

İSTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE
ENGINEERING AND TECHNOLOGY

**A DATA FUSION APPROACH FOR MONITORING ACTIVITIES IN DOUBLE
SHIFT CONSTRUCTION SITES USING SENSOR-BASED DATA TRACKING
TECHNOLOGIES**



Ph.D. THESIS

Gürşans GÜVEN İŞİN

Department of Civil Engineering

Structural Engineering Program

FEBRUARY 2016

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(501092016)**

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Thesis Advisor: Assoc. Prof. Dr. Esin ERGEN PEHLEVAN

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

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VERİ TAKİP TEKNOLOJİLERİ KULLANILARAK TESPİT EDİLMESİ İÇİN
BİR VERİ FÜZYONU YAKLAŞIMI**

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**Gürşans GÜVEN İŞİN
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Gürşans GÜVEN IŞIN, a Ph.D. student of ITU Graduate School of Science Engineering and Technology student ID 501092016, successfully defended the dissertation entitled “A DATA FUSION APPROACH FOR MONITORING ACTIVITIES IN DOUBLE SHIFT CONSTRUCTION SITES USING SENSOR-BASED DATA TRACKING TECHNOLOGIES”, which she prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

Thesis Advisor : **Assoc. Prof. Dr. Esin ERGEN PEHLEVAN**.....
İstanbul Technical University

Jury Members : **Assoc. Prof. Dr. G. Emre GÜRCANLI**
İstanbul Technical University

Assoc. Prof. Dr. Deniz İLTER
İstanbul Technical University

Asst. Prof. Dr. Ragıp AKBAŞ
Ozyegin University

Assoc. Prof. Dr. Beliz ÖZORHON
Bogazici University

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To my grandmother,



FOREWORD

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February 2016

Gürşans GÜVEN IŞIN
Civil Engineer



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ABBREVIATIONS

BIM	: Building Information Modeling
GNSS	: Global Navigation Satellite System
GPS	: Global Positioning System
OBI	: On-board Instrument
RFID	: Radio Frequency Identification
ID	: Identification/Identity/Identifier
UWB	: Ultra Wideband
PSM	: Physiological Status Monitoring
LOD	: Level of Detail
IDEF0	: Integrated Defition for Function Modeling



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A DATA FUSION APPROACH FOR MONITORING ACTIVITIES IN DOUBLE SHIFT CONSTRUCTION SITES USING SENSOR-BASED DATA TRACKING TECHNOLOGIES

SUMMARY

Although it is common in our country to work double shifts in large construction projects to shorten the total construction time; there is not an effective project control and monitoring approach to ensure construction resources are used effectively throughout the shifts. Moreover, there is less number of personnel responsible for project control and monitoring in the night shift. Project control and monitoring in both shifts is based on the information that is collected from field and this information is mostly missing and/or incorrect. Also, it is time consuming to transfer the manually collected performance data of activities (progress and productivity) to a computer platform for carrying out analyses and the data is not up-to-date. There is a need for automated tracking of construction progress for double shift projects and developed approach need to function well both nighttime and daytime conditions.

Previous studies on automated progress monitoring at construction sites focused only on monitoring of daytime work and the potential of construction equipment that are utilized at different stages of a construction activity to provide information about the progress of that on-going activity has been overlooked. However, a solution addressing the issues of a daytime work might not be able to function well during the nighttime work due to different working conditions (e.g., less lighting, less number of personnel in charge). Therefore, in this PhD research, it has been targeted to develop a method that will enable continuous monitoring of both day and night shifts in a construction project, ensuring that the construction resources (material, labor and equipment) are used effectively throughout the shifts and hence, the intended productivity levels are achieved.

The main objective of this PhD research is to identify the requirements for monitoring the progress of activities in double shift building projects using construction equipment and to develop an automated sensor-based approach that tracks equipment and the related parameters for this purpose. To achieve this objective; the equipment tracking requirements (i.e., activities, equipment and related parameters to be tracked, and the technology-independent requirements) were determined for double shift construction sites and appropriate technologies were selected. Initial tests were performed with the selected technologies for determining the functional (i.e., technology-specific) requirements.

Once the functional requirements were identified, necessary reasoning mechanisms needed to be defined for utilizing sensor-based technologies for monitoring the progress of construction activities by tracking construction equipment. To achieve the equipment tracking-based activity monitoring vision of this PhD research study, data obtained from several construction equipment via sensor-based technologies are needed to be fused with project related information, such as quantity takeoffs, schedules and site reports. These different data sources provide data at different time

intervals and are fragmented in nature. The necessary reasoning mechanisms were determined and a data fusion approach was developed to fuse this fragmented data in a complementary and supporting fashion for monitoring the progress of construction activities.

To validate the identified requirements and reasoning mechanisms developed for monitoring the progress of activities in double shift building projects with sensor-based tracking approach, a prototype system was developed. The physical prototype was implemented as a proof of concept, and field tests were performed for validating the developed approach in terms of determining the progress of (1) masonry, (2) rebar installation, and (3) steel component transfer to installation area at a double shift construction site in Istanbul. Actual progress data were collected for three months using the tower crane sensors, RFID system on the elevator, wireless accelerometer on a hand drill and total station device for masonry work and rebar installation at a building. Since no steel installation was scheduled within the time period of the field experiments; the approach to monitor the progress of steel component installation was demonstrated by fusing the generated data that represent a steel component transfer to installation area with the steel quantity takeoff.

Masonry work was monitored at eight floors (i.e., floors 20 to 27) and the results showed that, masonry work progress can be predicted with an average of 96% accuracy by fusing the data about the amount of material delivered to the floor obtained from tower crane sensors and the amount of material utilized at the floor obtained from the RFID data. These findings demonstrate that the developed approach can be effectively used in determining the progress of masonry work at double shift construction sites.

Rebar installation was monitored at six floors (i.e., floors 27 to 32) and the progress and performance of the rebar installation activity was estimated based on the data obtained from the tower crane sensors and total station. The developed approach estimated the rebar installation progress daily, by comparing the total weight of rebar brought to the floor with the rebar quantity takeoff of the floor. The developed approach was able to estimate the percentages of completion at six floors with 95% accuracy (i.e., average of six floors).

The approach developed for monitoring the progress of steel component installation activity was demonstrated on a fictitious data set that was generated to represent the movements of a tower crane transferring a steel component from the laydown area to the installation location on the building. The developed monitoring approach compares the weight of the steel component that is transferred to its installation location with the total weight of the steel project and calculates a percentage of completion. The sample data set illustrated the transfer of a 2.0 tons of steel component to the building. Considering the total steel project quantity takeoff (i.e., 20 tons), the progress was calculated 10%.

For visualizing and using the progress and performance data of the activities in further analysis and for creating reports, user interfaces were developed. Technical office personnel and site management were envisioned as the users of the developed user interfaces. Technical office personnel will be able to integrate the field data collected via sensor-based technologies with the quantity takeoffs and planned start and end dates of activities to obtain realistic progress and productivity information. While the site management will be able to visualize the utilization of material and equipment in more detail. User interfaces targeted at enabling the presentation of the progress data obtained from the field to the executives through graphical and visual data.

Practitioners can use the automated activity progress and productivity monitoring approach developed in this study to avoid conflicts that occur between the employer and the contractor on the amount of completed work at the time of progress payments and develop timely solutions for productivity problems. The developed approach was tested on a reinforced concrete building construction, however, this approach is very suitable for prefabrication or steel construction as activities in these construction sites are more organized as opposed to reinforced concrete construction and similar activities are performed repeatedly.

Due to continuous material supply to construction sites, it can be very difficult to keep a realistic track of the amount of material transferred to floors and left in site stocks, and to know how much more material is needed and how much material is wasted. Developed activity monitoring approach can enable practitioners to know the amount of material delivered to the site, transferred to the floor, and left at the stock; and therefore projecting future material needs and updating schedules accordingly.

The focus of this study was equipment tracking. Main reason was that the equipment at construction sites are less in number, and therefore provide a less complicated and more economic means of resource tracking. Field experiments showed that the equipments provide reliable sources of information for progress tracking of activities. In addition to the sensor-based technologies mounted on construction equipment, developed prototype utilized data collection methods readily available on construction equipment. Therefore, practitioners can utilize the developed approach at their sites only by small investments and by applying the reasoning mechanisms described in this study to collect data from field for progress monitoring of activities. The equipment tracking requirements identified in this study are expected to provide a starting point for practitioners and researchers to develop systems based on different data collection technologies.

