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# RFID AND BIM-ENABLED WORKER LOCATION TRACKING TO SUPPORT REAL-TIME BUILDING PROTOCOL CONTROL AND DATA VISUALIZATION

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EDITOR: Rezgui Y.

***Aaron M. Costin, Ph.D. Candidate,***
***School of Civil and Environmental Engineering, Georgia Institute of Technology,***
***Email: info@aaroncostin.com***

***Jochen Teizer, Ph.D.,***
***RAPIDS Construction Safety and Technology Laboratory,***
***Email: jochen@teizer.com***

***Bernd Schoner, Ph.D.,***
***Trimble ThingMagic,***
***Email: bernd.schoner@trimble.com***

***SUMMARY:*** *As construction job sites get larger and more complex, the need to maintain building protocol is becoming more necessary. Having a real-time tracking system for materials, equipment and personnel installed on a job site can help project managers to enhance the security, safety, quality control, worker logistics, and maintain local ordinances of a construction project. In this paper we will present the method of integrating passive Radio Frequency Identification (RFID) and Building Information Modeling (BIM) for real-time tracking of personnel. The purpose of this research is to utilize RFID-BIM integration to generate real-time data to produce leading indicators for building protocol control. Building protocol includes monitoring safety, security, and verification of maintaining the San Francisco Office of Economic and Workforce Development hiring mandate. Hardware components include passive RFID tags, portal RFID readers, fixed turn-style readers, and mobile handheld devices, and a cloud server. The system was deployed on a 900,000 square feet hospital project that consisted of three major buildings, 125 contractors, and 1,200 workers. An algorithm is presented that reduces and organizes the data that the system produces. Linking RFID into industry foundation classes (IFC) has been highlighted. Preliminary results show that the integration of these technologies produces data that is used in real-time resource tracking, data analysis, ordinance compliance, and zone safety violations. Additionally, the system also provided real-time visualization information that can provide a variety of benefits. Significantly, based on experimental analysis, we demonstrate that the RFID and BIM system is a practical and resourceful tool to provide real-time information and location tracking to maintain building protocol control.*

***KEYWORDS:*** *building protocol, building information modeling, data visualization, economic and workforce development, local ordinances, construction logistics, radio frequency identification, safety, tracking, industry foundation classes (IFC)*

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## 1. INTRODUCTION

The safety and security of everyone on site, including workers and visitors, is the utmost importance on any jobsite, regardless of size. However, larger and more complex projects can be more challenging to maintain the highest level of safety and security. For instance, in the event of an emergency, an evacuation, or a lock down, being able to determine the exact number of workers and personnel on site will be critical, and the more people there are the bigger the challenge it is to have every single person account for. Manual recorded keeping of daily personnel and visitors could be potentially be in adequate, and would require much time to account for. Additionally, the monitoring of a large amount of personnel can be tedious and time consuming. On a traditional construction site, options addressing the challenges associated with safety and security are limited. Before, security officers would need to be placed at each entrance zone to verify the authorization and monitor the head count of workers entering. Even with personal identification (ID) badges, a security guard would have to write down who enters, thus limiting the amount of workers that can enter at a time and slowing down the flow of traffic.

Controlling access to hazardous zones of the jobsite is also important to verify only authorized and trained personnel are allowed access. Having an untrained worker enter a hazardous space, such as a high voltage utility room, can lead to serious injury or death. Ensuring workers are properly trained before they are allowed to enter a more stringent building protocol project zone is important. However, it is difficult to monitor who has access to certain zones, even if some workers received proper training. Having a security guard or supervisor at each zone entrance is unfeasible and uneconomical.

Projects may have certain rules or regulations imposed on them by local, state, or federal government entities. Maintaining these rules or regulations is critical to avoid harsh fees or penalties. The San Francisco Office of Economic and Workforce Development (OEWD) mandates that certain government funded projects hire a percentage of local workers by trade (OEWD, 2011). Various protocols were issued to maintain safety, security, and quality of the work throughout the project duration.

About the project: The University of California San Francisco's (UCSF) Medical Center at Mission Bay is a large, public construction project. The project is 900,000 square feet hospital that consists of three major buildings. The completed campus will include:

- UCSF Benioff Children's Hospital at Mission Bay with 183 beds, an urgent care/emergency department, pediatric primary care, and specialty outpatient care;
- The UCSF Women's Specialty Hospital with 36 beds, cancer care, specialty surgery, and birth center;
- UCSF Cancer Hospital at Mission Bay, part of the Helen Diller Family Comprehensive Cancer Center which will house 70 beds and offer inpatient and outpatient surgery for cancer specialties;
- A 207,500-sq.-ft. outpatient building; and
- 36,500-sq.-ft. energy center, helipad, parking and support services.

Large scale projects with a large work force area are expected to contain issues with the sequencing of trades, the safety and security of the site, and quality control. Planning and sequencing of trades throughout this project could potentially be difficult as there will be more than 125 subcontractors, and over 800 workers on the site daily (peak hours will even have close to 1,200 employees on site). Consequently, it is extremely important to be able to monitor all personnel onsite at any given time, especially during the interior build-out of the facility, since the trades (e.g. mechanical, drywall, electrical) will often be overlapping.

Being such a large project, it is critical to monitor and maintain building protocol control, including the San Francisco OEWD mandates. Although the UCSF hospital does not meet the OEWD criteria to follow the ordinance, it is voluntarily doing so to benefit the local community. Therefore, the project utilizes Building Information Modeling (BIM) and an RFID-based building access control system that provides visibility of personnel on the jobsite. The method of integrating Radio Frequency Identification (RFID) and Building Information Modeling (BIM) for real-time tracking of personnel is discussed in this article. The use of this technology creates a more intelligent and automated job site, resulting in numerous observed benefits, which will be discussed in the paper. Additionally, an algorithm is present to filter and manages the data that the system produces.

# 2. LITERATURE REVIEW

## 2.1 Sensing Technologies in Construction

Real-time access to the locations of workers, materials, and equipment has been a significant advancement to the management of construction processes. There have been attempts to automate the analysis and tracking such as mobile tracking in lay down yards. Examples of these attempts include pre-cast concrete, fabricated steel elements, and automated tool tracking. Technology that has been researched to provide real time access include radio frequency identification (RFID) (Song et al, 2006; Ergen et al. 2007; Costin et al. 2012a), ultra wideband (UWB) (Cheng et al. 2011; Yang et al. 2011), and global positioning system (GPS) (Grau et al. 2009; Pradhananga and Teizer 2013), and multiple sensors (Razavi and Haas, 2010). RFID, UWB, and WLAN technology has been shown to be successful in a variety of applications including asset tracking, inventory management, on-site security upgrades, productivity analysis, and identifications of personal protective equipment (Goodrum et al. 2006; Rueppel and Stuebbe, 2008; Li and Becerik-Gerber, 2011; Cheng et al. 2011; Taneja et al. 2012; Kelm et al. 2013). Ultra wideband can be implemented to track and determine the location of resources in a jobsite by utilizing multiple readers to identify the location of tags in (Teizer et al. 2007; Bohn and Teizer, 2010; Cheng et al., 2011). However, UWB requires a careful installation of multiple readers at known locations and cannot be used when the tags are stationary and the reader is mobile. Additionally, RFID implementation with GPS in an outdoor environment led to a 4.2% increment in steel erection productivity (Grau et al. 2009). Several commercial approaches have been in place since then on capital intensive construction projects, mostly using active RFID technology. Pradhananga and Teizer (2013) noted that larger construction assets can be tracked with GPS or in a combined approach with active RFID at reasonable cost and at reasonable accuracy for logistics purposes; however, they do not work well indoors due to signal line-of-sight issues.

Large scale projects require a productive and efficient workforce to stay on schedule and under budget. Maintaining high efficiency and productivity requires the constant monitoring the work force and project. In particular, the status of labor forces is an important area to maintain for completing a project on schedule. A large percentage of construction costs result from the quantity of labor hours spent completing the desired tasks. Thus, by maximizing labor productivity, companies can avoid additional costs due to falling behind schedule. Many factors determine whether workers are able to complete their tasks at the necessary pace including experience, age, skill, motivation, and leadership. Appropriate work conditions can also influence the entire operation, such as project size and complexity, site accessibility, labor availability, equipment use, and local climate (Hendrickson 2009; Lee et al 2008). In order to determine whether the construction process is operating at maximum efficiency or can be adjusted to improve its effectiveness, additional construction improvements can be identified in terms of productivity analysis of work crews, material transport, and the overall approach to a project. However, the monitoring and analysis of labor productivity has mostly been done manually, in which manual analysis have been shown to be time consuming, subjective to judgments and error prone (Ogelsby 1988; Allmon et al. 2000; Goodrum et al. 2006). Integrating technology to automate the monitoring and analyses is a way to reduce the human component and increase accuracy and reliability. Projects with higher automation and integration of information technology improved between 31% and 45% in productivity (Zhai et al. 2009).

## 2.2 Radio Frequency Identification (RFID)

Radio Frequency Identification (RFID) is a method of communication that uses radio waves. The system is composed of a tag, which is read by an RFID Tag reader, and a computer that receives the data from the reader. The tags can be active (battery powered), semi-passive (battery-assisted) or passive (no battery). The transponder and transceiver (reader) gather and transmit the information to a RFID tag wirelessly, without needing to be necessarily in the direct line-of-sight to the tags. First, the reader sends a radio frequency signal to the tag. The tag then sends the signal back to the reader along with any information or data that it may be storing, such as an identification number as each tag can have its own unique identification number. Upon receiving this data/information, the reader sends it to the computer where it is stored and analysed. The information sent to the computer includes items like the time at which the signal was received, what reader received it, the frequency, and received signal strength (RSS). The data is then processed through middleware (e.g. filters, processes, algorithms etc.) in order to make the data useful before being stored. The database in which the information is sent to can be utilized in many ways as the data can be linked to additional information that is stored on the tag. For example, a tag's unique identification number can be linked to further information held in a database that further describes that tag with items like a unit name, trade performed, manufacturer. This information can be made easily accessible to users, such as a project manager, and can utilize queries help to increase productivity and efficiency throughout a project.

This technology is rapidly becoming more capable and complex, helping to track materials, workers, and equipment in real time as well as produce a visual of the locations and resources on a construction site. The use of RFID technology has been found to enhance the user's ability to locate materials that have been tracked by the RFID readers with an improvement ratio of 8:1 over manual tracking (Grau et al., 2009). The enhancement of this technology has led to testing of passive tags. Tests found that passive ultrahigh frequency (UHF) tags are durable enough to work in various harsh conditions, despite the existence of extreme moisture, pH, temperature, and pressure (Ross et al., 2009). This technology, compared to the limited bar code system that requires line-of-sight read range, provides significantly greater read ranges and can be utilized in both outdoor and indoor conditions ranging in temperatures from −40 °C to 200 °C (Ross et al., 2009). Though there are many benefits of passive RFID tags, there is a drawback in that there are no self-reporting capabilities. The read range also is limited to 4 to 10 meters, depending on antenna type. So though this is significantly greater than a bar code system for example, there are still some limitations. The benefit of having a larger readability range, however, is that a single reader can be utilized to read multiple tags within this range (Costin et al., 2012a). This capability is also limited in that environments exposed to either multipath or metal surfaces are at risk of experiencing signal attenuation due to the metal surfaces and the signal bouncing (Vogt and Teizer, 2007).

