction environment** (ability to work in snow, dirt, sand, and vegetation; ability to work in the presence of metals; ability to work in extreme temperatures, corrosive environments, and moisture)
12	**Interfaces** (internet, communications, user friendly and easy interfaces for system operations)
13	**Fast invoicing** (the ability of the system to generate quick reports on the status of the materials received, issued, and installed)

Further, the automated materials management and tracking system should have the minimum or no human input involved in order to be considered truly automatic and at the same time reduces/minimizes the errors/problems associated with the human role.

5.6 Implementation Options/Alternatives

In this part of the process, implementation options which are available for using as an automated materials tracking system are generated. Different options or alternative design configurations should be considered. These options and alternatives should be considered in respect of the various automated materials tracking technologies and system architectures discussed in Section 3.6 of this thesis. The implementation options can include the use of any of the automated data collection and identification technologies such as bar codes, RFID, GPS or an integration/combination of any of these technologies. Section 3.6 defines the most advanced options for the field deployment of an automated materials tracking system. These automated tracking architectures include: (1) mobile reader system; (2) fixed reader system; and (3) gates or portal system. The development of options depends on the specific requirements of the projects, the materials to be tracked and managed, the cost of the automated tracking system, the morphology of the materials supply network, and the expected performance of the automated system.

The level of automation and sophistication such as bar codes only, active or passive RFID tags, GPS, or combination of these have been provided for different types of materials in table 5.1. Similarly the advantages, disadvantages and associated costs of different automated materials tracking field deployments options have been explained in section 3.6.

5.7 Evaluation of Options

When different implementation options of the automated materials tracking system are identified, the next process in the implementation process is the evaluation of these options. These options will be evaluated against the criteria described in Table 5.2 and Section 5.5 (implementation evaluation criteria) of the process above. The advantages and disadvantages of each system option can be characterized or scored for each criteria. The criteria may also be weighted using a rigorous method such as the analytical hierarchy process (AHP), and final option scores can be calculated based on totals of weighted criteria scores for each option. This is a standard approach, but the effort involved should be considered when weighing whether a table of characteristics of each option with respect to each criteria would be more appropriate.

A cost-benefit analysis should also be carried out. The fixed and variable cost of the system should be compared with the benefits that are expected to be provided by the system. These benefits can be direct benefits such as the number of man hours reduced for locating materials and reduction in lost labor hours due to otherwise delayed materials locating. The indirect benefits such as increase in productivity should also be considered. Estimates of indirect benefits and costs avoided may be based on simple risk analyses as described in the following section. Elements of the economic analysis include:

- Estimating the savings per standard locate reduced duration.
- Estimating the savings per temporary loss avoided.
- Estimating the savings per total loss and re-procurement avoided.
- Estimating benefits of expected improved productivity
- Total estimated cost for the system.
- Benefit/Cost ratio.

Besides the above economic analysis, certain strategic analyses should also be considered such as repeatability or reuse of the design elements (once the initial investment is made, how much could be used again on future projects). For example the bar codes can be used for one time only, whereas the RFID tags are reusable. The life of RFID tags, the purchase of software or per year usage charges etc. should also be considered while evaluating the options.

In the remainder of this section, an example of an analysis based on the preceding principles is presented with a typical industrial project such as Portlands or Rockdale in mind. Time value of money is not considered because of the project level planning horizon for the process described in this chapter. A benefit/cost analysis for a typical industrial project is presented in Table 5.3. This table provides the costs of active RFID tags, antennas, readers, GPS units, handheld PCs, and software required for the system. The costs are based on current average prices. It is assumed that the duration of the project will be 500 days and the project will be an industrial one which involves thousands of high value engineered materials items such as spools, valves, steel members, turbines, and pumps etc. The project has vast scattered lay down yards, where the materials are frequently moved around before their final installation.