Manual steps included in the data collection and implementation phase of the current version of the prototype can be automated. For example the project related information, such as the quantity takeoff, planned start and end dates of activities, material information, were entered manually to the data fusion user interface. Future research is directed to automate these steps by integrating Building Information Models for extracting such information automatically. The requirements will be identified for defining the necessary LOD levels needed for this type of usage of BIMs and steps will be determined for practitioners on how to define necessary project related data within building elements.



ŞANTİYELERDE AKTİVİTE İLERLEMELERİNİN ALGILAYICI TABANLI VERİ TAKİP TEKNOLOJİLERİ KULLANILARAK TESPİT EDİLMESİ İÇİN BİR VERİ FÜZYONU YAKLAŞIMI

ÖZET

Büyük inşaat projelerinde toplam süreyi kısaltmak için çift vardiyalı çalışılması ülkemizde de çok yaygın olmasına rağmen, kaynakların vardiyalar arasında verimli dağıtılmasını sağlayacak etkin bir proje kontrolü ve izlemesi yapılamamaktadır. Ayrıca, gece vardiyalarında proje izlemesi ve kontrolünden sorumlu teknik personel sayısı da azdır. Gerek gündüz gerekse gece vardiyalarında proje kontrolü ve izlemesi sahadan kağıt üzerinde toplanan bilgiler ile yapılmakta; çoğu zaman bu bilgiler eksik ve/veya hatalı olmaktadır. Ayrıca, aktivitelerin performansına ilişkin bilgilerin (ilerlemeler ve verimlilikler) bilgisayar ortamına geçirilip analiz edilmesi de ekstra zaman almakta ve bu bilgiler yeterince güncel olmamaktadır. Aktivitelerin ilerlemelerinin izlenmesi için otomatik bir yöntem ihtiyacı duyulmaktadır ve geliştirilen yöntemin hem gündüz hem de gece vardiyalarında çalışabilmesi gerekmektedir.

Literatürde inşaat sahalarının otomatik izlenmesi ve kontrolü için yapılmış çalışmalarda sadece gündüz işlerine odaklanılmış ve inşaatın çeşitli aşamalarında kullanılan ekipmanlarının devam eden aktivitelerle ilgili ilerleme bilgisi sağlama potansiyeli göz ardı edilmiştir. Oysa gündüz vardiyasındaki problemleri çözmeye yönelik geliştirilen çözümler, gece vardiyalarının farklı çalışma koşullarına sahip olmasından dolayı (ör. daha az ışıklandırma, daha az sorumlu personel) etkin çalışmayabilir. Bu nedenle bu doktora araştırmasında gece ve gündüz kesintisiz olarak aktivitelerin izlenmesi için bir yaklaşım geliştirilerek, kaynakların (malzeme, işgücü ve ekipman) vardiyalar arasında efektif şekilde kullanılmasını ve amaçlanan verimlilik seviyelerine ulaşılmasını sağlamak hedeflenmiştir.

Bu doktora araştırmasının ana hedefi çift vardiya çalışılan bina inşaatlarında aktivitelerin ekipman takibi yapılarak izlenmesi için gereksinimlerin belirlenmesi ve algılayıcı-tabanlı teknolojiler ile inşaat ekipmanlarını takip ederek aktivite ilerlemelerini otomatik olarak tespit eden bir yaklaşım geliştirmektir. Bu hedefe ulaşmak için, çift vardiya çalışılan inşaat sahalarında ekipman takibi gereksinimleri (takip edilecek aktiviteler, ekipmanlar ve ilgili parametreler ile veri takip teknolojilerinin çift vardiya çalışılan inşaat sahalarında kullanılmaları için üst düzey gereksinimler) belirlenmiştir. Uygun algılayıcı-tabanlı teknolojilerinin seçimi bu gereksinimler baz alınarak yapılmış ve ön testler gerçekleştirilerek, fonksiyonel (teknolojilere has) gereksinimler belirlenmiştir.

Fonksiyonel gereksinimlerin belirlenmesinden sonra algılayıcı-tabanlı teknolojilerin inşaat aktivitelerinin ilerlemelerini izlemek üzere ekipmanları takip edebilmeleri için gerekli olan çıkarım mekanizmalarının oluşturulması gerekmektedir. Bu doktora araştırmasının vizyonu olan ekipman takibi tabanlı aktivite izleme vizyonunun gerçekleştirilebilmesi için pek çok inşaat ekipmanından algılayıcı-tabanlı teknolojiler ile toplanan verilerin ve inşaat projesi ile ilgili metraj, iş programı, saha raporları gibi

çeşitli bilgilerin birleştirilmesi gerekmektedir. Bu veri kaynakları farklı zamanlarda veri sağlamakta olup dağınık yapıdadır. Gerekli çıkarım mekanizmaları belirlenerek bu dağınık yapıdaki verilerin birbirini tamamlar ve destekler şekilde birleştirilmesi için bir veri füzyonu yaklaşımı geliştirilmiştir.

Çift vardiya çalışılan inşaat sahalarındaki aktivite ilerlemelerinin algılayıcı-tabanlı takip yöntemi ile izlenmesi için geliştirilen gereksinimlerin ve çıkarım mekanizmalarının geçerliliğinin sınanabilmesi için bir prototip geliştirilmiştir. Kavramın ispatı amacıyla fiziksel bir prototip uygulanarak İstanbul, Türkiye'de bir çift vardiya çalışılan bina inşaatı şantiyesinde saha testleri gerçekleştirilmiş ve geliştirilen yöntemin geçerliliği (1) duvar işleri, (2) donatı montaj işleri, ve (3) çelik elemanların montaj yerine taşınması işleri için gösterilmiştir. Kule vinç algılayıcıları, cephe asansörü üzerine kurulan RFID sistemi, el mikseri üzerine yerleştirilen kablosuz ivmeölçer ve total station cihazı kullanılarak duvar işleri ve donatı montaj işleri için gerçek ilerleme verileri üç ay süreyle toplanmıştır. Saha testleri süresince herhangi bir çelik eleman montajı gerçekleşmediğinden, çelik elemanların montajının izlenmesi için geliştirilen veri füzyonu yaklaşımı fiktif olarak oluşturulan bir veri setinin ve çelik eleman metrajının birleştirilmesi üzerinden gösterilmiştir.

Duvar işleri sekiz katta (20-27. katlar arası) izlenmiştir ve sonuçlar duvar imalatındaki ilerleme bilgisinin, kule vinç algılayıcılarına göre kata getirilen malzeme miktarı ve RFID sistemine göre katta kullanılmış malzeme miktarı bilgilerinin birleştirilmesiyle ortalama olarak %96 doğrulukla tahmin edildiğini göstermektedir. Bulgular, geliştirilen yaklaşımın duvar imalat ilerlemelerinin belirlenmesinde başarı ile kullanılabileceğini göstermektedir.

Donatı montajı işi altı katta (27-32. katlar arası) izlenmiştir ve donatı montaj işinin ilerlemeleri ve performansları kule vinç algılayıcılarından ve total station cihazından elde edilen bilgilerin birleştirilmesiyle tahmin edilmiştir. Geliştirilen yöntemde donatı montajı işindeki ilerleme günlük olarak kata getirilen donatı miktarı ile kat metrajındaki donatı miktarı oranlanarak hesaplanmaktadır. Sonuçlar geliştirilen yöntemin altı katın ortalaması alındığında %95 doğrulukla donatı montajı işindeki ilerlemelerin tespit edilebildiğini göstermiştir.

Çelik imalatının izlemesinin geliştirilen ekipman takibi yaklaşımı ile nasıl yapılacağı, takibi yapılan bloğa bir çelik elemanın getirilmesi ve montaj yerine kule vinç ile taşınmasını gösteren kule vinç hareketlerinin fiktif olarak oluşturulduğu bir veri üzerinden gerçekleştirilmiştir. Çelik imalatının takibinin yapıldığı kullanıcı arayüzünde kule vinç verilerine göre yerine taşındığı belirlenen çelik eleman ağırlığının, bloktaki çelik elemanların toplam metrajına oranlanmasıyla yüzdesel bir tamamlanma hesap edilmektedir. Örnek veri setinde 2.0 ton'luk bir çelik elemanın çelik stok sahasından binanın üzerine getirildiği tespit edilmiştir. Yerine getirildiği belirlenen çelik eleman ağırlığı projenin toplam çelik metrajına (20 ton) oranlanarak işin tamamlanmasının %10 olduğu hesaplanmıştır.