Resource monitoring and tracking sometimes require systems with high reliability and accuracy to locate assets. Some applications may need pin-point accuracy (within a few centimetres), while others only require general locations (10 meters). There are various algorithm and techniques to improve the accuracy of RFID location tracking. Skibniewski et al. (2009) introduces a new tracking architecture using wireless sensor modules and shows an accuracy performance using a numerical simulation approach based on the time-of-flight method. RFID has even been shown to estimate object pose (Umetani et al., 2011).

RFID technology has been even further utilized by successfully pairing with Building Information Modelling (BIM) for supply chain management (Sawyer, 2008). There are other technologies being researched, but they require the additional resources provided by the facility (Costin et al. 2012b). Linking these two technologies will allow for tracking location in real time and lead to more productivity and efficiency on a job site. A digital link between the virtual models and the physical components in the construction process can improve the information handling and sharing in construction and building operation management (Sørensen et al., 2010).

Integrating RFID and BIM can be done via the application program interface (API) of the technology software (Costin et al. 2012b). Linking the technologies on a case-by-case basis can be time consuming and tedious, and is important to make the integration scalable and reusable. Therefore, using a neutral software schema, such as the industry foundation class (IFC) (buildingSMART, 2013) can provide the standards and semantics to promote widespread adoption. However, the current release of IFC4 has no explicit standards for RFID and therefore cannot be directly linked. Motamedi et al. (2013) list what IFC definitions can be reused for RFID and propose extensions to incorporate RFID directly, including new data types, classes, and attributes. Until extensions get implemented, linking RFID (and other sensing technologies) to BIM must utilize the available definitions provided by the current release of IFC4 paired with user defined property sets (e.g. *IfcPropertySet*). Although this study did not explicitly use IFC, the main definitions needed to incorporate RFID into IFC in this project will be highlighted throughout the paper.

## 2.3 Data Management

Increasing productivity has always been a high priority on a construction jobsite, since it can result in the reduction of time and costs. A productivity analysis is a common practice that measures how productive a jobsite is, based on tasks or trades. The study produces statistical data (e.g. "task a" takes four times as long to complete then the industry average) that can be used to implement changes to optimize productivity (e.g., "task a" needs an additional worker to complete). Poor materials management can also result in large and avoidable costs during construction. First, if materials are purchased early, capital may be tied up and interest charges incurred on the excess inventory of materials. Moreover, materials may deteriorate during storage or be stolen unless special care is taken. Second, delays and extra expenses may be incurred if materials required for particular activities are not available. Accordingly, insuring a timely flow of material is an important component for optimizing productivity. A productivity analysis can show at what points in the construction process delays and time wasted exist (e.g., windows were moved to three different locations before it was installed). Again, analyzing the statistical data can be used to implement changes (e.g., windows are placed in a dedicated section until they are needed).

Manual productivity analyses are shown to be error prone and time consuming (Goodrum et al. 2006). Yet Radio Frequency Identification (RFID) is one of a few technologies that is utilized to automate a productivity analysis. RFID technology has been shown to have a multitude of benefits from the implementation within various construction sites including asset tracking, inventory management, and on-site security upgrades (Ergen et al., 2007; Grau et al., 2009). Most importantly, its implementation has been shown to be feasible and cost effective (Costin et al., 2012a).

However, a few problems exist that prevent the full implementation of such system for a construction job site. First, the system produces massive amounts of data that is difficult to handle manually and produces data overloads. Second, the data may contain read anomalies such as false negatives, false positives, and duplicate reads, which can ultimately decrease the integrity of the data for analyses.

A method using geometric algorithms for air protocol filtering was used to reduce the amount of filtering required before the data is stored in the database (Parks et al., 2009). The method was shown to reduce the amount of meaningless data which ultimately reduces time and cost associated with filtering and analyzing the data. In attempts to solve the problem of missed reads of passive RFID tags, Darcy et al. (2009) proposed a methodology that fuses the use of data analysis techniques and Non-Monotonic Reasoning in order to restore the missing data. Their reasoning engine had an average success rate of 87.7% which is shown to be beneficial. Non-Monotonic Reasoning is further incorporated with Clausal Defeasible Logic (CDL) in an enhanced a cleaning tool that detects any suspicious data sets and eliminates duplicate readings and intrusions (Darcy et al., 2010). The previous algorithms that help eliminate read anomalies have yet to be tested with data produced on construction jobsites.

A proper materials management is an important aspect in the improvement of the productivity and efficiency of a construction project. The automation of the identification and tracking materials with technologies, such as GPS and RFID, has been shown to improve productivity and efficiency. However, a standardized implementation model has not yet been established. Therefore, Nasir et al. (2010) presents a model for the automated tracking and locations of construction materials. The model consists of 1) identifying the needs, 2) project definition, 3) implementation evaluations criteria, 4) implementation options, 5) evaluation of options, 6) deployment process, and 7) measurement and evaluation for next project implementation. The model that is presented is well established for the implementation of the automation of tracking materials. However, the model lacks an in depth evaluation of the results from the technologies and there is implementation of the results. Chen (2009) proposed the Automatic Productivity Evaluation (APE) method that utilizes RFID and GPS technologies to automatically evaluate productivity. The focus is mainly on worker productivity, i.e., output per man hour, and therefore materials management is not adequately covered, although the methodology can be applied to materials management. Shahandashti et al. (2010) developed a simulation based framework to support the identification of the information requirements for assessing productivity performance of earthmoving, in which RFID was used to assess labour hours and cycle durations. Ilic et al. (2009) utilized a rule-based RFID data analysis to detect inefficiencies, such as shipment delays, theft, or inventory problems in supply-chain management. The generic consistency rules can be applied in a real-time analytics system in order to process streams of RFID. Otondo et al. (2009) investigated the ways mangers evaluate and adopt the implementation of RFID technology. The results show that the manager's report a wide range of problems that can inhibit the full potential of RFID technology. Baars et al. (2009) utilized the Online Analytical Processing (OLAP) tool multidimensional data sets for analytical applications as known from the realm of "Business Intelligence" (BI).

## 3. EXPERIMENTAL ENGINEERING DESIGN

The purpose of this research is to utilize RFID-BIM integration to generate real-time data to produce leading indicators for safety and building protocol control. Additionally, the executed approach is to optimize cost and schedule while maintaining the scope, quality and performance. One of the many goals of the innovative project delivery models implemented on this site is to enhance quality control by reducing rework or damage of finished work.

The UCSF Medical Center team partnered with a commercial RFID technology provider in order to implement RFID-based tracking devices on the project. These devices are a proposed solution to the sequencing, safety and quality challenges previously mentioned. The RFID based building access will ensure more visibility and tracking of the equipment, materials, and personnel entering and exiting the jobsite while also allowing for the project team to increase work planning efficiency. RFID technology will present measures and data to help prevent these issues. The data analysis will allow for more efficient planning and work flow. This method of planning will help limit the amount of rework performed and limit access to zones where work has been completed, helping to limit damage. The entry security as well as asset and personnel tracking will help enhance the safety of the job site. Figure 1 displays the control center for data gathering, analysis, and communication of the system. The data can be transferred and stored on a central cloud server.

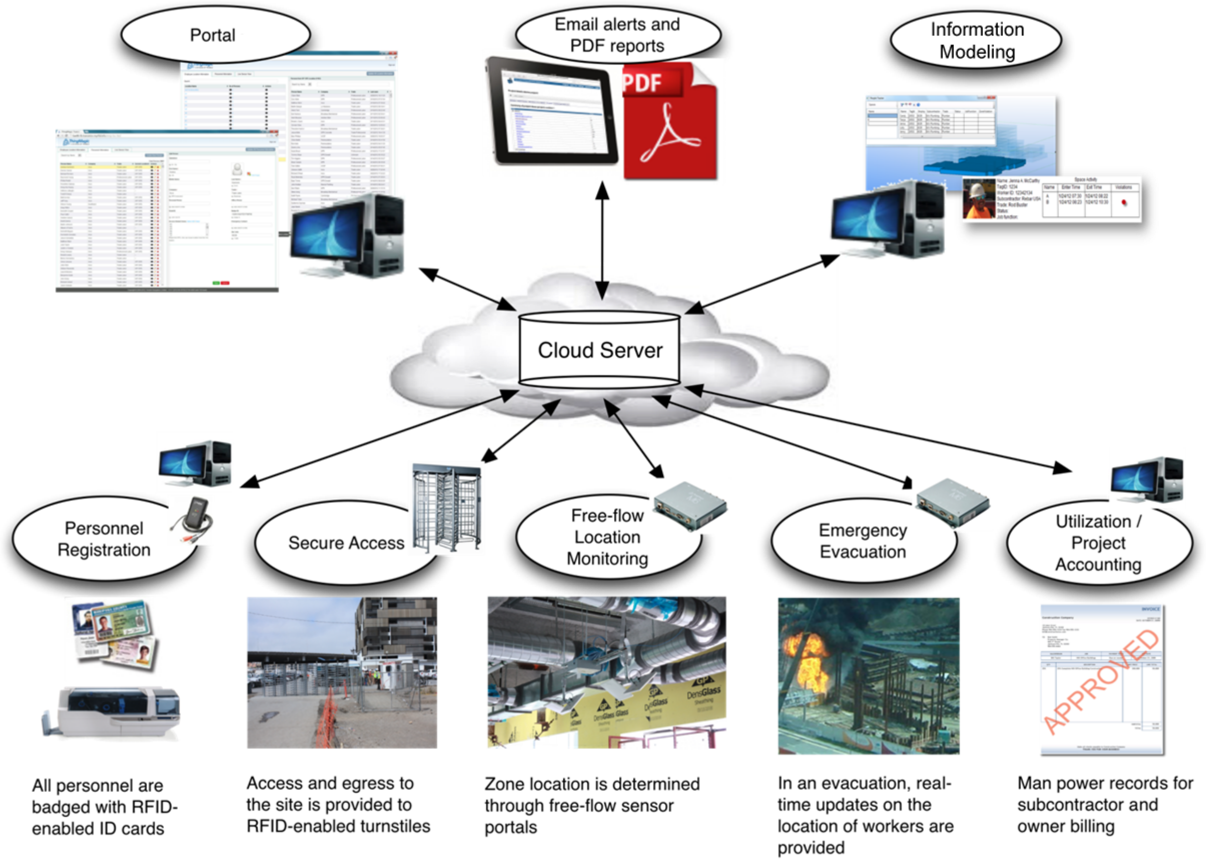


*FIG. 1: Control center for data gathering, analysis, and communication.*

Each person who enters the site (e.g., workers, subcontractors, visitors) would register and receive a UHF-RFID-enabled identification badge with breakaway lanyard (Figure 2). They would each be defined as an *IfcActor.* All construction personnel are required to wear the badge plainly visible. When entering the site, the person must manually tap the badge in front of the RFID reader of the turnstile for single entrance. This process ensures that only a single authorized person can enter the site at a time. Multiple turnstiles are used to avoid congestion and delay of entry and egress. Approximately 80 RFID tag readers were installed in the infrastructure of the new building and multiple secure turnstiles with tag readers were places at the access points for each work zone (Figures 3 and 4). Since the readers are fixed, they can be classified under *IfcBuildingElement*. The associated property sets of *IfcBuildingElement* include manufacturer, warranty, and environmental impact indicators, which can all be used for RFID readers.