Three different scenarios are considered; scenario 1 being the least favourable situation where the least number of critical items are tagged, and the least expected number of materials' locates are made per day, whereas scenario 3 represents the most favourable situation where the highest number of critical items are attached with tags and the expected number of locates per day is highest. The time saved per locate of items is based on the experience gained in the field trials at Portlands Energy Centre, Toronto, and Rockdale, Texas.

The benefit cost ratios calculated as shown in Table 5.3 are without considering benefits of improved productivity and costs avoided due to reduced risk of lost and re-procured items. The savings or benefits are high compared to the total cost of the system. Therefore, the estimated benefit/cost ratios are also very high from worst to best case scenarios. Even in scenario 1, which is considered the least favourable situation, the B/C ratio suggests implementing the system on the typical project described. It is interesting that anecdotally, one major constructor on CII RT 240 estimated a B/C ratio of between 5/1 and 40/1, so it is possible that remaining benefits need to be considered.

Table 5.3: **Benefit Cost Model for RFID/GPS based automated materials tracking system**

	Scenario 1	**Scenario 2**	**Scenario 3**
Variable Cost			
No. of items	5000	10000	15000
No. of tags	5000	10000	15000
Cost per tag	20	20	20
Costs of tags	$100,000	$200,000	$300,000
Total Variable Cost	$100,000	$200,000	$300,000
Fixed Costs			
No. of Readers	2	4	6
Cost per Reader	1500	1500	1500
Cost of Readers	$3,000	$6,000	$9,000
No. of Antennas	2	4	6
Cost per Antenna	1500	1500	1500
Cost of Antennas	$3,000	$6,000	$9,000
No. of GPS units	2	4	6
Cost per GPS unit	2000	2000	2000
Cost of GPS units	$4,000	$8,000	$12,000
No. of handheld PC	2	4	6
Cost per PC	1500	1500	1500
Cost of handheld PCs	$3,000	$6,000	$9,000
Software and Vendor Profit	$100,000	$100,000	$100,000
Total Fixed Cost	$113,000	$126,000	$139,000
Total Costs	$213,000	$326,000	$439,000
Benefits			
Standard Locating			
No. of locates/day	50	150	300
Time saved per locate (hrs)	0.5	0.5	0.5
Cost of labor per hour in dollars	100	100	100
Project Duration (days)	500	500	500
Savings/Benefits for standard locates	$1,250,000	$3,750,000	$7,500,000
Benefit/Cost Ratio	**5.9/1.0**	**11.5/1.0**	**17.1/1.0**

The analysis presented above, so far did not consider the risks and costs avoided associated with reducing the number of permanently lost materials, if a project is run with the automated system. These analyses are presented below. The benefits of reusing the tags and system on future projects have not been estimated because of lack of data on long term reliability at this point. It is also possible that this technology will require reduced materials management staff on the project.

To estimate costs avoided due to reduced risk of lost materials from using the technology, a worst case scenario is considered. Suppose that 6 valves were lost which required re-procurement on an urgent basis, because they were critical path items. This is typical on a large project. Each valve costs $5,000 plus $10,000 transportation charges to re-procure. The project is delayed by two weeks due to missing critical path items. The contractor has to pay $50,000 per day as liquidated damages due to project delay. The estimated risk and savings in this case are as follows:

$$\text{Risk} = \text{Probability} \times \text{Impact}$$

$$\text{Impact} = 6\times(5{,}000+10{,}000)+(50{,}000\times 14)=\$790{,}000$$

From experience and consultation with the industry experts (Murray 2007), we assume that the probability of one of these situations on a project without the automated materials tracking system is 50%, and the probability of loosing the critical items with the automated system is 5%. This is conservative, according to the industry experts (Murray 2007).

$$\text{Risk}_{\text{Without system}} = (50\%)\times\$790{,}000=\$395{,}000$$

$$\text{Risk}_{\text{With system}} = (5\%)\times\$790{,}000=\$39{,}500$$

$$\text{Estimated Savings} = \$395{,}000-\$39{,}500=\$355{,}500$$

These estimated savings of $355,500 in the form of costs avoided are in addition to the savings made in locating the materials in everyday operations of the project as shown in

Table 5.3. If this cost saving is added to the benefits of Table 5.3, the B/C ratio and the total savings estimated would increase further. Therefore, the automated materials tracking system based on the integration of RFID and GPS is highly recommended for use on the typical industrial project specified in this hypothetical estimate.