Prototip kapsamında aktivitelerin performanslarına ilişkin bilgilerin analize ve raporlamaya hazır hale getirilmesi için gerekli yazılım geliştirme çalışmaları yürütülerek, kullanıcı dostu bir arayüz geliştirilmiştir. Geliştirilen arayüzün hedef kullanıcısı olarak şantiye teknik ofis personeli düşünülmüştür. Teknik ofis personeli geliştirilen kullanıcı arayüzüne sahadaki algılayıcılardan toplanan veriler ile imalatların metraj ve planlanan başlangıç ve bitiş tarihlerini birleştirerek, imalat ilerlemeleri hakkında gerçekçi bilgiye ulaşabilmektedir. Sahadan elde edilen ilerleme bilgileri, haftalık/aylık toplantılarda görüşülmek üzere görsel araçlarla ve sayısal olarak özetlenmiş şekilde geliştirilen kullanıcı arayüzü aracılığıyla üst yönetime sunulabilmektedir.

Bu çalışmada aktivitelerin ilerlemelerinin ve verimliliklerin otomatik olarak izlenmesi için geliştirilen yaklaşımın uygulamada kullanılmasıyla işveren ve yüklenici arasında tamamlanan iş miktarının belirlenmesi konusunda hakediş zamanlarında yaşanan anlaşmazlıkların önlenmesi ve verimlilik problemleri için zamanında çözüm üretilmesi mümkün olacaktır. Geliştirilen yaklaşım bir betonarme konut inşaatında test edilmiş olmasına rağmen; imalatların daha organize yürütüldüğü ve benzer aktivitelerin tekrar edildiği prefabrik ve çelik konstrüksiyon şantiyeleri için de oldukça uygundur.

Şantiyelerde sürekli bir malzeme temini söz konusu olduğundan; sahaya gelen malzeme katlara iletildiğinde bunların ne kadarının kata dağıtıldığı, ne kadarının imalata girdiği, ne kadar daha malzemeye ihtiyaç olduğu ve zayıtının ne kadar olduğu tam olarak bilinmemektedir. Önerilen ekipman takibi vizyonu ile, şantiyeye getirilen, katlara çıkarılan ve stokta kalan malzeme miktarlarını gerçekçi şekilde bilerek, oluşacak malzeme ihtiyaçlarını bilmek ve iş programlarını güncellemek mümkün olmaktadır.

Bu çalışmada ekipmanların takibine odaklanılmıştır. Bunun temel sebebi, sahada işgücü ve malzemeye göre ekipmanların sayıca çok daha az olması ve bu sebeple takibinin daha az karmaşık ve ekonomik olmasıdır. Yapılan testler ekipmanların aktivitelerle ilgili ilerlemelerin izlenmesinde güvenilir bir veri kaynağı olduğunu göstermiştir. İnşaat ekipmanları üzerine yerleştirilen algılayıcı-tabanlı takip teknolojilerine ek olarak bazı ekipmanlar üzerinde halihazırda yer alan veri toplama yöntemlerinden de faydalanılmıştır. Bu nedenle uygulamada, şantiyelere sadece ufak yatırımlar yapılarak bu çalışmada tariflenen çıkarım mekanizmaları kullanılarak aktiviteler ile ilgili sahadan bilgi toplanabilir. Ekipmanlar üzerinden izlenmesi kararlaştırılan parametrelerin, aktivitelerin ilerlemelerini farklı teknolojiler yardımıyla takip etmek isteyen araştırmacılar için başlangıç noktası olacağı ve bu parametreler kullanılarak farklı teknolojilere dayalı sistemler geliştirilebileceği düşünülmektedir.

Prototipin mevcut durumunda imalatların izlenmesi için gerekli olan proje ile ilgili metraj, iş programına göre planlanan tarihler, malzeme bilgileri vb. bilgiler manuel olarak girilecek şekilde tasarlanmıştır. Bu çalışmanın ileriki adımlarında proje ile ilgili veri girişlerinin otomatikleştirilmesi planlanmaktadır. Bunun için, gerekli bilgiler örneğin binaların Yapı Bilgi Modelleri'nden otomatik olarak çekilebilir. Bilgilerin modellerden otomatik çekilmesi için kullanıcıların hangi detay seviyesinde (ör. LOD 300) BIM modellerine ihtiyaç duyacağı, projeye özgü hangi bilgileri, nasıl tanımlayacaklarını gösteren adımların belirlenmesi ve gereksinimlerin tespit edilmesi, bu çalışmanın bir sonraki adımı olarak planlanmaktadır.



1. INTRODUCTION

To shorten the duration of a construction project, double shift work is commonly practiced; however, some problems arise from working in shifts. Project monitoring and control at night shifts is usually not effective due to lack of supervisors and challenging site conditions (e.g., insufficient light) that differ from that of the day shift. Night shift conditions affect the productivity of night shift workers both physically and mentally (Mostafavi et al., 2012) and disruptions are likely to occur in night shifts (Jun and El-Rayes, 2010). This results in lower quality levels and defects in the work performed in the night shifts, as well as lower productivity levels.

Another problem that is common in both shifts is that the current method for project monitoring in construction sites relies heavily on manual and paper-based data collected from field through visual investigation. Progress of activities are estimated based on the field investigation which is very subjective and intuitive as it can change from person to person depending on personal experience. Progress payments are built on these activity progress estimations and consequently conflicts occur between the employer and the contractor on the amount of completed work at the time of progress payments. As the progress of activities cannot be reliably determined and monitored on a regular basis (1) the actual progress can barely be determined at the end of a month, which is too late to take actions, and (2) productivity cannot be identified properly, and timely precautions cannot be taken to prevent productivity problems.

Existing studies in the literature have been overlooking the problems of double shift construction projects and mostly focusing on solving the problems of a daytime work. However, a solution addressing the issues of a daytime work might not be able to function well during the nighttime work due to different working conditions (e.g., less lighting, less number of personnel in charge). Therefore, in this PhD research, it has been targeted to develop a method that will enable continuous monitoring of both day and night shifts in a construction project, ensuring that the construction resources

(material, labor and equipment) are used effectively throughout the shifts and hence, the intended productivity levels are achieved.

1.1 Problem Statement

Effectively monitoring the progress of construction projects is crucial for better allocation and control of construction resources and for avoiding delays and cost overruns. However, current methods that are used for monitoring construction projects are not effective. The traditional approaches heavily rely on manual data collection from field through visual investigation based on personal experience. The report of the Construction Industry Institute stated that, about 1% of the gross budget of a typical construction project is spent on monitoring the status of construction activity (Son and Kim, 2010). It has also been stated through previous observations that field supervisory personnel allocate on average 30% to 50% of their time to record and analyze field data (McCulloch, 1997). Furthermore, manually tracking and recording the progress in the field takes up to 2% of the work at construction sites; still the completeness and accuracy of the collected data relies on the judgments and writing skills of the people collecting data (Akinici et al., 2006). Besides, it takes time to transfer the manually collected progress and productivity data of activities to a computer platform to carry out analyses, and in the meantime, the data might become out-of-date.

Monitoring the project is even more problematic in double-shift construction projects. Working conditions of night shifts (e.g., weather, lighting) differ from that of the day shifts and this affects the productivity of night shift workers both physically and mentally (Mostafavi et al., 2012). Moreover, night shifts are more prone to disruptions (Jun and El-Rayes, 2010) and less number of supervisory personnel is available in the night shift. This jeopardizes effective progress tracking at night shifts and the data collected for documenting productivity is inaccurate and less reliable than that of the day shift. There is a need for automated tracking of construction progress for double shift projects and developed approach need to function well both nighttime and daytime conditions.

Previous studies on automated progress monitoring at construction sites focused only on monitoring of daytime work using several automated field data capture technologies (e.g., Radio Frequency Identification (RFID) technology, Global

Positioning System (GPS), Ultra Wideband (UWB) technology, laser scanning) (Jaselskis et al., 2005; Song et al., 2006; Ergen et al., 2007a; 2007b; Golparvar-Fard et al. 2009a; 2009b; 2009c; Brilakis et al. 2011; El-Omari and Moselhi, 2011; Yang et al. 2012; Turkan et al., 2012a; 2012b; Montaser and Moselhi, 2012; Akhavian and Behzadan, 2012; Costin et al., 2012; Cheng et al. 2012; 2013a; 2013b; Pradhananga and Teizer, 2013; Shahi et al., 2013; 2014) and there has been no attempt to monitor both the daytime and nighttime work. In one of those studies, it has been suggested that the construction activities could be monitored based on the identified locations and movements of the equipment used in performing the activities (Sacks et al. 2005). However, most of the studies that use equipment to monitor activities focused on pieces of equipment that is used in earthmoving and excavation activities (Kannan and Vorster, 2000; Heydarian et al., 2012; Montaser and Moselhi, 2012; Akhavian and Behzadan, 2012; Pradhan and Akinci, 2012; Pradhananga and Teizer, 2013; Rezazadeh Azar et al., 2013), and a few studies tracked the equipment used in building construction. In an earlier study, researchers proposed to track the sound of the tools that are used in performing construction activities (e.g., carpentry work such as nailing with nail gun or hammer, sawing) to identify the type of activity being performed (Weerasinghe and Ruwanpura, 2009). The collected data was used for measuring the tool time and productivity of an activity. Other related studies were limited to tracking one type of activity (i.e., concrete pouring with crane bucket method) that is identified from video footage of cranes (Gong and Caldas 2010; Yang et al. 2012). In another building-related study, mobility and availability of resources, such as buck hoist, material cart and personnel, were tracked with a passive RFID system deployed in a high-rise building project (Costin et al., 2012). However, additional information can be gathered from equipment for progress monitoring. For example, built-in data collection systems that are either available or that could be later integrated with some construction equipment can collect and store information related to the equipment. Sacks et al. (2005) demonstrated that the built-in monitors located inside the tower crane cabins that show the weight of the lifted equipment and the position of the crane can be used for monitoring the activities performed with cranes. However, studies on integrating data from such integrated data collection systems (e.g., on-board instruments (OBIs)) on construction equipment are limited. To conclude, the potential of equipment tracking for progress monitoring in building construction has been overlooked.