IFC contains an object-based inheritance hierarchy (e.g. project, site, building element etc.) that allows for the modelling of spatial and entity relationships required in this research. The site was designated into three different zones: A (up to floor six), B (up to floor seven), and C (up to floor 3), which are modelled in IFC using *IfcZone* since the zones are a collection of *IfcSpace*. There are a total of sixteen distinct work zones that are monitored with the RFID readers. Since the RFID readers create each distinct work zones, these zones are model in IFC using *IfcSpatialZone.* Each reader is assigned to a zone by *IfcRelAssigns*. Therefore, when a tag is read, it will be located in the zone that the reader is assigned to. A project build protocol was enacted for each work zone, which can be assigned using *Pset_ZoneCommon.* Throughout the life of the project, there are four levels of access protocol: site/shell work, construction rough-in, punched area, and clean area. The intent of the protocol is to ensure that all necessary measures are taken during construction for the proper delivery of the newly built areas. The protocol level was based on the safety, security, and cleanliness, and authorized workers need specific qualification and training for each level to enter. Different zones of the building may be under different levels of protocol during the same time period, and therefore it was critical to monitor authorized access in those zones.

*FIG. 2: Hardware components: RFID badge printer (left); passive RFID badge (center); and RFID turnstile (right).*


*FIG. 3: Installed hardware components: turnstile with readers (left); and antennas overhead (right).*

The modeling began at 25% design phase, thus ensuring that subcontractors were able to report their constructability inputs into the permit drawings. Superintendents also worked with the modelers in order to create a model that accurately portrays the means and methods of the planned construction as well as provide the details specific to the project conditions that may become part of the permit documents. This collaboration ensures that the project is in compliance with all the necessary permit documents and requirements. The models created are directly used to create the fabrication and installation drawings. By doing this, it will guarantee that everything installed meets the design requirements while satisfying the required permitting documents. The design models will also feed into the Total Station units for an accurate site layout and installation. Many benefits come from creating a highly detailed model, such as the validation of the design, user requirements, and constructability as well as benefits in cost-savings, more reliable scheduling and increased field productivity. The time and effort put into creating these highly coordinated models results in higher predictability for schedule, material, and labor, leading to cost savings for the owners as the contingency budget can be lowered. These models allow for the modelling of detailed architectural, structural, and MEP systems, including hangers and seismic bracing, drywall framing, concrete, rebar, exterior skin and site utilities. The detail can go as far to show drywall models including "critical" framing, such as corners, doors, and MEP opening framing, as well as the infill framing for crowded rooms such as patient rooms, ICUs, and operating rooms.

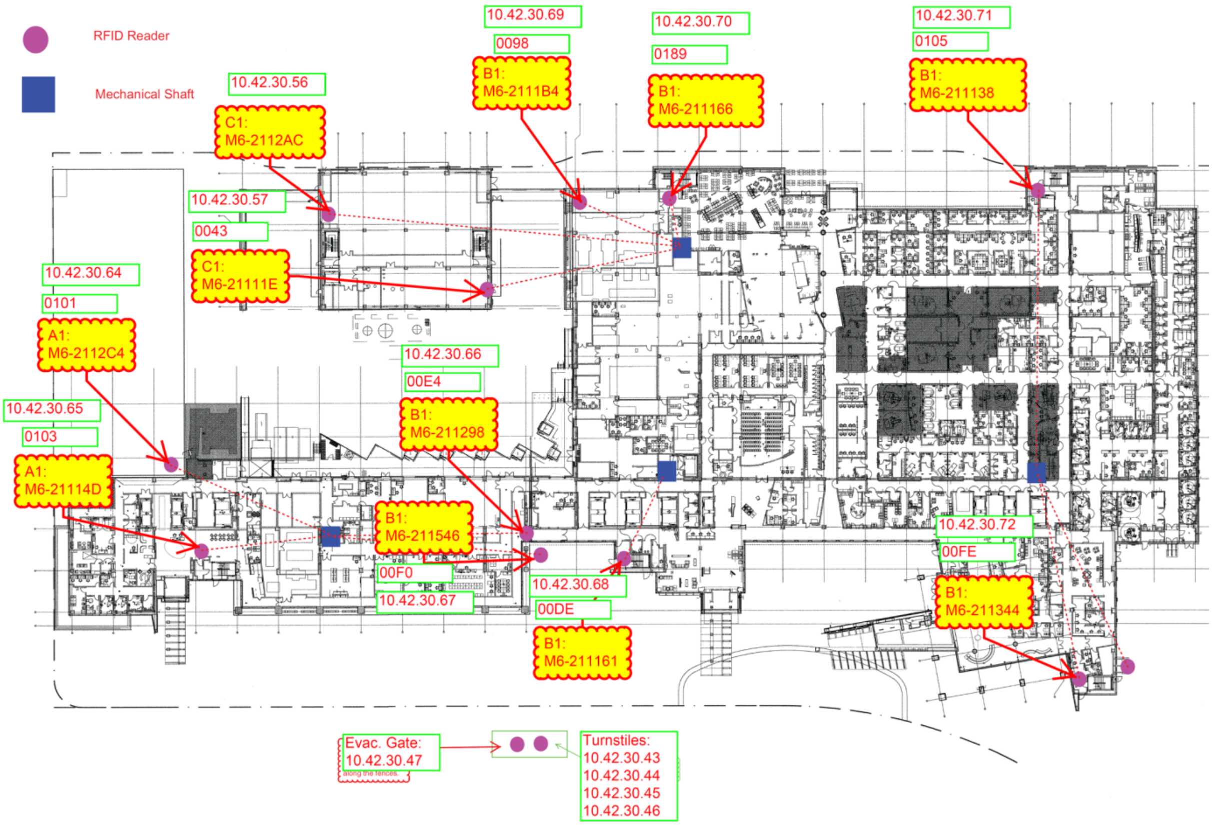


*FIG. 4: Map of access level 1 (ground floor) with RFID hardware.*

# 4. DATA MANAGEMENT

## 4.1 Data Collections

The system generates real-time data which is then filtered and stored for later use. The real-time data reports the current location of a tag being read, along with any additional data the user chooses (such as tag ID, name of the worker, and trade). The system can support real time notifications in addition sending the reports via email. All the real-time data is then stored to a cloud-based web portal where real-time email notifications and reports can be delivered daily. The stored data can then be used for analyses or reports. In addition to this reporting, a web service has been created in order to provide external software clients access to the data. This is done so the data can be analyzed and visualized in 3D. For example, commercially-available BIM software has a custom plug-in that enables the users to query the data to zoom in on the relevant data of the building section, time span, or people. It is to note that the filtering happens before the data is modelled, and thus does not need semantically linked to IFC. However, the final output of the data would need to be linked to IFC to promote interoperability. This study did not use IFC in the data collection and testing, but details of how to use IFC will be provided.

Since an RFID tag is placed on an object (e.g., building component, worker, equipment), we can assume that the tag is an object itself. To model in IFC, each RFID tag needs to be assigned to the object it is tagged on by using *IfcRelAssigns*. For instance, if a worker is tagged then *IfcRelAssignsToActor* would be used since the tag relates to the defined properties of a worker (name, trade, zip, etc.). The RFID technology generates the real-time data. For each read, in which the read rate can be adjusted accordingly, the main data produced consist of the a) RFID badge ID number, b) timestamp, and c) reader internet protocol (IP) address, which can determine what zone the read is in. The RFID badge ID number data is linked with additional data about the tagged item by setting or defining properties using *IfcPropertySet*. Therefore, when a tag is read, all information about the worker can be available. In this case, workers were given tags (badges), and thus information (kept private) such as name, company, trade, and authorizations can be linked to that badge. Therefore queries such as "start time," "end time," and "zone" can produce reports for analysis. Additionally, the queries enable the real-time feed to be filtered allowing the user view the current location of the tag.

For the data analysis, worker data was first grouped based on their trade. The zip code determined whether or not the worker was from San Francisco. The data then segregated weekly in order to compute the percentage of San Francisco worker each week. RFID data was filtered base on their subcontractor affiliation. Duplicate or redundant reads (reads with duplicate information) were removed to reduce the size of the files.

## 4.2 Data Filtering

Each reader in the RFID system produces a raw data output file, prior to processing through middleware, similar to the one shown in Table 1. Note that this is different from the final output data, as previously mentioned. Regardless of what type of RFID reader is used, the general output produced is consists of what reader is being used (Reader ID), the identification number of the tag being read (Tag ID), the timestamp of the read (Time Read), the frequency of which the tag is read in MHz (Operational Frequency), and the ID number representing the protocol (Protocol ID). Additional hardware information and statistics can be provided if necessary, such as read cycles, read timeouts, observed thresholds, or antenna number. This data is then processed through middleware to capture the information from the raw data. The raw data can be processed through middleware before or after data storage (sometimes before and after). The middleware in this research is used to reduce and correct anomalies, remove redundant data, and organize the data before being processed by the software application.

*Table 1. Data produced by readers.*

| *Reader ID* | *Tag ID* | *Time Read* | *Operational Frequency* | *Protocol ID* |
|---|---|---|---|---|
| 10.0.0.101 | 1200000000000044 | 12:51:34 PM | 911250 | 1 |
| 10.0.0.101 | 1200000000000044 | 12:51:35 PM | 911250 | 1 |
| 10.0.0.58 | 90000000000013c5ac | 12:51:35 PM | 919750 | 8 |

### 4.2.1 Anomaly Reduction

The first portion of the middleware uses an algorithm detects and eliminates read anomalies. An RFID system may produce read anomalies, such as false negatives (the tag was in range but was not read) and false positives (the tag was not in range but was read), which can ultimately decrease the integrity of the data for analyses. For instance, the dual location anomaly will show a tag being in two different locations simultaneously, which is impossible unless there is overlap. This event is an example of a false positive, in which there is a tag read that should not exist. A time threshold needs to be defined, in which is the time that a tag is moving from one reader to the next would be impossible (e.g. traveling between rooms, stair wells, and elevators). Further testing is required to determine the most efficient threshold for each system set up, but the extreme scenario would be if the readers are in adjacent rooms (since rooms further apart would be a higher threshold). If it takes at minimum 5 seconds for a tag (in this case a worker) to walk from one room to the next, the threshold would be 2 seconds, since anything less than 2 seconds would be impossible. The following is the code of the dual location algorithm, given two readers, three consecutive reads (RA, RB, and RC), and the threshold t of 2 seconds.

$$If\ RA == RB\ \&\ RC \sim= RB\ \&\ |Time\ B - Time\ C| < t \quad (1)$$

$$Delete\ Row\ C$$

This states, if the reader of read A equals the reader of read B, and the reader of read C does not equal reader of read B, and the time between reads B and C is less than two second, then read C is a dual location anomaly and should be deleted. Table 2 shows an example, in which same tag is read by two different readers simultaneously.