The cost of the automated materials tracking system, its flexibility and scalability, accuracy, assets identification and automation ability, time to locate and track assets and integration with other materials management system are some of the important factors to be considered in evaluating the design option for automated materials tracking. The final selection of the design option would be made considering the: (1) criteria described in Table 5.2, (2) benefit/cost analysis, and (3) risk analysis.

5.8 Deployment of the Automated Materials Tracking System

This step of the implementation process involves the actual deployment of the automated materials tracking system into the construction environment. The deployment process consists of the procurement process and the mobilization process.

5.8.1 Procurement Process

This is the first phase of the automated materials implementation system. The procurement process starts with identifying the purchasing responsibility. It should be defined who will be responsible for purchasing of the automated materials tracking system. Usually the home office of the owner, or in some cases the main contractor, should be made responsible for this job. The field site office role should be clearly defined in the procurement process. The next step is the making of an Approved Suppliers List (APL). Potential suppliers/vendors of the automated materials tracking technologies and related components should be identified. The suppliers should be selected on the basis of their past experience, technical expertise, financial position, and market reputation. However, the most important factor in selecting the supplier should be the performance rating of their automated materials tracking system in terms of lay down yard set up, receiving materials, moving materials, lay down yard status (reports and snapshots), issuing materials, software, and hardware technology effectiveness compared to other vendors. A formal agreement should be signed with the suppliers indicating all the terms and conditions and specifying all the procedures and responsibilities of each party.

The hardware, software, infrastructure requirements and usable materials involved in the automated materials tracking system should be preferably obtained from a single supplier. This would potentially reduce the conflicts which may arise later due to the unsatisfactory working of the different components of the automated system. This is particularly important in the case of the RFID component, which does not operate if RFID tags and readers are not synchronized or if they are obtained from different suppliers.

5.8.2 Mobilization

In this step of the deployment process, the installation of the automated materials tracking system components takes place. The different automated materials tracking technologies discussed in Chapter 2 and their related fixed infrastructure setup required are put in place in the construction site/environment. This means an integrated system of automated tracking technologies is installed or put in place at the construction site. Similarly, the necessary training required for the construction personnel to successfully and efficiently implement and run the automated system should be provided. The operations and maintenance of the automated system should be carried out effectively in a manner that it should run the operations smoothly without disturbing the construction activities going on the site. Periodic maintenance activities need to be planned so that there is no disruption of the automated materials tracking process. The system should be readily available at all the times. This can be achieved by keeping the necessary back up/spares of all the Automated Data Collection (ADC) technologies, their hardware and software requirements fulfilled and updated.

5.9 Measurement and Evaluation for Next Project Implementation

The last and one of the most important steps in the process is the measurement and evaluation of the automated materials tracking system for the next project implementation. The performance should be measured and evaluated against other projects which have implemented automated materials tracking systems. If no such data exists, the performance should be compared with the traditional materials management systems. The actual performance should be compared against the expected targets.

This measurement and evaluation should be a continuous process, which would allow making improvements to the system. The measurement and evaluation process should point out if there are any shortcomings in the expected results of the automated system implementation. If the system does not yield the performance which was expected of it, or it does not produce optimum results, then it needs to be evaluated for the reasons. This measurement and evaluation against the desired goals and expected results will help in suggesting the corrective steps to be undertaken for the improvement of the automated tracking system. It will help in the effective implementation of the system in following projects. The measurement and evaluation of the system should be a continuous and ongoing process.