This PhD research aims to identify the requirements for monitoring the progress of activities in double shift building projects using construction equipment and to develop an automated sensor-based approach that tracks equipment for this purpose. First, the high-level requirements were determined for data collection technologies to be used at double shift construction projects. Based on the high-level requirements, appropriate sensor-based technologies were selected and initial tests were performed to identify the functional requirements and appropriate hardware. Then, the necessary reasoning mechanisms for fusing the data collected from construction equipment and a prototype system were developed. Finally, a physical prototype was implemented as a proof of concept, and field tests were performed for validating the developed approach in terms of determining the progress of (1) masonry, (2) rebar installation, and (3) steel component transfer to installation area at a double shift building construction project.

The vision that this research is based on is provided in the next section (Section 1.2) and the research questions of this PhD study is described in the following section (Section 1.3).

1.2 Research Vision

Figure 1.1 shows the equipment tracking vision of the research study developed for monitoring the progress of construction activities and the productivity of activities where available. In this vision, different types of construction equipment is tracked throughout the different stages of construction for collecting information about the ongoing construction activities. By tracking how a particular equipment is used at what location and for how long; activities are monitored from the beginning of the material delivery stage until the end of the production stage at site: (1) delivery: tracking the delivery equipment during the transfer of materials from plant to construction site and return to plant/dumping area, (2) transfer: tracking the forwarding equipment during the transfer of material and other necessary items to production area within the construction site, and (3) production: tracking the equipment that are utilized while the production activities are performed. In this vision, the equipment that are directly or indirectly involved in each of these stages will be tracked. The equipment tracking performed at the construction site and at the

production area is the part of the research vision that was implemented in this PhD thesis and it is shown with a dashed box in Figure 1.1.

It is envisioned that the existing construction equipment and available means of on-board data collection is used for minimum interference with the current work flows. Following this vision, the next paragraphs give an overview on the data that needs to be collected through all stages, and the type of sensor-based data tracking and positioning technologies that were proposed for data collection. This vision proposed to collect data wirelessly where available, otherwise data is stored on-board and transferred to a central computer at the site office using a flash disc or an SD memory stick later on. Project related documents, such as schedules, project drawings, are also used as alternative and/or complementary data sources.

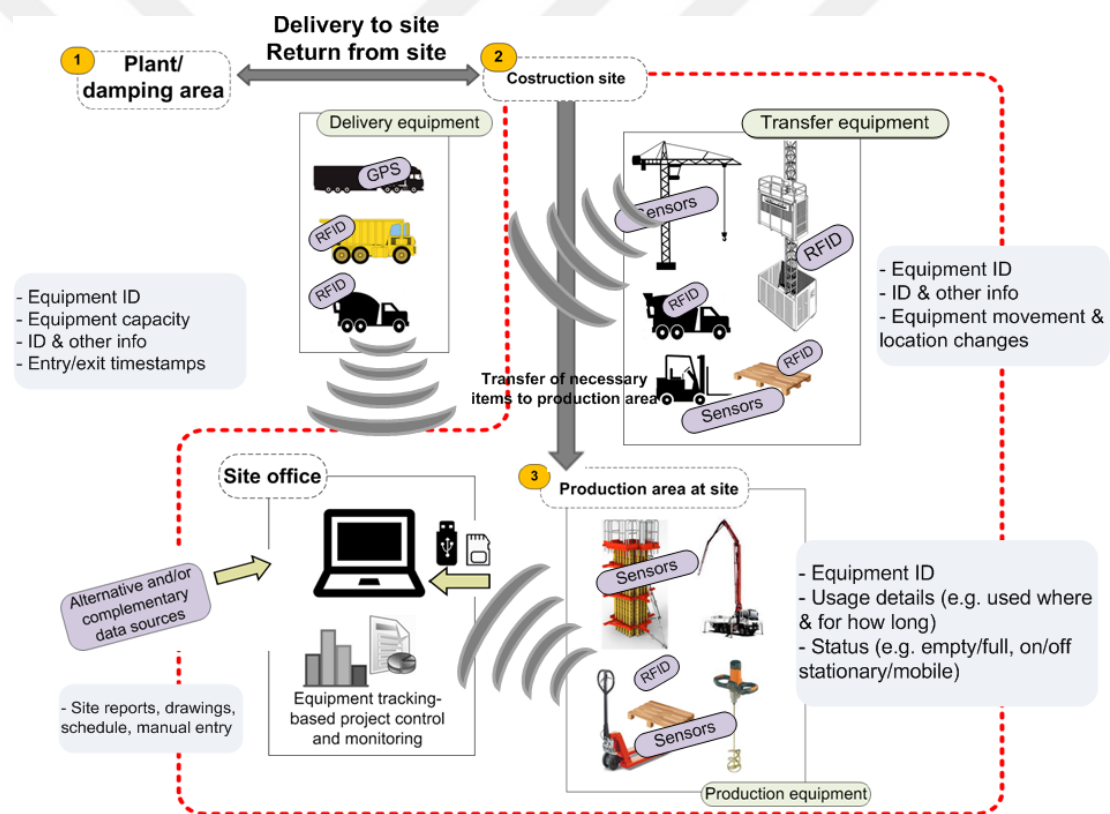


Figure 1.1 : Vision of equipment tracking for activity monitoring.

Tracking during delivery from plant to construction site and return to plant/dumping area: In the first step, delivery equipment such as trailers, trucks, concrete mixer trucks are physically tracked. They are used (1) to bring necessary materials to construction site and (2) to remove items such as construction and demolition wastes from site. The ID information of the delivery equipment, and the ID and other descriptive information of the item being delivered are tracked. Additionally, the

capacity of the delivery equipment (e.g., payload truck capacity in tons) and the entry/exit times of the equipment to/from site and plant/dumping area are included. For example the type and number of concrete mixer trucks that arrived at a construction site and the amount of concrete received and used at site on a particular day is tracked by attaching a GPS unit and an RFID tag to the concrete mixer trucks. The trajectory of a truck is instantly tracked via GPS from the time it is loaded at the concrete plant and to the time it is brought to site while the truck's RFID tag is read as it passes through the RFID-enabled gate at the entrance of the construction site. The data in tag includes volume and grade of concrete that is arrived at site, and the time of arrival to site. The time that the truck leaves the site is also tracked as the truck exits from the construction site.

Tracking during the transfer of material and other necessary items to production area within the construction site: In the second step, the ID information, location and movement (e.g., global or local coordinates and trajectory of an equipment) of the forwarding equipment such as cranes, elevators, are tracked. For example, the progress of steel construction performed on a particular day is monitored by tracking the tower crane load lifting activities in between the steel component laydown area and the building, along with the weight of loads carried by the tower crane. Related position and load data (i.e., (x, y, z) coordinates of the crane boom and hook, weight of the lifted item) is collected using the on-board sensors of a tower crane. Additionally, if a location-based progress tracking is needed, an RFID reader that is mounted on the crane hook reads the ID of the lifted steel component from the attached RFID tag attached, and the type and weight of the lifted component is identified. To prevent the performance reduction of the RFID system due to presence of metal in the environment, tags can be encapsulated or isolated with rubber or plastic. The percentage of work complete is calculated by comparing the weight of the lifted and installed component, to the total weight of all steel components in the project.