*Table 2. Read data showing a dual location anomaly for read C.*

| *Row* | *Reader ID* | *Room No.* | *Tag ID* | *Time Read* |
|---|---|---|---|---|
| A | 10.0.0.101 | 101 | 9000000000000013c5ac | 12:51:56 PM |
| B | 10.0.0.101 | 101 | 9000000000000013c5ac | 12:52:37 PM |
| C | 10.0.0.58 | 102 | 9000000000000013c5ac | 12:52:37 PM |

### 4.2.2 Redundant Data Reduction

An RFID system continuously reads tags in range, thus inherently producing large amounts of data. The number of tags being read and read rate (how often a tag is read) can be adjusted according to the reader, but typically can read up to 1000 tags per second. For instance, it takes roughly 1 kB for every 10 data reads and at the rate of 1000 lines of data per second, each reader produces about 28.8 million data reads (2.75 GB) per eight hour workday. Since the RFID system in this research has 80 readers, each day the system is capable of producing nearly 2.3 billion lines of reads (220 GB). All of those reads would be stored in a database. However, the majority of those reads would be considered redundant and would take up valuable space. The only significant data needed is the time the object arrived to a location and the time the object leaves. All the reads in between that show that the object is still there are considered redundant. The problem with redundant data is that it takes up much space, ultimately costing time and money. All redundant data starts out as important reads, since they show in real-time where the tag is located. Once the next read occurs, then that previous read would then be considered redundant, and is no longer needed

In order to reduce the redundant reads and optimizes the raw data, the system utilizes a Redundant Data Reduction Algorithm (RDRA). The algorithm, seen in Figure 5, eliminates the redundant data by determining the first read (when the tag enters range) and last read (when the tag leaves). If a tag is read within a time threshold, t, then the previous read is considered redundant and then eliminates. If time t passes without a read, then the previous read is the last read before the tag exits and is saved. The time threshold, t, is determined based on factors such as read rate and performance measures.

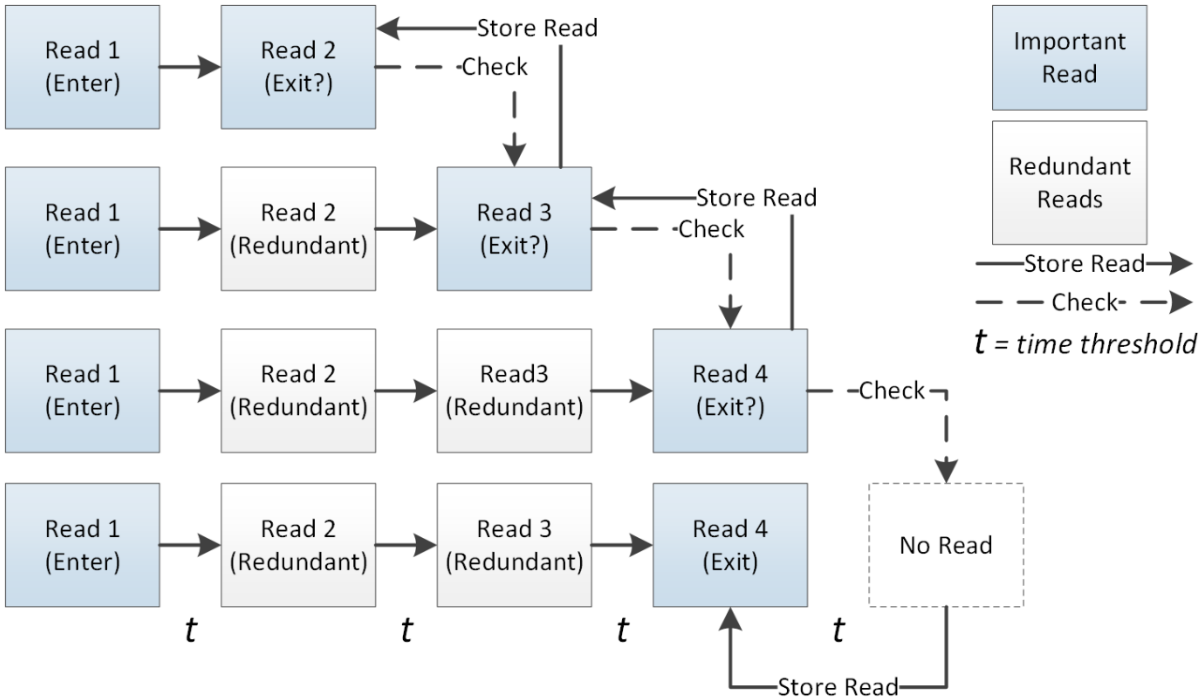


*FIG. 5: Schematic diagram of the developed Redundant Data Reduction Algorithm (RDRA).*

### 4.2.3 Organization

The third portion of the middleware organizes the data in a way to optimize the computational or manual analysis of the data. Organization is extremely important so that data can be processed properly by the software application. The middleware can produce multiple organization outputs, in which can each be tailored to meet the end goal. For instance, Table 3 shows the filtered data used to determine performance measure, which is the raw data after being processed through the RDRA. Once all the anomalies and redundant data are removed, only the entrance and exit times of the worker are left. However, although the data in the table are suitable for analysis, it still requires additional calculations to compute the analysis.

*Table 3. Filtered data.*

| *Tag ID* | *Reader ID* | *Room No.* | *Time Read* |
|---|---|---|---|
| 9000000000000013c5ac | 10.0.0.101 | 101 | 8:00:00 AM |
| 9000000000000013c5ac | 10.0.0.101 | 101 | 8:16:39 AM |
| 9000000000000013c5ac | 10.0.0.103 | 103 | 8:20:12 AM |
| 9000000000000013c5ac | 10.0.0.103 | 103 | 8:26:51 AM |
| 9000000000000013c5ac | 10.0.0.101 | 101 | 8:28:26 AM |
| 9000000000000013c5ac | 10.0.0.101 | 101 | 8:38:25 AM |

## 4.3 Performance Measures

Metrics can be set to measure various work activities. The metrics that will be measured will be the time that the worker spends in the work zone (Work Time) and time it takes the worker to travel from one area to the working area (Travel Time). Work time will calculated by subtracting the last time read from the first time read by the reader (R1) that is in the working area. Since travel time is the time between locations, the time will be calculated by subtracting the first time read by the reader in the new location (R2) from the last time read from the last time read by the reader (R1) that was in the previous location. The simplified definitions of these two metrics are as follows:

$$Work\ Time = R1\ last\ time\ read - R1\ first\ time\ read \tag{2}$$

$$Travel\ Time = R2\ first\ time\ read - R1\ last\ time\ read \tag{3}$$

where: R1 is the reader in the work zone. R2 is the reader in the destination room.

Efficiency for time will be measured by the expected time divided by the actual time multiplied by 100. The expected time will be determined by the project manager for each case, which can be based on industry standards. For the most accurate time, trials would measure the time from the starting location to the destination. Then, once the average is calculated, then this would be the "recorded time." Either this time or performance goals can be used as the expected time.

$$Time\ Efficiency\ = \frac{expected\ time}{actual\ time} x\ 100 \tag{4}$$

Efficiency for output will be measured by the expected output divided by the actual output multiplied by 100. The expected time will be determined by the project manager for each case, which could be based on industry standards or billable hours. The actual output would be measured by the total amount of time spent in the work zone.

$$Output\ Efficiency\ = \frac{expected\ ouput}{actual\ output} x\ 100 \tag{5}$$

Although the RFID system cannot accurately determine whether the worker is actually working while in the work zone, it still provides important data. It is important for a project manager to know when and where the workers are located, as well as how to optimize the work and travel times. Having the ability to calculate the work and travel times enables the development of trends and patters. Calculations include average wait time and average travel times. Comparing and graphing multiple instances during variant times (day, week, project duration etc.), trends and pattered can be visualized and further assist in the analysis. Then the patterns can be compared to the calculated averages to investigate whether delays exist. If there were to be a delay, a project manage will be able to investigate, discover the delay, and implement a solution.

## 4.4 Data Testing

The middleware was tested using sample and simulated data. The first experiment tested the reduction of anomalies (which were simulated based on experience from real data) and redundant data. Four data files of 2000 RFID tag reads were passed through the middleware and the results are shown in Table 4. Significantly, the data files were shown to be reduced to upwards of 90%.

*Table 4. Results of the experiments.*

| *Test* | *Anomalies Contained* | *Anomalies Remain* | *Original Size* | *Final Size* | *Reduction* |
|---|---|---|---|---|---|
| 1 | 40 | 0 | 2000 tuples (78.4 KB) | 5 tuples (8.74 KB) | 88.9% |
| 2 | 40 | 0 | 2000 tuples (78.1 KB) | 9 tuples (8.84 KB) | 88.7% |
| 3 | 40 | 0 | 2000 tuples (77.1 KB) | 7 tuples (8.83 KB) | 88.5% |
| 4 | 40 | 0 | 2000 tuples (79.4 KB) | 3 tuples (8.67 KB) | 89.1% |

Table 5 shows the data for Test 1 after being processed through the organization metrics of the RDRA. The new organization of the data can help visualize the movement of the material. For instance, a material dolly stayed in room 101 for 16 minutes and 39 seconds, before traveling to room 103. It took 3 minutes and 33 seconds to travel from room 101 to 103, but took only 1 minute and 35 seconds to travel back from room 103 to 101. This shows that there could be a possible delay on the travel cycle, and further data can confirm this. If there were to be a delay, a project manage will be able to investigate and take action to resolve the issue to prevent further delays.

*Table 5. Filtered data of test 1.*

| *Tag ID* | *Room No.* | *Duration (hh:mm:ss)* |
|---|---|---|
| 9000000000000013c5ac | 101 | 0:16:39 |
| 9000000000000013c5ac | Travel Time | 0:03:33 |
| 9000000000000013c5ac | 103 | 0:06:39 |
| 9000000000000013c5ac | Travel Time | 0:01:35 |
| 9000000000000013c5ac | 101 | 0:09:59 |

# 5. OPERATING RESULTS

## 5.1 Real-time Resource Tracking

With the ability to link RFID tracking data with BIM, managers can now monitor the flow of people in and out of different zones. Although the system cannot pinpoint the exact location of a worker, knowing what zone or room the worker is in is important, especially for safety and security. The system allows for an instant email alert to be sent when an employee enters an unauthorized zone. These real time updates will be crucial in the event of an emergency as it will provide authorities the information to determine who has been left in the building and in what location (Zhang et al. 2015). Figure 6 displays a demonstration of the RFID-BIM integration with real RFID data, but fictitious names and companies (due to privacy concerns). The simplicity of the interface (start and end time of observation period) allows a user to draw automated reports including visuals of which work areas are impacted. Joe Sample, for example, has the worker ID 8103 and entered the building in Level C on November 27, 2012 at 8:18 a.m. He used the staircase A2 to exit the building at 4:21 p.m. The visitor with ID 9950 had no permit to enter the work site at 7:35 a.m. and Jenna (ID 1657) of Ed’s Plumbing Company had no work permit for Area C. More data to each worker are shown in Table 6. More detail to data can be visualized and automated alerts can be generated. Figure 7 shows a violation of a person entering a hazardous space where a work permit is required, but did not match the authorization or training code of the person entering.