5.10 Typical or Generalized RFID/GPS Based Automated Materials Tracking Process

The schematic representation of a typical RFID/GPS based automated material tracking process is shown in Figure 5.2. The process is implemented by combining the portals and mobile readers field deployment architectures as explained in Sections 3.6. The portals would be installed for receiving materials, while mobile readers would be deployed throughout the lay down and staging areas. The process is almost similar to that which was prototyped at the Portlands and Rockdale site for automated materials tracking, and explained in detail in Section 4.4; except that portals are used for receiving materials in addition to the mobile readers field deployment.

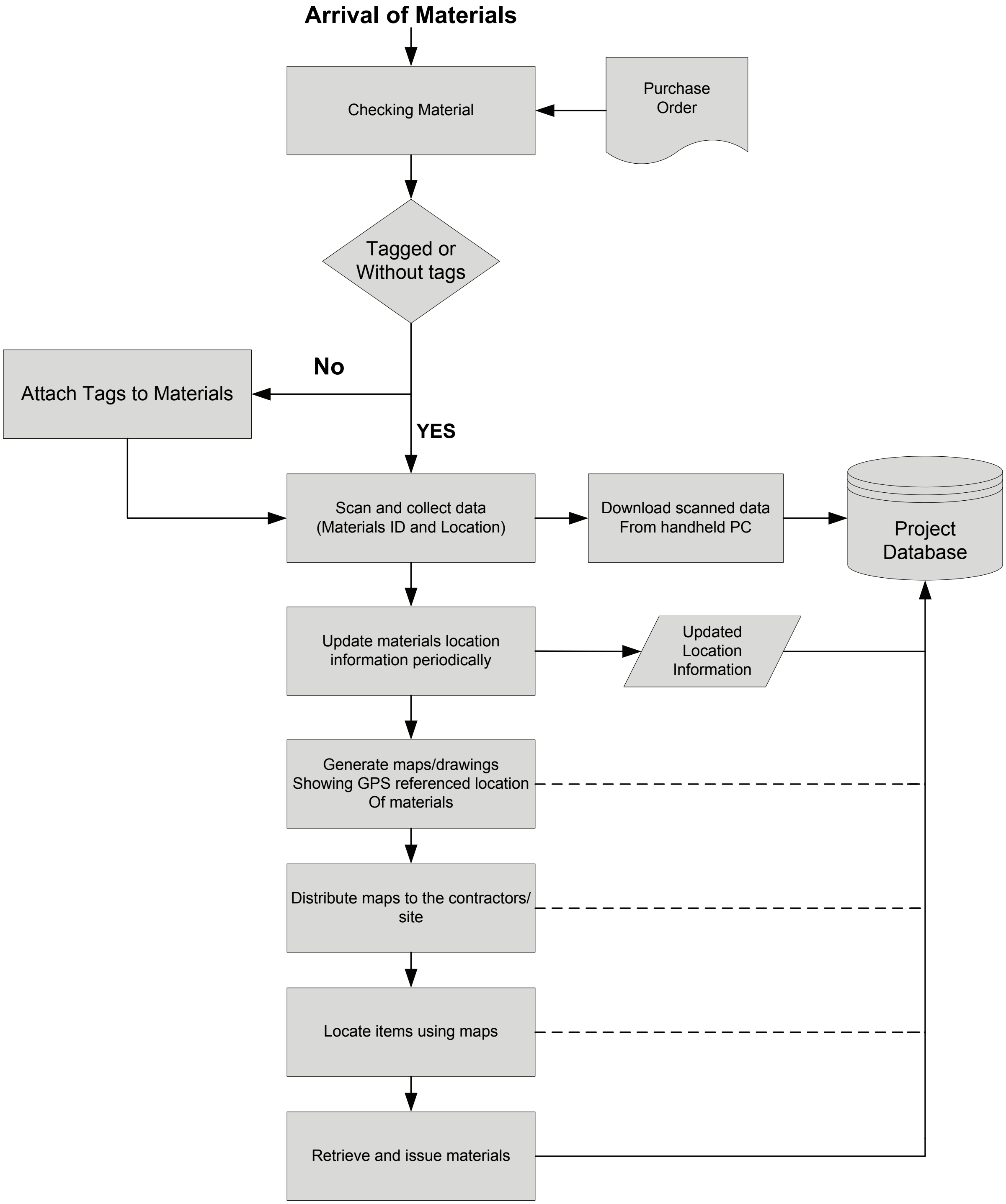


Figure 5.2: RFID/GPS based automated materials tracking process

The process starts by attaching RFID tags to the materials required to be identified and tracked in the supply chain. The tags can be attached to the materials either at the manufacturers' location before shipping the materials to the site, or they can be attached to the materials when they arrive at lay down yards at the construction site. If the materials arrive at site with RFID tags already attached, they are automatically identified by the reader when they pass through the gate or portal with fixed reader installed to them. The materials receiving status report includes the unique identification of the materials, the RFID tag number attached to items, the date and time of materials arrival. Their proposed location or storage information is automatically updated in the project database.

If the materials arrive at site without tags, they are off loaded at their specified lay down yards and warehouse areas. The RFID tags are attached to the materials, and their unique identification number from the shipment list or purchase order and their corresponding RFID tag number are recorded. The materials are scanned by the crew while walking around the materials in a lay down yard or moving in a vehicle (possibly the materials handling vehicles) and their identification information and position is logged by the PDA or handheld PC equipped with the RFID reader, antenna and the blue tooth enabled GPS. As the tags come into the reading range of the reader, they are identified by the reader a large number of times and their GPS referenced reads are stored in the handheld PC. After the initial data is logged, the information recorded in the handheld PC is transferred to the computers in the warehouse and the location of tagged materials is estimated using the algorithms or software provided by the commercial vendors, and the project database is updated with the materials information including their location.