Tracking during the activities are performed at the production area: In the third and last step, the equipment such as hand drills, concrete pumps that are used to perform certain construction activities are tracked in terms of the whereabouts (e.g., at which building floor) of the equipment and the total equipment usage time (e.g., minutes, hours). For example the progress of a concrete pouring activity is tracked by

attaching wireless sensors (e.g., pressure, vibration) to a concrete pump and a GPS unit mounted near to the end of the concrete placing hose. The information about the amount of concrete delivered to site is obtained from the RFID readings of the concrete mixer truck in the delivery stage. This information is combined with the duration of the concrete pouring activity that is obtained from the operation time of the pump measured by the sensors and the location of the concrete pouring that is obtained from the GPS coordinates of the hose.

This research vision can provide advantages in terms of understanding the actual progress and related productivity of the monitored activities, along with the usage details of material and other resources while performing these activities. This enables (1) performing planned vs. actual progress analysis by comparing the calculated and/or predicted values from quantity takeoffs and schedules with actual values, (2) determining actual productivity and the amount of loss in material and other resources, and (3) projecting future material needs and updating schedules.

1.3 Research Questions

This PhD research addresses the following research questions:

1. What type of construction activities and related equipment can be tracked for progress monitoring in double shift building projects?
2. What are the requirements needed for using sensor-based tracking technologies to track the progress of activities in double shift building projects?
3. What are the necessary reasoning mechanisms for fusing the data obtained from the sensors deployed on construction equipment and from other project related information for monitoring construction activities?

Below is the detailed description of these research questions:

RQ1: What type of construction activities and related equipment can be tracked for progress monitoring in double shift building projects?

Several types of construction equipment are involved in different stages of construction activities and construction activities are performed with the assistance of these equipment. While some equipment can be used for multiple construction activities (e.g., tower cranes), others might be specialized in specific job types and

cannot be used for other activities (e.g., concrete mixers). Regardless of their type, all construction equipment that are utilized at different stages of a construction activity have the potential to provide information about the progress of that on-going activity.

The vision behind this research question is that the progress of typical building construction activities could be monitored by tracking information related to the equipment. For example, identified locations and operating durations of the equipment used in performing these activities. Equipment tracking studies in the literature were limited to the tracking of some construction equipment such as excavators, dump trucks and back-hoes for monitoring the progress of earthmoving and excavation activities (Kannan and Vorster, 2000; Heydarian et al., 2012; Montaser and Moselhi, 2012; Akhavian and Behzadan, 2012; Pradhan and Akinci, 2012; Rezazadeh Azar et al., 2013; Pradhananga and Teizer, 2013) and compactors for monitoring road construction activities (Navon and Shpatnitsky, 2005). However, a few studies focused on building construction and the tracked equipment were limited to (1) cranes and crane buckets that were used for monitoring concrete pouring (Sacks et al. 2005; Gong and Caldas, 2009; Yang et al., 2012), (2) hand tools used in carpentry works (Weerasinghe and Ruwanpura, 2009) and (3) concrete mixer trucks for monitoring concrete delivery activities (Lu et al., 2009). Therefore, this study aims to fill this gap in the literature by addressing this research question and aiming at identifying (1) the types of construction activities to be monitored in typical residential building projects, and (2) the type of equipment to be tracked to obtain the data about the progress of the identified activities.

In addressing this research question data collection was performed using these methods: (1) literature review, (2) investigation of project-related documents from six different residential projects located in Maslak and Atasehir region of Istanbul, (3) site observations at two residential projects in Istanbul, Maslak, and (4) face-to-face interviews with eleven technical personnel. The collected data was combined to identify the current paper-based methods that are conventionally used for activity progress monitoring and tracking, and the problems caused by estimating the construction progress based on the manually collected data from field. The potential improvements for the current approach were examined and the type of activities to be automatically monitored in typical residential projects were identified. The type of

equipment used for performing these construction activities were examined and the equipment that can be tracked for automated progress monitoring of each identified construction activity were determined. Chapter 2 elaborates this research question, along with the approach and the results in answering this question in detail.

RQ2: What are the requirements needed for using sensor-based tracking technologies to track the progress of activities in double shift building projects?

Current methods for monitoring projects are problematic and insufficient as they rely on paper-based data collection from field through visual investigation based on personal experience. Data collected in this manner is prone to be incomplete and inaccurate as the success of the data collection relies on the judgments and writing skills of whom collected it. Site visits and initial interviews with site personnel from different levels showed that timely and reliable means of progress monitoring of activities is needed to avoid conflicts at construction sites where large number of crews are working simultaneously and work is split among different subcontractors. In the case of double shift construction projects, it is even more critical as less number of supervisory personnel is available at nighttime, and workers are exposed to physical and mental fatigue (Mostafavi et al., 2012). Current practice highlights the need for an automated approach that functions well under both nighttime and daytime conditions for tracking of construction progress in double shift projects.

This research question was addressed in two steps: First, technology-independent high-level requirements for data collection technologies to be used at double shift construction projects were determined. This was achieved through observations at two double shift building sites and developing use cases for each of the construction activities that were identified in the previous research question. Second, based on the identified high-level requirements, the appropriate technologies were selected and initial tests were performed for determining the technology-specific requirements for the technologies selected. Details and the findings of the studies for determining the requirements needed for using sensor-based tracking technologies for tracking the progress of activities in double shift building projects are provided in Chapter 2.

RQ3: What are the necessary reasoning mechanisms for fusing the data obtained from the sensors deployed on construction equipment and from other project related information for monitoring construction activities?

This research question was addressed by (1) developing the necessary reasoning mechanisms and the data fusion approach for fusing the data obtained from the sensors deployed on construction equipment and other project related information for monitoring construction activities; and (2) developing and implementing a prototype as a proof-of-concept and conducting field experiments. A detailed literature review was performed on the existing studies that utilized technologies for progress monitoring and equipment tracking, and the existing data fusion models and studies in both the construction management domain and in other domains were investigated.

Previous studies have shown the need to fuse data from multiple data sources to support construction management tasks, such as productivity and progress monitoring, as a single data source will only contain a limited number of data items (Pradhan and Akinci, 2012). This method is called multi-source data fusion and there are several examples of data fusion in the construction management domain performed for localization and tracking of construction components and material, for progress and productivity monitoring, and for personnel and equipment tracking purposes (Song et al., 2006; Ergen et al., 2007b; Grau and Caldas, 2009; Razavi and Haas, 2010; Pradhan and Akinci, 2012a; Cheng et al., 2012; 2013a; 2013b; Shahi et al., 2013; 2014; Vasenev et al., 2014). In these studies, researchers developed a customized data fusion approach to address the specific needs of the problem at hand and did not provide a generic data fusion model that is applicable to all data fusion problems in the construction industry. To fulfill the need for a generic formalism for fusing data from multiple sources for construction management tasks; Pradhan and Akinci (2012) described a generic taxonomy of reasoning mechanisms to fuse a pair of spatial and temporal data sources to support construction productivity monitoring in road excavation projects.

To achieve the equipment tracking-based activity monitoring vision of this PhD research study, data obtained from several construction equipment via sensor-based technologies are needed to be fused with project related information, such as quantity takeoffs, schedules and site reports. These different data sources provide data at different time intervals and are fragmented in nature. Therefore, there is a need for developing a data fusion approach and the necessary reasoning mechanisms to fuse

this fragmented data in a complementary and supporting fashion for monitoring the progress of construction activities.

The reasoning mechanisms for fusing the data collected from construction equipment and a prototype were developed based on the identified functional requirements. While developing the reasoning mechanisms, the taxonomy of reasoning mechanisms described by Pradhan and Akinci (2012) was extended to fulfill the needs of monitoring the progress of construction activities in double shift building constructions. A new type of data source (i.e., physical properties) was described and new mechanisms related to this data source were added to the existing taxonomy of reasoning mechanisms.

Based on the determined reasoning mechanisms and the developed data fusion approach, a physical prototype was implemented as a proof of concept, and field tests were performed for validating the developed approach for monitoring the progress of identified activities at a double shift building construction project. The studies related to development of the necessary reasoning mechanisms and the data fusion approach are provided in Chapter 3, and the details of the implementation of the prototype and the validation results are provided in Chapter 4.

1.4 Research Methodology and Scope

The research methodology consisted of five stages and included the following tasks:

Stage 1 - Identifying the current methods for progress monitoring and determining the construction activities and related equipment to be tracked for automated progress monitoring in double shift residential projects: Data collected from multiple data sources (i.e., literature review, face to face interviews, site observations and investigation of the project related data) were combined to identify the current methods for progress monitoring of projects and their deficiencies. Moreover, the types of activities and construction equipment to be tracked for progress monitoring were determined in this stage.

Stage 2 - Determining the high-level requirements for data collection technologies to be used at double shift construction projects: Use cases were developed based on site observations and face-to-face interviews and high-level requirements for the technologies to be used at nighttime and daytime at a double shift construction sites

were elaborated based on the use cases. Based on the high-level requirements, the appropriate technologies to be used for equipment tracking at double shift construction sites were selected.