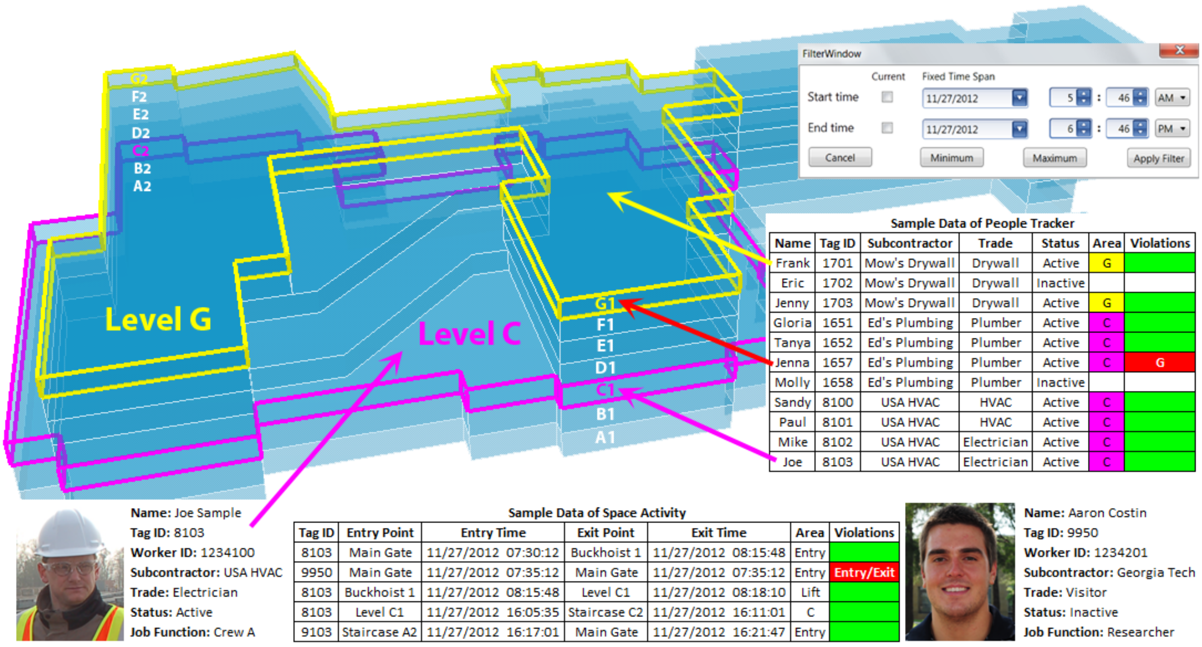


*FIG. 6. Screen shot of software plug-in with workers (fictitious) and locations in BIM model.*

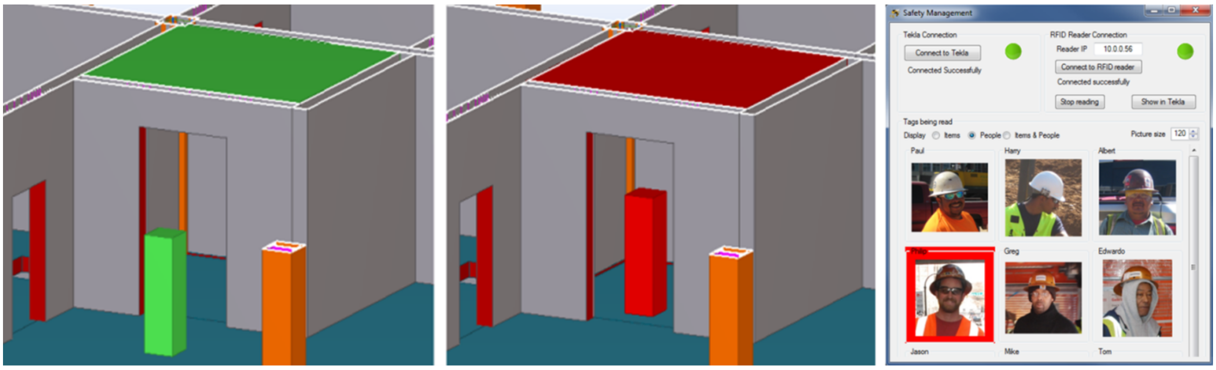

*FIG. 7: Worker entering a hazardous and unauthorized workspace generates an alert and visual in BIM and on handheld pagers.*

*Table 6. Sample data of activity and space (fictious names).*

| *Name* | *Tag ID* | *Company* | *Trade* | *Last Seen* | *Working Space ('Floor level' or 'not in building (-)'* | *Entry Time* | *Exit Time* |
|---|---|---|---|---|---|---|---|
| Paul | 124 | Ed's Plumbing | Plumber | - | B1 | 8/15/2012 6:53 | 8/15/2012 6:53 |
| Paul | 124 | Ed's Plumbing | Plumber | B1 | B2 | 8/15/2012 6:54 | 8/15/2012 8:54 |
| Bill | 119 | Ed's Plumbing | Plumber | - | B1 | 8/15/2012 6:58 | 8/15/2012 7:01 |
| Bill | 119 | Ed's Plumbing | Plumber | B1 | B2 | 8/15/2012 7:01 | 8/15/2012 7:02 |
| Bill | 119 | Ed's Plumbing | Plumber | B2 | B3 | 8/15/2012 7:02 | 8/15/2012 7:09 |
| Bill | 119 | Ed's Plumbing | Plumber | B3 | B4 | 8/15/2012 7:09 | 8/15/2012 7:12 |
| Bill | 119 | Ed's Plumbing | Plumber | B4 | B3 | 8/15/2012 7:12 | 8/15/2012 12:02 |
| Frank | 84 | USA Electric | Electrician | - | B5 | 8/15/2012 7:27 | 8/15/2012 9:27 |
| Gloria | 99 | USA Electric | Electrician | - | B5 | 8/15/2012 7:29 | 8/15/2012 7:42 |
| Gloria | 99 | USA Electric | Electrician | B5 | B6 | 8/15/2012 7:42 | 8/15/2012 12:07 |
| Frank | 84 | USA Electric | Electrician | B6 | B1 | 8/15/2012 9:29 | 8/15/2012 11:57 |
| Frank | 84 | USA Electric | Electrician | B1 | B5 | 8/15/2012 11:57 | 8/15/2012 12:41 |
| Bill | 119 | Ed's Plumbing | Plumber | B5 | B1 | 8/15/2012 12:02 | 8/15/2012 12:02 |
| Bill | 119 | Ed's Plumbing | Plumber | B1 | - | 8/15/2012 12:32 | 8/15/2012 12:36 |
| Bill | 119 | Ed's Plumbing | Plumber | - | B3 | 8/15/2012 12:36 | 8/15/2012 14:26 |
| Paul | 124 | Ed's Plumbing | Plumber | B3 | - | 8/15/2012 12:38 | 8/15/2012 12:39 |
| Paul | 124 | Ed's Plumbing | Plumber | - | B1 | 8/15/2012 12:39 | 8/15/2012 14:32 |
| Paul | 124 | Ed's Plumbing | Plumber | B1 | B2 | 8/15/2012 12:39 | 8/15/2012 14:30 |
| Frank | 84 | USA Electric | Electrician | B2 | - | 8/15/2012 12:41 | 8/15/2012 12:44 |
| Gloria | 99 | USA Electric | Electrician | - | - | 8/15/2012 12:42 | 8/15/2012 13:12 |
| Frank | 84 | USA Electric | Electrician | - | B5 | 8/15/2012 12:45 | 8/15/2012 15:23 |
| Gloria | 99 | USA Electric | Electrician | B5 | B5 | 8/15/2012 13:12 | 8/15/2012 15:25 |
| Bill | 119 | Ed's Plumbing | Plumber | B5 | B1 | 8/15/2012 14:26 | 8/15/2012 14:27 |
| Paul | 124 | Ed's Plumbing | Plumber | B1 | B1 | 8/15/2012 14:30 | 8/15/2012 14:32 |

Frank, an electrician (ID 84) enters the building and takes the elevator to space B5 where he is first seen at 7:27 AM. He then takes elevator to space B1 and works there for a few hours. He then travels back up to B5 to work some more, before taking a short break outside (assuming to pick up his lunch that was delivered) at 12:41 PM. He then returns to B5 where he works until 3:23 PM. He worked a total of 8 hours inside of the building.

Gloria, an electrician (ID 99), inspects zone B5 at 7:29 AM for about fifteen minutes before proceeding up to zone B6. She then works there until 12:07 PM when she exits the building. She returns back from lunch to zone B6 at 1:12 PM and finishes up work at 3:25PM.

Bill, a plumber (ID 119), enters zone B1 at 6:68AM. He then takes a few minutes walking up the stairs up to zone B4. After a few minutes, he walks back down to zone B3 and works until lunch. He takes the elevator down to zone B1, and exits the building. He takes a half an hour lunch and returns to zone B3 at 12:36 PM to work. He then takes the elevator to zone B1 at 2:26PM and then exits for the day.

Paul, a plumber (ID 124), enters zone B1 at 6:53 AM and walks up to zone B2. At 8:54 AM, He exits the building and doesn't return until 12:39 PM. He spends a few minutes in zone B1 to chat before walking up to zone B2. He works until 2:32 PM and then walks down to zone B1 to exit for the day.

## 5.2 Data Analysis

The system has the ability to record the time spent in each zone. This feature is important because it provides the required data for project manager to conduct an activity analysis. In addition to the real time data the system produced, the stored data was filtered and analyzed for various aspects. Automating the analysis of recorded data saves significant time when examining labor productivity. For instance, the data can be graphed to compare the work in the different zones. Activities such as productivity, number of workers, and scheduling can be visualized to see the trends, progress, or even compare whether the work is on schedule. Having the data in visual form is important to for planning and coordinating future work. Importantly, knowing the current status and productivity rate allows for a more accurate assessment of what is needed.

For instance Figures 8 and 9 show the work is becoming to completion, and therefore not many workers are needed. Also, Figures 10 and 11 show the increase in number of workers to maintain the current schedule.

The system can also produce automated worker reports. Queries enable various display options, such as daily, weekly, or monthly reports. Additionally, the trade, zone, worker can also be selected.

Figure 12 displays the total man hours based on zone from 9/6/12 until 10/25/12. Figure 13 displays the total work hours by week for a portion of the project, including both workers of San Fransico (SF) and not San Fransico workers (Non SF). These automated reports are important because they can be used for billing purposes, since the system can recorded the correct amount of time a worker spends on the site. Although the system can't verify that work is being conducted, it can verify that the worker is in the correct zone. For instance, if a worker is being paid for work in zone B1, any time spent outside of that zone signifies the worker is not working on the paid task.