After recording the initial locations of the materials, their position is periodically recorded in the lay down yards using the handheld PC and GPS, once or twice a day depending on the site operations and movement of the materials. The data from the handheld is downloaded again and the project database is continuously updated with the new information. Once the positions of the materials become known, they are graphically represented by generating maps using Google Earth and AutoCAD drawings or other format convenient to workers. These drawings or maps are then provided to the contractors. The crew workers use these maps in identifying and tracking the materials in the lay down yards

When the materials required for installation are identified and retrieved, they are issued to the subcontractors and their information recorded. When the materials are finally ready to be installed into the facility and it is confirmed that they will not be moved around further, the RFID tags attached to them are removed. The tags are returned back to the warehouse office, and the materials list and the database is updated with the removed tags. The tags collected could be used for other materials as they arrive on site.

Chapter 6

Conclusions and Future Research Recommendations

6.1 Summary

The main objective of the research was to propose an implementation model for automated materials tracking and locating. A comprehensive literature review was made; and the past research on the benefits of materials management in construction, the use of the ADC technologies in construction and their potential benefits explained. The materials tracking process, and various ADC technologies which can be used in materials identification, tracking, and locating were described and their advantages and disadvantages explained. The attributes and characteristics required for an efficient automated materials tracking system were defined. New field deployment architectures for RFID/GPS based systems were defined. Large scale field trials were conducted on an industrial construction site, where the RFID and GPS based automated materials tracking system was prototyped and experiments were conducted.

Based on a synthesis and analysis of the literature and field trials at the Portlands Energy Centre, Toronto, and Rockdale, Texas, US, a generic process model for the implementation of the automated materials tracking was developed. The general process model consists of seven sequential stages: (1) identify needs, (2) define project, (3) establish implementation evaluation criteria, (4) develop implementation options, (5) evaluate options, (6) implement process and (7) measure and evaluate for the next project.

6.2 Conclusions

The following are the main conclusions of this research.