Stage 3 - Determining the technology-specific requirements for the selected sensor-based technologies to be used for activity monitoring by tracking equipment: Initial tests were conducted to identify the technology-specific requirements for the selected sensor-based technologies. The usage of the selected technologies were further detailed at the prototype implementation stage.

Stage 4 - Developing the reasoning mechanisms and a data fusion approach for activity monitoring at double shift construction sites: Reasoning mechanisms needed for fusing the data obtained from sensor-based technologies with the project related information (e.g., schedules, quantity takeoffs) for monitoring the progress of activities in double shift sites were described. The data fusion approach was developed based on rule-based reasoning.

Stage 5- Developing a prototype and conducting field tests at a construction site: A prototype was developed and implemented as a proof-of-concept at a double shift construction site and tested on monitoring the selected construction activities. To validate the results, the findings of the developed data fusion approach was compared with actual data and the possible areas of improvement for a larger-scale implementation were identified.

Scope and limitation of the research study

The scope of this PhD research is defined as:

- Focusing on double shift construction sites,
- Utilizing sensor-based technologies,
- Performing equipment tracking,
- Residential, reinforced concrete buildings.

There are a number of limitations of this PhD research. The studies performed in the context of this thesis demonstrated the tracking of (1) forwarding equipment (tower crane, elevator, wall block material pallet) inside the construction site, and (2) production equipment (hand drill) when the activities are performed at the related production area, and the tracking the delivery stage was out of scope of this research

Data from the hand drill cannot be collected due to technical difficulties encountered at site, and therefore, fictitious data was created to describe the necessary reasoning mechanisms and to illustrate how that particular format of data is combined with other sensor-based and project-related information. Progress monitoring approach was implemented for tracking (i) masonry work, (ii) rebar installation, and (iii) steel component transfer to installation area. The actual progress data was obtained for both the masonry work and the rebar installation through the field tests. However, no steel installation was scheduled within the time period of the field tests and therefore, the approach to monitor the steel component installation was also demonstrated using the progress data fictitiously generated for steel component transfer to installation area. Finally, the main assumptions of the studies performed were that the transfer of materials within a construction site is realized through the use of tower cranes and elevators and the wall block material pallets were tagged at the fabrication stage. The findings of this study are not unique to the project at which the field experiments were conducted as the requirements were identified and reasoning mechanisms were developed to meet the general needs to perform progress monitoring at double shift building sites by tracking construction equipment with sensor-based technologies. Also, the developed prototype user interface is designed to be applicable to all building constructions through the use of filters that sort the activities based on time, location and context (i.e., weight of the load carried by the crane).

1.5 Readers' Guide to the Dissertation

This thesis comprises of six chapters. First chapter is the Introduction that presents the overview of the research, the vision of the study and the research questions. The three chapters following the Introduction chapter provide the details of the studies performed on investigating the three research questions that this PhD study is based on. Finally, the discussions chapter and the conclusions chapter discuss the findings and the contributions of the study and the possible future research directions. Description of each chapter is given below:

Chapter 2 provides the details about the studies on identifying equipment tracking requirements that include identification of the construction activities, related equipment and the parameters to be tracked for progress monitoring in double shift residential projects, and determining the high-level requirements for the technologies

to be used at nighttime and daytime at a double shift construction site. This chapter also elaborates the process of selecting the sensor-based technologies and initial tests that were conducted to identify the technology-specific requirements for the technologies selected.

Chapter 3 provides studies related to the development of the necessary reasoning mechanisms needed for data fusion to monitor the construction activities by tracking construction equipment.

Chapter 4 provides the details about the field tests and the proof-of-concept prototype development for tracking the progress of the masonry work and rebar installation, and the implementation of the prototype at a real double shift construction site. This chapter also describes the studies for demonstrating how the developed reasoning mechanisms are applied on the fictitious data that represent a steel component transfer to installation area.

Chapter 5, the Discussions chapter discusses the findings of the study, evaluates the implementation cost of the developed approach, and provides the details of the main steps that are needed to be applied for implementing and using the developed approach.

Finally, Chapter 6, the Conclusions chapter, summarizes the contributions of this research, explains how they were validated and provides a list of recommended future research along with the expected practical implications.

2. IDENTIFICATION OF ACTIVITIES AND EQUIPMENT TO BE TRACKED AND TECHNOLOGY SELECTION

To identify the appropriate activities to be monitored via equipment-based tracking, data collected from three data sources: (1) site visits and visual investigation, (2) investigation of project related documents from different residential projects, and (3) face-to-face interview with technical personnel. The collected data was combined to identify (1) the conventional methods currently used for activity progress monitoring, (2) the types of activities to be tracked for progress monitoring, and (3) the type of equipment used to perform each type of activity. After the activities were identified, use cases were developed to determine the high-level requirements for technologies to track construction equipment in double shift construction sites to monitor the progress of construction activities. Based on the high-level requirements, sensor-based technology were selected and initial tests were performed at a construction site to determine the technology-specific functional requirements and the appropriate hardware.

Following sections provide the findings of these studies. The outcomes of the studies performed in this chapter are used to determine the necessary reasoning mechanisms for data fusion and to develop a prototype system in the following chapters.

2.1 Conventional Methods Used for Activity Progress Monitoring and Their Deficiencies

To identify the appropriate activities to be monitored via equipment-based tracking two construction sites were visited and interviews with technical personnel were conducted. One of these construction sites (Site 1) is a multi-purpose residential project located in Maslak, Istanbul consisting of apartments, and other social spaces such as shops, cafes and restaurants. The total construction area of Site 1 is 320,000 m², that includes three different types of 24 towers that contain 4,039 apartments and

642 residence that were built in four stages. Approximately 50 subcontractors actively worked in this project.

The other construction site that was visited (Site 2) is also in Maslak, Istanbul. It is also a multi-purpose project that includes residents, offices, hotel and shopping center. The total construction area of this project is 250,000 m², there are 458 residents located in two 42-floor towers. Approximately 20 subcontractors worked in this project. Both visited sites were double shift construction sites, where the contractor's and some subcontractors' personnel were working in double shifts. During the site visits and visual investigations at site, eleven technical personnel from site and site offices were interviewed (Ateşagaoglu, O., (2014), Düzcan, M., (2014), Işın, K., (2014), Korkut, B., (2014), Köseokur, H., (2014), Türkel, B., (2014), Dikbaş, C. (2015), Bestel, T., (2015), Kazmazoğlu, H., (2015), Kantar, E., (2015) and Demirdilek, G. (2015)). The findings of the site visits, interviews and investigation of project-related documents helped identifying the following issues related to project control and monitoring of progress and productivity of construction activities:

- Factors that impact both the daytime and nighttime work performance are determined based on the interviews with technical personnel and visual investigation at site:

(1) During the daytime work, especially in summer, hot weather is the most important factor that negatively affects the productivity of workers. Bad weather conditions, such as strong winds, storms, rain, disrupts the work both at daytime and nighttime, lowering the productivity.

(2) As crews of several trades are working during daytime, it is more likely to experience logistic issues related to the allocation of material and equipment during the daytime work. For example, tower crane serves multiple trade's work coordinately during the daytime, such as lifting formwork for formwork crew, carrying rebar for rebar crew and transferring material for another crew. On the other hand, during the nighttime it is more likely that only one trade benefits from the tower crane (e.g., formwork crew only).

(3) Usually (i) unfinished activities started during the day shift are completed, (ii) preparation for next day's activities are performed and/or (iii)

material procurement for the next day's activities are performed during the night shift. However, the number of supervisory personnel in the night shift is less than that of the day shift. This lowers the quality and defective works are likely to occur more in the night shifts.

(4) Usually the defective work is identified when checked in daytime and correction of the defective work is performed during the day shift. This correction of the defective work delays the activities that need to be performed on that day.

(5) The artificial lighting used at nighttime provides a limited visibility and usually is the main reason for defective work performed in the night shift. In addition to insufficient lighting in the nighttime, the physical fatigue of workers at nighttime also affects the quality of work and likely to cause accidents.

(6) The interviewees stated that if the workers are paid on a daily basis, then the workers tend to go slow when less number of supervisory personnel is available at night and be more unproductive than usual.

(7) It has been observed that season changes and particular times within a year, for example, religious holidays such as Ramadan in Muslim countries, alter the way that workers usually work and change their productivity. For instance, workers prefer to work at nighttime rather than in the daytime due to long fasting times in Ramadan when it coincides with summer, to avoid long hours spent without water.