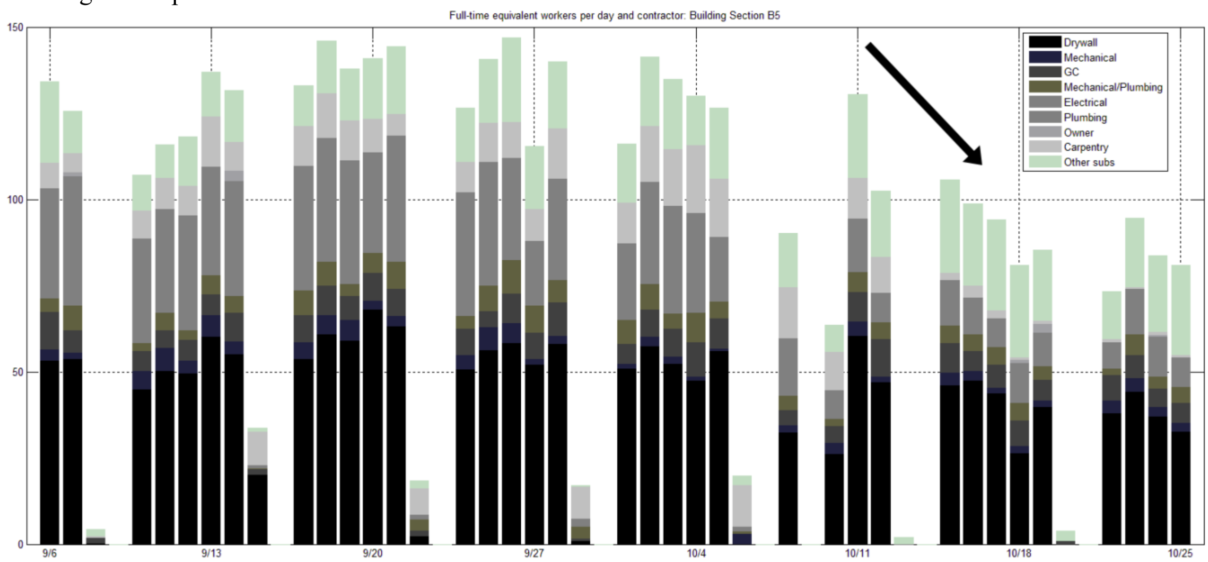


*FIG. 8: Full-time equivalent workers per day per contractor for Section B5: Drywall ramping down after end week of October 11.*

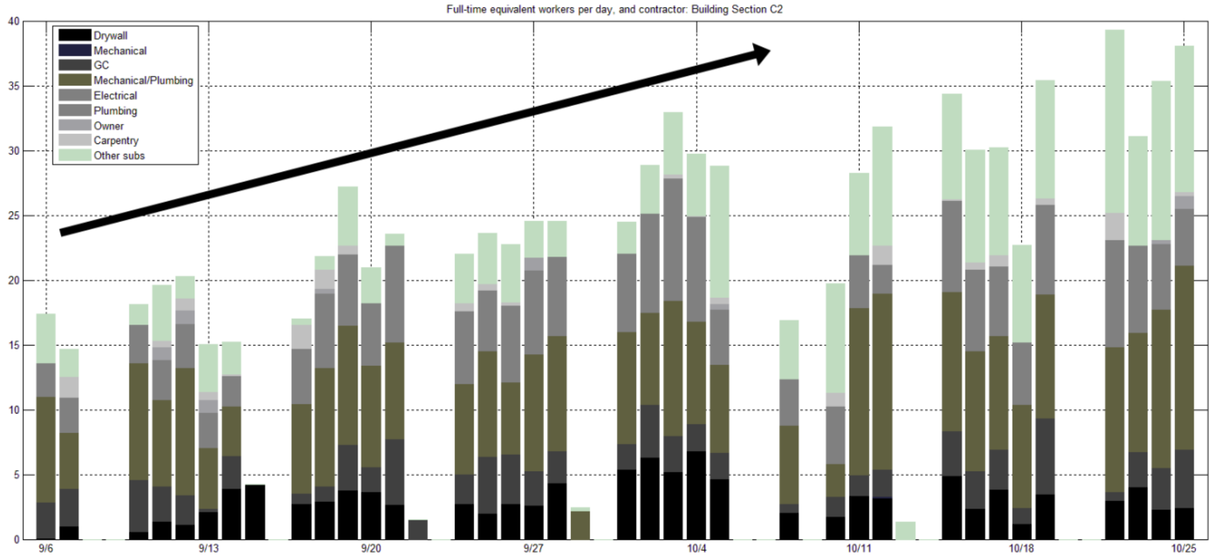


FIG. 9: *Full-time equivalent workers per day per contractor for Section C2: Steady resources increase.*

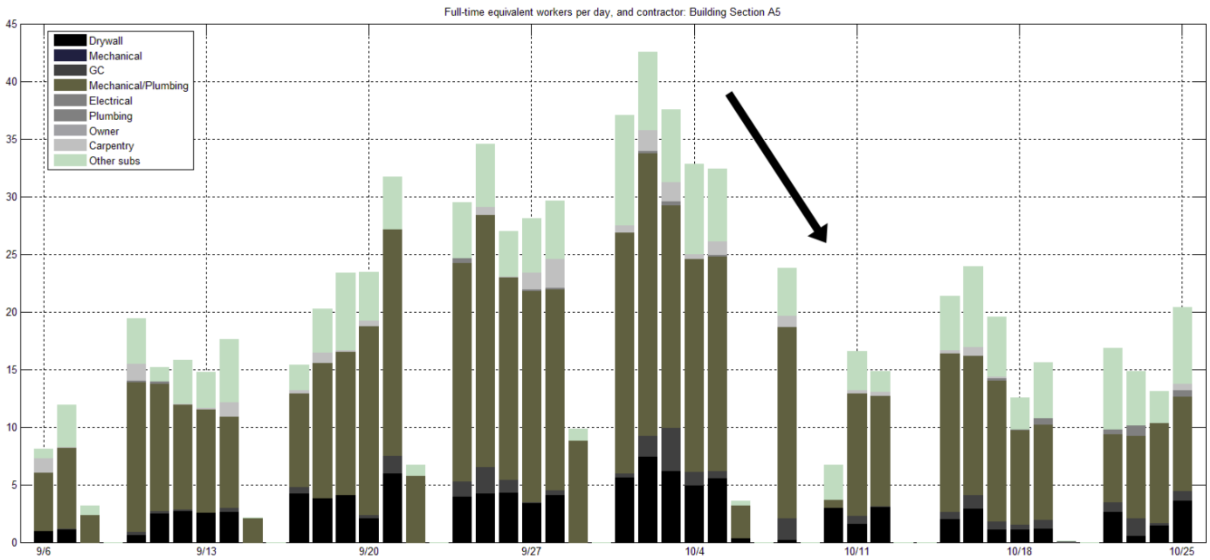


*FIG. 10: Full-time equivalent workers per day per contractor for Section A5: Heavy lifting nearly done at the end of week October 4.*

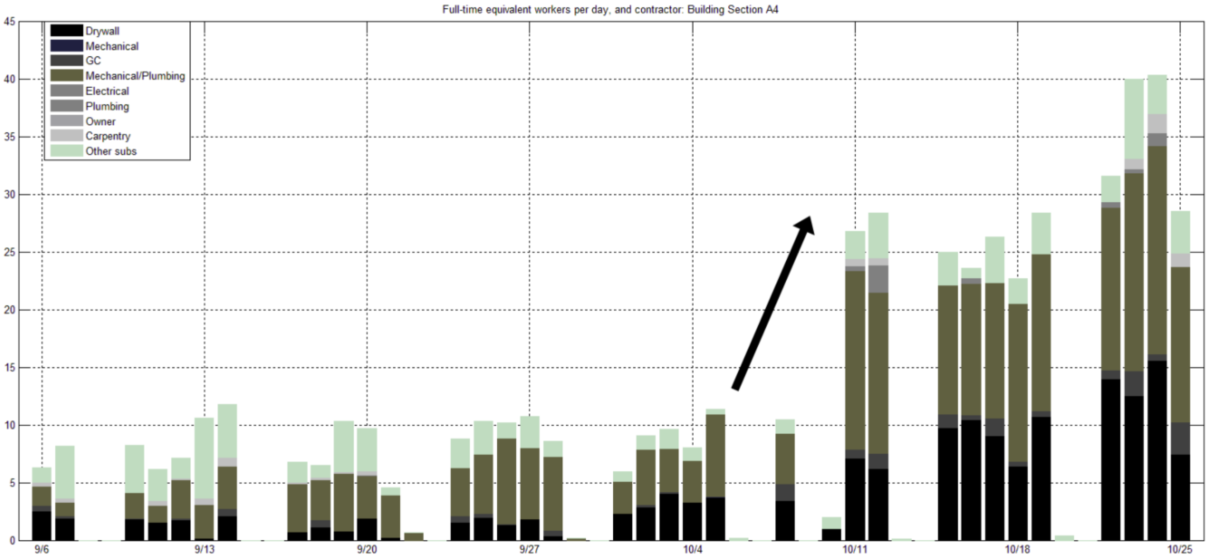


*FIG. 11: Full-time equivalent workers per day per contractor for Section A4: Trying to stay on schedule takes extra efforts.*