- The model developed in this thesis was successfully implemented on two large construction sites.

- The automated materials tracking system was found feasible and can be successfully applied on future construction projects.
- The integrated, automated materials tracking system consisting of active RFID tags, reader, GPS and handheld PC was able to collect data about the materials with reasonable accuracy, identify and track materials, and locate materials in the supply chain.
- The automated system can be integrated with the project information technology systems and materials management processes. A commercial firm has begun this process.

Besides the above specific conclusions derived from this research, the following conclusions can also be inferred from this research based on the field trials and discussions with the materials managers in the construction industry.

- The automated process is faster, more accurate and less liable to suffer from transmission and transcription errors than manual reporting.
- It assists the managers in making informed decisions. The managers and crews know dynamically what's happening with the materials and therefore will be in better control.
- It reduces the total cost of the project by reducing the number of lost items and wastage of materials. The project risks are reduced when materials are visible, traceable, and controllable.
- The automated system ensured the availability of the right materials at the right time. This helped the materials managers and crew foremen in making short term and crew-level work planning decisions based on real time information of materials locations.
- The system potentially facilitates the just-in-time delivery concept, and potentially reduces multiple materials moves.

Three of the top ten North American construction companies have chosen to implement the technology on upcoming mega-projects in North America and Africa.

6.3 Contributions

The following are the main contributions of this research:

- Participated in and contributed to significant field trials of a new technology.
- Proposed a model for automated construction materials tracking, primarily for industrial projects. The model suggests principles, implementation evaluation criteria, implementation options, evaluations of options, and an implementation process.
- Defined new architectures for the field deployment of an RFID and GPS based materials tracking system. These field deployment options include fixed readers, mobile readers, and gate/portal systems. This research has analyzed their respective advantages and disadvantages for various construction site environments. The mobile readers system for automated materials tracking was successfully implemented on a large industrial project.

6.4 Recommendations and Future Research

This thesis presented a general model for automated materials tracking. However, there are still many areas which need improvement for successful materials management. Following are some of the recommendations and suggested areas for future research.

- The construction industry is largely fragmented. Different stake holders have different interests and it is practically impossible to consider a construction project under the control of a single stakeholder. The multi-disciplinary and multi-organizational team consisting of architects, designers, engineers, contractors, manufacturers and suppliers must coordinate and integrate their efforts across different locations of projects and adopt the new and innovative technologies for the materials management and tracking. Implementation guidelines should be developed for achieving this in a practical and efficient manner.

- The majority of the contractors/subcontractors construction firms are small companies, and their employees are not used to the adoption of new and innovative ideas. The construction industry as a whole and these small firms in particular, are hesitant or shy to use new automated technologies for project and materials management. Therefore, the project managers, materials managers, and crew foremen should be trained and motivated for the use of new automated technologies for materials tracking and management. They should be encouraged to attend seminars, workshops, and conferences on the development and use of new and innovative technologies in construction industry.
- There should be a standardization of the automated technologies used in the materials tracking in construction industry as in the case of manufacturing and other industries. The automated technologies and particularly RFID should have standard protocols so that the technologies obtained from different vendors are compatible with each other.
- This research focused on the use of active RFID tags for materials tracking. The use and effectiveness of passive RFID tags should be studied. Due to the relatively low prices of passive RFID tags, this can make the automated materials tracking system more cost effective.
- The combination of bar codes and RFID technologies should also be considered.
- Localization algorithms should be developed for better positional accuracy. They should be able to exploit data from different simple to complex sensor sources, and contextual information to estimate object location for tens of thousands of construction objects at an adequate frequency and in a scalable manner. This should be robust to measurement noise and future advances in technology.
- The RFID tags should be attached to the materials at the manufacturing facilities. This will increase the visibility of the materials through the supply chain. This practice could allow contractors to effectively know which components are arriving at the site and have an automated notice of this event as it happens.

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