- *Manual and paper-based data collection:* Based on the interviews and site visits, the current methods used for tracking the progress of activities were determined. It mainly relies on daily or weekly manual and paper-based data collected from field through visual investigation and the field data is entered into a computer platform (e.g., Microsoft Excel) for further use. Later, manually collected field data is used to create graphics and reports to be presented to the top management levels. Figure 2.1 shows the steps of the conventional method for activity tracking in construction sites.

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| 4 | A ETAP | 0A2 BLOK 8 | M3 C40 - | KADEME PERDE BETONU | |
| 5 | B ETAP | C4 BLOK 3 | M3 C14 - | TEMEL ALTI GRO BETONU (TAMAMLANDI) | |
| 6 | B ETAP | C4 BLOK 7 | M3 C14 - | 462.00 KOTU TEMEL ALTI GRO BETONU | |
| 7 | B ETAP | C4 BLOK 2 | M3 C40 KVB - | DRENAJ BACASI TEMEL BETONU | |
| 8 | B ETAP | A2 BLOK 4 | M3 C14 - | TEMEL ALTI BETONU | |
| 9 | B ETAP | C4 BLOK 4 | M3 C30 KVB - | ZEMİN ÇİVİSİ BETONU (İMALAT DEVAM EDİYOR) | |
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| 11 | B ETAP | A2 BLOK 6 | M3 C30 KVB - | ZEMİN ÇİVİSİ BETONU (İMALAT DEVAM EDİYOR) | |
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| TAKİP EDİLECEK İŞLER | | | | | |
| SU TANKERİ MESAİDE | | | SU TAŞIYACAK. | | |
| BETONLAR, SULAMAKA. | | | | | |
| BETON DÖKÜMLERİNDE | | | BORUTARUVARI ARANAK. | | |
| A1 VE C2 BLOK TA FÖRE KAZIK İMALATI DEVAM ETTİRİNDEN METRAJ YAKLAŞIK YAZILMIŞTIR, YERİNDE KAZIK DERİNLİKLERİ KONTROL EDİLEREK METRAJ DÜZELTİLMİ. | | | | | |
| A1 BLOK 0100 LÜK KAZIKLAR C30 0120 LÜK KAZIKLAR C40 , C1 BLOK KAZIKLAR C30 BETON SİNFLARİ LİRE DÖKÜLECEKTİR. | | | | | |
| B ETAP C4 BLOK DRENAJ BACASI TEMEL BETONU DÖKÜLECEK (C40 KVB) ÖNEMLİ. | | | | | |
| B ETAP C4 BLOK ZEMİN ÇİVİ İMALATI DEVAM EDİYOR. TAKİP EDİLECEK. | | | | | |
| B ETAP A2 BLOK ZEMİN ÇİVİ İMALATI DEVAM EDİYOR. TAKİP EDİLECEK. | | | | | |
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- *Double-checking and confirming the site data:* Site office personnel spend significant time on checking and confirming the values entered by the site personnel. If the site office personnel realizes a missing or incorrect data entrance or suspects a mistake, he/she calls the site personnel responsible of that particular activity to confirm the value entered. Since the weekly meeting preparations are performed in a very tight schedule, site office personnel might not be able to realize the mistakes in the data. If the person cannot be reached by phone and the time is limited, then the site office personnel checks the project drawings and other related document to figure out whether the suspicious value might actually be correct. Sometimes site office personnel might need to visit the production area himself/herself and observe the amount of production completed. However this may not always be the case as the site office personnel might be dealing with the management of more than one construction projects at the same time. Last check is performed by the head of the site office before the reports are presented to the top management to prevent any mistakes.
- *Disagreements on the amount of work completed:* Interviewees stated that conflicts are very likely to occur in between the employer and the contractor on the amount of completed work at the time of progress payments due to not having a reliable way of monitoring the progress of activities in a timely manner, as large number of crews are working simultaneously and work is split among multiple subcontractors. Especially in the case of daily-paid workers, the real amount of work progress can be determined barely at the end of a month, which is usually late to take actions. Findings show that at large-scale construction sites where different subcontractor crews and trades are working simultaneously the progress of activities cannot be tracked effectively.

2.2 Determining the Activities and Related Equipment to be Tracked for Progress Monitoring

This step of the study aimed at determining the activities and the related equipment to be tracked for progress monitoring. To achieve this goal, documents (i.e.,

schedules) collected from four residential projects were examined, findings of the interviews with technical personnel and the site visits were used.

The investigated four construction projects are large scale and high rise residential projects located in Istanbul. To identify the activities and the related equipment to be tracked for progress monitoring, the common and critical activities that are typical in building construction were identified in the schedules of these four projects and listed in Table 2.1.

Table 2.1 : Common and critical activities identified in schedules of four residential projects.

Activity Name	Activities included
Earthworks	Excavation
Deep soil improvement	Pilework
Shoring	Shoring works
Structural works	Foundation construction Reinforced concrete construction Tunnel formwork
Finishing works	Masonry work Door buck assembly Gypsum plaster work Plasterboard suspended ceiling construction Trowel coating Plasterboard suspended ceiling casing Satin plaster and undercoating work
Insulation works	Wet area waterproofing
Interior works at each apartment unit	Entrance door assembly Wall ceramic coating Floor ceramic coating Ceiling paint Ground color paint Top coat paint Wallpaper Laminated flooring Wooden skirting board assembly Door assembly Wardrobe installation
Facade works	Exterior scaffolding Jacketing works Window buck installation Glass mounting

Table 2.1 (continued): Common and critical activities identified in schedules of four residential projects.

Mechanical/electrical works	Heating and cooling fitting (radiators, towel racks, VRV piping) Sprinkler installation Copper piping above gypsum plaster Radiator installation
Parking area works	Parking area works
Landscaping works	Landscaping works
Infrastructure works	Phone line Power line Natural gas pipeline Water and wastewater piping Rainwater piping
Superstructure works	Road construction Curb construction Embankment Irrigation system Plantation Ground leveling

The following activities were identified as common and critical activities in residential projects:

- Earthworks,
- Deep soil improvement,
- Shoring,
- Structural works,
- Finishing works,
- Insulation works,
- Interior works at each apartment unit,
- Facade works,
- Mechanical/electrical works,
- Parking area and landscaping works,
- Infrastructure works,

- Superstructure works.

Out of the listed common and critical activities, activities to be monitored were selected considering the following requirements: (1) activities that are typically performed in all building constructions, (2) activities have tasks performed both at daytime and nighttime (e.g., production and/or material procurement), (3) activities that have logistic issues regarding the material and equipment allocation, and (4) activities that are problematic in terms of progress monitoring.

This study focused on two activity groups that meet the identified requirements: (1) structural works, and (2) finishing works. These activity groups are typical for all types and sizes of building constructions and have critical importance. Also, these activity groups have tasks that are performed in both shifts and this will assist in demonstrating the activity monitoring capabilities of the prototype throughout all shifts. To decide the specific type of activities for prototype implementation and site tests; the equipment used in performing the structural works and finishing works need to be examined in terms of their applicability to the vision of this PhD study that envisions tracking equipment with sensor-based technologies for progress monitoring. Therefore, the activities involved in the identified activity groups (i.e., structural and finishing works) were investigated as to whether these activities are performed with construction equipment that physically allow for prototype development at site and are appropriate for repetitive tests at site.

Technical specifications that describe the work processes and the procedures for using the related equipment and material for each type of activity were examined. Moreover, textbooks used as references in graduate and undergraduate courses provided in Istanbul Technical University Civil Engineering Departments (Gransberg et al., 2006; Yüksel, 2008) and construction method books (Peurifoy, 2006; Allen and Iano, 2008) were investigated. Theoretical information obtained from descriptions provided in textbooks and technical specifications were combined with the insights obtained from site visits and interviews to develop a fully understanding of the construction methods and equipment used in performing particular construction activities. Table 2.2 provides the list of equipment that are used at different stages of the structural and finishing works and have the potential to provide information about the progress of the related activity. The term equipment

refers to the mechanical hand tools, large construction equipment and tools without any mechanical parts but have critical role in the completion of a particular activity and are used repetitively. Unless advanced innovative methods, such as robotics and automation technologies, are used for construction, the conventional methods for constructing a building are similar at all construction sites. Table 2.2 showed that the proposed equipment tracking approach have a great potential for tracking structural work and finishing works as various types and number of equipment are available for performing these activities.

Table 2.2 : Equipment used in performing activities included in structural and finishing work stages.