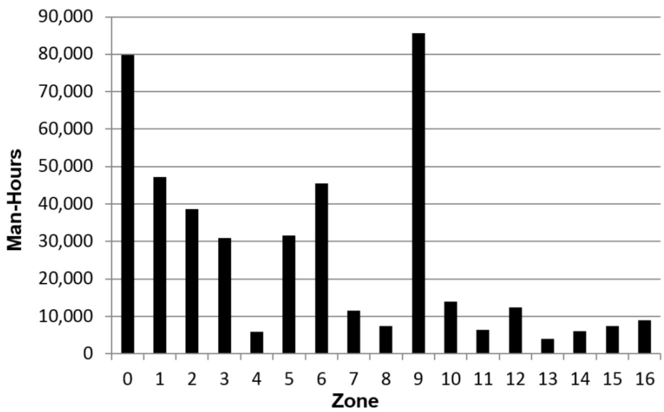


*FIG. 12: Total man hours per zone from 9/6/12 until 10/25/12.*

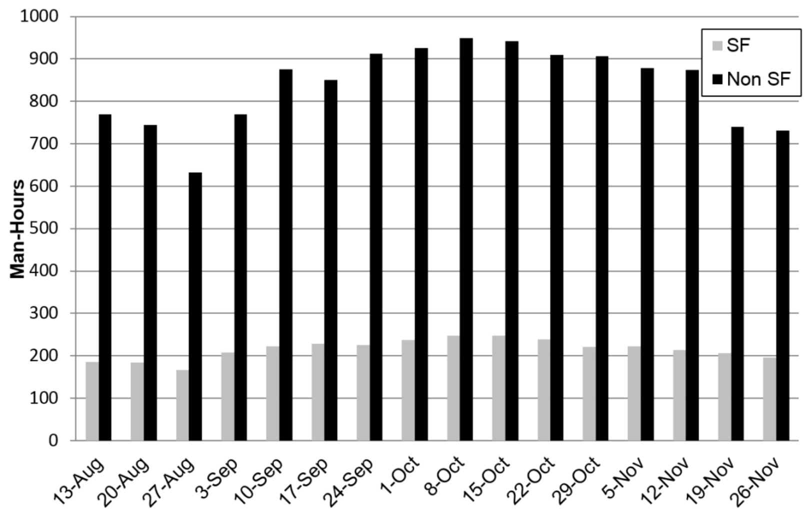


*FIG. 13: Number of worker hours per week, Monday through Friday.*

## 5.3 Code, Regulation, and Ordinance Compliance

Verifying the compliance to local, state, or federal regulations is another important feature this system provides. For example, The San Francisco Office of Economic and Workforce Development (OEWD) mandates that certain government funded projects hire a percentage of local workers by trade. The purpose of the OEWD is to enhance San Francisco's economic vitality and strengthen the community. The Mandatory Local Hiring Ordinance states that the mandatory participation level will increase annually over seven years up to a mandatory participation level of 50% of project work hours within each trade performed by local residents, with no less than 25% of all project hours within each trade performed by disadvantaged workers ([7]Office of Economic and Workforce Development, 2011). The project will be periodically review by the OEWD and the Controller's Office every three years from the effective date of the policy to determine whether there is a sufficient supply of local workers to meet the increase in mandatory participation level, assess the length of time to develop a pool of workers per trade, and, if necessary, propose amendments to the policy. There are additional rules and stipulations within the mandate and any violations will result in penalties.

Although the UCSF hospital does not meet the criteria to be required to follow the ordinance, it is voluntarily doing so to benefit the local community. The goal for the project is to follow the mandatory participation level guidelines and regulations. Each employee's information, including their trade and zip code, will be placed in a data base that is linked to their identification number. This system will be able to track all employees by their given identification number, thus providing the resources to obtain an accurate assessment of the amount of employees with the local residential zip code. With this information, USCF has been able to accurately report the number of local residents on the site and the amount of hours they have performed in their trade. As seen in Figure 14, the UCSF Medical Center successfully met their goal to reach 25% local resident employees for the electrician trade for the majority of the duration. Unfortunately, they did not meet the goal with the other trades. This information is useful in showing the company the need to hire more local workers in order to achieve the goal.

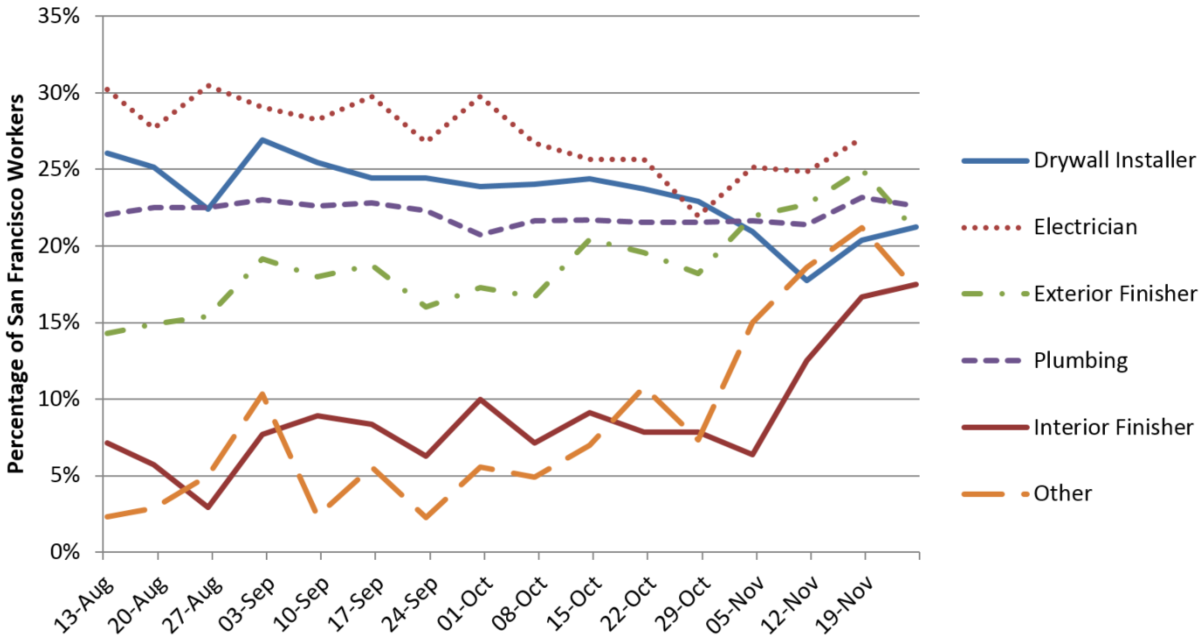


*FIG. 14: Percentage of San Francisco-based workers by sub, Monday through Friday.*

## 5.4 Zone Safety Violations

The system records all safety and security violations (based on predefined rules set my the project managers), which is important for recorde keeping and the production of leading indicators for safety and building protocols. When a worker enters an unauthorized zone, an alert is sent to the project manager notifying him of the breach. In addition, each breach is kept in a log, which can then be analyzed to fix the problem. For instance, if an unauthorized worker enters in by mistake, he will learn to not go in there without proper training. Additionally, a log will notify what workers still need to be trained to enter that zone. Table 7 shows the log of violations for a specific duration. Since the violations were created by visitors, it is important they had special authorization to enter the zone (Teizer 2015a, Teizer 2015b, Teizer et al. 2015c, Teizer 2015d).

*Table 7. Sample data of activity and space (fictious names).*

| *Zone* | *Company* | *Trade* | *Individual* | *Most Recent Violation for Zone* | *Total Violation for Zone* |
|---|---|---|---|---|---|
| A1 | DPR | Visitor | DPR 3 | 2012-10-10 16:14 PDT-0700 | 1 |
| B1 | DPR | Visitor | DPR 3 | 2012-10-11 07:05 PDT-0700 | 1 |
| B5 | DPR | Visitor | DPR 5 | 2012-10-11 11:01 PDT-0700 | 1 |
| B6 | DPR | Visitor | DPR 5 | 2012-10-11 10:24 PDT-0700 | 1 |

# 6. CONCLUSIONS

The integration of RFID technology and BIM creates a more systematic, automated, and intelligent job site and results in benefits to both the project team and the UCSF Medical Center. Mapping this research to a neutral schema, such as IFC, can provide interoperable standards and semantics to promote widespread adoption. The goal is to keep the site environment as safe and secure as possible, while keeping productivity and the quality of work high. This system is able to detect personnel and assets as far as three to five meters away from the reader antenna, which is unlike the current, conventional access control. As observe in Teizer et al. (2015e), with this kind of range, workers will no longer have to swipe a badge at each sensor (exception for the turnstiles as a safety measure) as they will be able to simply pass through check points and portals. Long range readers reduce the numbers of readers need to be installed, which is important on a large, congested site such as a hospital.

## 6.1 Observed Benefits

### 6.1.1 Improved Safety and Security

Providing an accurate headcount has made it easier to ensure the safety of everyone, which is important on this large, newly developed, urban site that the hospital is being developed on. Crews are now easier to find and convey important messages to. Being able to locate the crews in a timely manner could be the difference in life or death in an emergency situation. When the workers assemble in their muster stations, they can all be accounted for in the matter of minutes. For those who are missing, the software can locate the last known zones, which can point emergency crews in the right direction to find them. The new technology allows for the assurance that only badged, authorized employees are entering the site and the zones that they are authorized for, which increases safety and lowers risks in those zones that may contain expensive equipment and materials. No longer will there need to be a hired security guard or supervisor just to monitor the work force in the various sections of the building. The use of this technology eliminates the need for these personnel and thus lowers costs.

### 6.1.2 Ordinances and Regulations

Verifying the compliance to local, state, or federal ordinances and regulations is another important feature this system provides. Fines and litigation can be prevented with the help of automated system linked with those regulations. Such systems can save much time and money by automating code compliance checks, which could send alerts to the managers notifying possible breach of compliances that need to be promptly resolved. This project demonstrates this by volunteering for the San Francisco OEWD trade regulations.

### 6.1.3 Resource Tracking and Protection

Equipment and materials can also be tagged with RFID tags. The RFID system allows for all assets and equipment to be securely tracked and located at all times. This prevents the equipment from being misplaced or lost, which could potentially be a negative impact on the project's cost and schedule. Reduction in the time locating resources is critical for the project to stay under budget. The data produced from the system can be analyzed to determine the most efficient place for material tracking. The time it takes a worker to walk to the material storage and back, the number of trips a worker travels to the material storage, and the location the worker comes from and goes to can be determined automatically. These and other factors play important roles increasing productivity on the jobsite.

Since this is a state of the art facility being constructed, there is a significant amount of expensive medical equipment to be installed. These, along with other expensive or critical assets, can be tagged to prevent theft. For instance, if an item is removed from its zone, alarms can be sent to the projected manager, notifying him that the item has been removed.

#### 6.1.4 Improved Quality

Rework and damage to completed work are very realistic threats to the quality of the project. Foot traffic over completed work can cause damage to these finished projects and without proper monitoring and planning, rework is possible. Minimizing this traffic and ensuring that subcontractors are only in locations where they are necessary will help to limit damage and rework. However, a supervisor that constantly monitors the workers to verify they do not walk through the wrong areas is not practical. A way to do this is to control and monitor access to the site and to ensure that workers are properly trained before they can enter the different project zones. With the new technology, the project team is able to do this and is better able to monitor the progress of the different work zones, helping to better protect the finished work.

#### 6.1.5 More Effective Workforce

As labor is almost half of a project's construction cost, it is imperative to improve the worker logistics on a job site. The RFID technology helps make this happen. With the data presented by the new technology, subcontractors are able to more efficiently plan their work, helping to meet project needs and identify variances. The data provides an understanding of how many workers are present on site daily and where majority of the work is being performed. This helps the subcontractors determine the appropriate amount of workers to deploy, preventing over- or under- staffing the project. The owner's dollars are being efficiently spent when the right people and skill sets are in the right place at the right time, and this comes from the improved work flow created. The real time data analysis during each work day is drastically different and more efficient than in the past when construction managers and owners used to have to wait for weeks or months to get the data analysis of how efficiently the workforce is performing, thus wasting money. The new system also provides the ability to measure travel times between work zones, with this information an adjustment can be made in material placement or path of travel, thus enhancing productive worker time.

#### 6.1.6 Billing and Record Keeping

The system can recorded the amount of time a worker spends on the site, including the exact zones. Automated reports can be generated for billing purposes (the legal issues are out of scope). The billable hours can be compared to actual hours spent on the site to verify the correct payment. This feature can possibly reduce fraud of being paid for work not conducted. Additionally, the reports can also be used for verification purposes of billable hours in case disputes arise.

#### 6.1.7 Cultural Factors

Initially, subcontractors and workers showed concern that the system monitored their exact location at all times, however, through seminars and training, it was conveyed that the purpose of the system is to identify the zones where the worker was last seen, not determine their exact location at all times. Communicating this to the workers allowed them to feel more comfortable and see the benefits of the RFID system. Benefits such as enhancing the security and safety of the project, only allowing authorized personnel onto the site, or ensuring that individuals without the proper training do not enter the wrong zones gave the workers a higher sense of security and assured the subcontractors that costly errors can be avoided.

### 6.2 Limitations, Barriers, and Future Work

The system for tracking workers was shown to be a success. The next steps include asset tracking of construction equipment and materials. Knowing the real-time locations of equipment and materials can potentially increase productivity. For example, using the tracking data, the most efficient storage location of the materials and equipment can be calculating by analyzing worker's travel locations and times. Knowing where the equipment was last may reduce time spent searching for it. Additionally, theft and damage may be reduced by having expensive equipment materials stored in secure rooms, and alerts can be sent when they are removed.

Additional work includes utilizing the system for more in-depth productivity analyses. For instance, using the cross-referenced man power with the progress data can provide accurate and efficient estimates of future manpower. Researching and defining behavioral metrics as leading indicators can be beneficial for construction management.

## 7. ACKNOWLEDGEMENTS

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## 8. REFERENCES

Allmon, E., Haas, C.T., Borcherding, J.D., & Goodrum, P.M. (2000), U.S. Construction Labor Productivity Trends, 1970–1998, ASCE Journal of Construction Engineering and Management, 126 (2), 97–104.

buildingSMART. (2013), IFC4 Official Release. http://www.buildingsmart-tech.org/ifc/IFC4/final/html/

Cheng, T., Venugopal, M., Teizer, J. & Vela, P. A. (2011), Performance Evaluation of Ultra Wideband Technology for Construction Resource Location Tracking in Harsh Environments, Automation in Construction, 20, 1173-1184.

Cho, Y. S., Lee, S. I. & Bae, J. S. (2014), Reinforcement Placement in a Concrete Slab Object Using Structural Building Information Modeling, Computer-Aided Civil and Infrastructure Engineering, 29, 47–59.

Costin, A., Pradhanang, N., & Teizer, J. (2012a), Leveraging passive RFID technology for construction resource field mobility and status monitoring in a high-rise renovation project, Automation in Construction, 24, 1-15.

Costin, A., Pradhananga, N., & Teizer, J., (2012b), Integration of Passive RFID Location Tracking in Building Information Models (BIM). EG-ICE, Int. Workshop, Herrsching, Germany,4-6.

Costin, A., & Teizer.J. (2014), Utilizing BIM for Real-Time Visualization and Indoor Localization of Resources, In Computing in Civil and Building Engineering, pp. 649-656. ASCE

Eastman, C., Teicholz, P., Sacks, R., & Liston, K. (2008), BIM Handbook- A Guide to Building Information Modeling, John Wiley & Sons, Inc., NJ.

Ergen, E., & Akinci, B. (2007), An Overview of Approaches for Utilizing RFID In Construction Industry, Proceedings of 1st Annual RFID Eurasia, Istanbul, Turkey.

Ergen, E. Akinci, B. East, B. Kirby, J. (2007). Tracking Components and Maintenance History within a Facility Utilizing Radio Frequency Identification Technology, Journal of Computing in Civil Engineering, 21, 11-20.

Ergen, E., Akinci, B., & Sacks, R. (2007), Tracking and locating components in a precast storage yard utilizing radio frequency identification technology and GPS, Automation in Construction, 16(3), 354-367.

Goodrum, P., McLaren, M. & Durfee, A. (2006), The Application of Active Radio Frequency Identification Technology for Tool Tracking on Construction Job Sites, Automation in Construction, 15, 292-302.

Grau, D., Caldas, C.H., Haas, C.T., Goodrum, P.M., & Gong, J. (2009), Assessing the Impact of Materials Tracking Technologies on Construction Craft Productivity, Automation in Construction, 18, 903–911.

Hendrickson, C. (2008), Project Management for Construction, http://pmbook.ce.cmu.edu (Accessed January 27, 2009).

Jaselskis, E. J., & El-Misalami, T. (2003), Implementing Radio Frequency Identification in the Construction Process. Journal of Construction Engineering and Management, 129(6), 680-688.

Kean, T. (2011), Current Trends and Future Outlook Examining the IFMA industry trend report, Military Engineer, 103(673), 67-68

Kelm, A., Laußat, L., Meins-Becker, A., Platz, D., Khazaee, M. J., Costin, A. M., Manfred, H., & Teizer, J. (2013). Mobile passive Radio Frequency Identification (RFID) portal for automated and rapid control of Personal Protective Equipment (PPE) on construction sites. Automation in Construction, 36, 38-52.

Lee, J.-B. & Han, C.-H. (2008), A Feasibility Study on Optimal Lifting Planning in the High-Rise Apartment Building Construction, Journal of Korea Institute of Construction Engineering and Management, 9, 185–193.

Li, N., & Becerik-Gerber, B. (2011), Performance-Based Evaluation Of RFID-Based Indoor Location Sensing Solutions for the Built Environment, Advanced Engineering Informatics, 25(3), 535-546

McGraw-Hill (2012), SmartMarket Report: The Business Value of BIM in North America Multi-Year Trend Analysis and User Ratings (2007-2012) Construction, McGraw-Hill Construction.

Motamedi, A., Setayeshgar, S., Soltani, M. M., & Hammad, A. (2013). Extending BIM to incorporate information of RFID tags attached to building assets. In International Conference on Computing in Civil and Building Engineering, Montreal, Canada.

Office of Economic and Workforce Development (2011), Local Hire, WorkforceDevelopmentSF,http://www.workforcedevelopmentsf.org/aboutus/index.php?option=com_content&view=article&id=88&Itemid=102, (Accessed January 13, 2012).

Oglesby C., (1988), Productivity Improvement in Construction, Construction Engineering and Project Management, 146–271.

Pradhananga, N. and Teizer, J. (2013). Automatic Spatio-Temporal Analysis of Construction Equipment Operations using GPS Data", Automation in Construction, 29, 107-122.

Razavi, S.N., & Haas, C.T. (2010), Multisensor Data Fusion for On-Site Materials Tracking in Construction, Automation in Construction, 19, 1037–1046.

Ross, W.A., Burns, S.E., Wu, P.Y., & Jared, D.M. (2009), Radio Frequency Identification Tracking Technology Applied to Testing of Transportation Construction Materials, Journal of the Transportation Research Board No. 2098, 3–12.

Rüppel, U., & Stübbe, K. (2008), BIM Based Indoor-Emergency-Navigation-System for Complex Buildings, Tsinghua Science and Technology Journal, Tsinghua University, 13(S1), 362-367.

Sawyer, T. (2008), $1-Billion Jigsaw Puzzle Has Builder Modeling Supply Chains, http://enr.construction.com/features/technologyEconst/archives/080423-1.asp.

Skibniewski, M. J. & Jang, W.-S. (2009), Simulation of Accuracy Performance for Wireless Sensor-Based Construction Asset Tracking, Computer-Aided Civil and Infrastructure Engineering, 24, 335–345.

Sørensen, K. B., Christiansson, P. & Svidt, K. (2010), Ontologies to Support RFID-Based Link between Virtual Models and Construction Components, Computer-Aided Civil and Infrastructure Engineering, 25, 285–302.

Song, J., Haas, C.T., Caldas, C., Ergen, E., & Akinci, B. (2006), Automating the task of tracking the delivery and receipt of fabricated pipe spools in industrial projects, Automation in Construction, 15(2), 166-177.

Taneja, S., Akcamete, A., Akinci, B., Garrett, J., Jr., Soibelman, L., & East, E. (2012), Analysis of Three Indoor Localization Technologies for Supporting Operations and Maintenance Field Tasks, Journal of Computing in Civil Engineering, 26(6), 708–719.

Teizer, J., Lao, D., & Sofer, M. (2007). Rapid Automated Monitoring of Construction Site Activities using Ultra-Wideband, Proceedings of the 24th International Symposium on Automation and Robotics in Construction, Cochin, Kerala, India, 23-28.

Teizer., J. (2015a). “Safety 360: Surround View and Alerts to Protect Workers from Hazardous Equipment”, Proc.32nd International Symposium on Automation and Robotics in Construction, Oulu, Finland.

Teizer, J. (2015b). “Status Quo and Open Challenges in Vision-Based Sensing and Tracking of Temporary Resources on Infrastructure Construction Sites”, Advanced Engineering Informatics, Special Issue Infrastructure Computer Vision, Elsevier, 29, 225-238.

Teizer, J., Golovina, O., Wang, D., and Pradhananga, N. (2015c). “Automated Collection, Identification, Localization, and Analysis of Worker-Related Proximity Hazard Events in Heavy Construction Equipment Operation”, 32nd ISARC, Oulu, Finland.

Teizer, J. (2015d). “Magnetic Field Worker Proximity Detection and Alert Technology for Safe Heavy Construction Equipment Operation”, Proceedings of the 32nd International Symposium on Automation and Robotics in Construction, Oulu, Finland.

Teizer, J. (2015e). Wearable, wireless identification sensing platform: Self-Monitoring Alert and Reporting Technology for Hazard Avoidance and Training (SmartHat). Journal of Information Technology in Construction (ITcon), Vol. 20, pg. 295-312, http://www.itcon.org/2015/19

Umetani, T., Inoue, K. & Arai, T. (2011), Pose Estimation of Construction Materials Using Multiple ID Devices for Parts and Packets Unification, Computer-Aided Civil and Infrastructure Engineering, 26, 356–367.

Vogt B., & Teizer J. (2007), Sparse Laser Scanning to Improve Off-Shore Pipe-fitting Productivity, Proceedings of the Construction Research Congress, Freeport, Bahamas, May 6–8.

Xie, H., Shi, W. & Issa, R. R. A. (2010), Implementation of BIM/RFID in Computer-Aided Design-Manufacturing-Installation Process, 3rd IEEE International on Conference Computer Science and Information Technology, Chengdu, China , 107-111.

Yang, J., Cheng, T., Teizer, J., Vela, P.A., & Shi, Z.K. (2011), A Performance Evaluation of Vision and Radio Frequency Tracking Methods for Interacting Workforce, Advanced Engineering Informatics, 25(4),736–747.

Zhai, D., Goodrum, P.M., Haas, C.T., & Caldas, C.H. (2009), Relationship between the Automation and Integration of Construction Information Systems and Productivity, ASCE Journal of Construction Engineering and Management, 135(8), 746–753.

Zhang, S., Sulankivi, K., Kiviniemi, M., Romo, I., Eastman, C.M., and Teizer, J. (2015). “BIM-based Fall Hazard Identification and Prevention in Construction Planning”, Safety Science, Elsevier, 72, 31-45.