Activity Name	Stage	Equipment used
Structural works	Rebar and formwork preparation	- Tower crane - Total station - Iron cutting and bending machine - Formwork tools and accessories - Scaffolding - Tunnel formwork tools and accessories
	Concrete pouring	- Stationary/mobile concrete pump - Hydraulic concrete dispenser pipeline - Concrete vibrator - Compressor
	Leveling works	- Vibrating screed - Power trowel - Concrete cutting machine - Electric hand tools (drill, hammer, etc.) - Concrete grinding machine
	Steel construction works	- Tower crane - Welding machine

Table 2.2 (continued): Equipment used in performing activities included in structural and finishing work stages.

Finishing works	Masonry work	- Hand drill - Wall block material pallets
	Gypsum plaster and plasterboard works	- Gypsum plaster machine - Vacuum sanding machine - Screed pump - Scaffolding
	Plaster board installation works	- Screw fastening machine
	Finishing	- Spray paint machine
Equipment for transferring material/other equipment/personnel within site	- Forklift - Elevator - Tower/mobile crane	

Only the types of equipment that have a critical importance in performing a particular activity and that can provide valuable information about the progress of an ongoing activity were included in the list in Table 2.2. On the other hand, there are other types of supporting equipment and tools used in performing construction activities, such as basic hand tools. However, a trowel and a hand drill are not equally important in terms of providing information about the ongoing masonry work, for example. It is possible to track the operating hours of a hand drill by looking at its behaviour (i.e., vibration) while it is not the case for a trowel. Also, it is possible to track the location of a hand drill, for example by attaching an RFID tag. Whereas a trowel can be used for other types of activities at a site, and can easily get lost and be replaced, and thus, tracking the location of a trowel will not provide meaningful information to extract progress of an activity. As it is illustrated in this example, to retrieve the progress information by tracking equipment, the equipment that can be directly associated with an activity should be selected. Therefore, basic hand tools, such as a trowel, were not added to the list of equipment given in Table 2.2.

Table 2.2 also reports equipment that is used for transferring material, other equipment and personnel throughout a construction site and are involved in the construction processes of different activities. This type of equipment include mobile

or stationary cranes, forklifts and elevators. These equipment have the potential to provide information about various activities regardless of the type of activity. For instance, tower cranes and/or mobile cranes are used to transfer various components (e.g., formwork, steel components, material pallets) from one point to another. Similarly, elevators are used for vertical transfer of material, personnel and other small equipment and components that can fit in its cabin.

The following activities included in the structural works and finishing works activity groups were selected to be monitored at a double shift construction site for demonstrating the feasibility of the equipment tracking-based progress monitoring approach:

- (1) masonry work,
- (2) rebar installation, and
- (3) steel component transfer to installation area.

These activities were selected since the equipment used in performing these activities are appropriate for repetitive tests at site and allows for prototype development at site. For tracking the masonry work:

- elevator,
- wall block material pallets,
- tower crane, and
- hand drill

were selected to be tracked with sensor-based technologies. The elevator is used for the vertical transfer of material, equipment and workers among the building floors. It was aimed to track the the movements of the elevator and the (tagged) items carried by the elevator with a passive RFID system installed on the elevator. The other equipment to be tracked was the reusable material pallets which is the packing unit of the wall blocks used during the masonry work. Tower crane is used for transferring the wall block material pallets from the laydown area to the building floors. The objective was to track the transfer of wall block material pallets using the

tower crane's built-in sensors and internal data storage capacity. Used material pallets, on the other hand, was aimed to be tracked with the RFID system on the elevator while the emptied pallets are being removed from the floor for return to the manufacturer. Finally, the hand drill is used to prepare mortar throughout the masonry work and it was aimed to be tracked with a wireless accelerometer and a passive RFID tag to identify the building floor at which the masonry work continues and for how long.

For tracking the rebar installation:

- tower crane, and
- total station

were selected to be tracked. The goal was to use built-in sensors and internal data storage capacities of the total station and the tower crane. Total station devices are periodically used for layout and alignment at different stages of the construction before the beginning and after the completion of certain activities, such as concrete pouring. Total station can provide information about the completion of structural work at a particular floor and starting of the rebar installation at the upper floor. Tower crane, on the other hand, is used to transfer the pieces of rebar from the rebar cutting and bending area to the building floor during the rebar installation process.

Finally, tower crane was selected as the equipment to be tracked for monitoring the progress of steel component installation. Tower crane is used to transfer the pieces of steel component that are manufactured upon order and brought to site with trailers. The weight of the steel component transferred to the installation area and the time of transfer are collected from the tower crane. The ID of the steel component is optional and can be used if a location-based tracking is performed or it is a steel construction. In such case, all steel components or only the critical ones can be tagged and an RFID system can be included in the tracking process (e.g., by attaching a reader on the tower crane hook) for identification purposes.

2.3 Developing Use Cases

To determine the high-level requirements for the technologies to be used at nighttime and daytime at a double shift construction site; use cases that identify and explain (1) the work processes of each activity to be tracked, (2) the usage details of the related equipment used for performing these activities and (3) the related site conditions were developed.

Use cases were based on the following assumptions:

- Use cases were developed for high rise residential building construction.
- Tower cranes are used for transferring masonry work material from laydown area to building floors.
- Tower cranes are used for transferring the pieces of rebar and ordered steel components to building floors.
- Tower cranes are used to remove damaged and waste material, and unused formwork pieces from floors.
- Elevators are used to remove the empty material pallets from floors and empty pallets are returned back to the manufacturer.
- All empty material pallets are removed from a floor within the same day.
- Elevators are used for vertical transfer of workers and necessary tools among building floors.
- Hand drill is used to prepare mortar by mixing powder glue with water and one hand drill is available for a masonry crew.

1- Use case name: Transferring wall block material pallets from laydown areas to floors and removing empty pallets from floors

Primary actors: Tower crane operator, masonry work subcontractor personnel

Description: This scenario describes the process of transferring wall block material pallets to building floors.

Preconditions:

- Wall block materials are ordered for a particular building floor in accordance with the schedule and the project.
- Transferring of wall block material from the laydown area to building floors is performed with the tower crane.

Transactions:

- Wall block material pallets are delivered to site with trailers and received by the personnel in charge and unloaded to a laydown area near the building.
- Wall block material pallets are carried with the tower crane to the building floor where the masonry work is to be performed.

Post conditions: Wall block material pallets are brought to the floor where the masonry work is performed.

Scenario: Masonry subcontractor company personnel receives the wall block material for B5 building block and has the material unloaded to the laydown area. He contacts the tower crane operator over the walkie-talkie and informs him that the tower crane is assigned to masonry crew in the afternoon, and wall block material needs to be transferred from the laydown area to the 11th floor of the B5 block in the afternoon. The tower crane operator completes his work with the rebar crew at 4 p.m. and starts transferring 50 wall block material pallet to the 11th floor. The transferring of wall block material pallets is completed at 6.30 p.m.

2- Use case name: Preparing mortar for masonry work using the hand drill

Primary actors: Masonry crew, warehouse personnel

Description: This scenario explains the use of hand drill for mortar preparing process.

Preconditions:

- Wall blocks and powder glue are transferred to the floor with the tower crane.

- Hand drill and other tools necessary for performing the masonry work are obtained from the warehouse at the beginning of working hours and returned to the warehouse at the end of each of the work day.
- Mortar is prepared using the powder glue mixed with water in accordance with the technical specifications and consumed within 4-5 hours and the dry glue is not reused by adding water and new mortar is prepared instead.

Transactions:

- Masonry work crew obtains necessary hand tools from the warehouse at the beginning of the working hours.
- Crew then goes up to the floor where the masonry work is to be performed using the elevator, bringing along the hand tools.
- Masonry workers prepare mortar by mixing the powder glue with the hand drill and start the masonry work. Mortar preparing is repeated every time the crew runs out of mortar and/or when the mortar is dry.
- At the end of the working hours, the crew loads the hand tools to the elevator and arrives at the ground floor and takes the hand tools back to the warehouse.

Post conditions: Masonry work is performed at the floor.

Scenario: Two workers from the masonry crew arrived at the warehouse at the beginning of their working hours and obtained the hand drill and other necessary tools, such as trowel, saw, etc. They loaded their tools to the elevator and went up to the 6th floor of the building in accordance with the schedule. One of them used the hand drill to mix the powder glue with water in accordance with the technical specifications to prepare the mortar. This process was repeated each time they needed new mortar. At the end of their work time around 5.30 p.m. they loaded their tools to the elevator and went down to the ground floor and took the hand tools back to the warehouse.

3- Use case name: Removing empty pallets from floors

Primary actors: Elevator operator, masonry work subcontractor personnel

Description: This scenario describes the process of removing the empty pallets from floors at the end of the masonry work.

Preconditions:

- Wall blocks are utilized and masonry work is completed.
- Empty material pallets are stored at the floor.
- Removing the emptied material pallets from the building floors is performed using the elevator.

Transactions:

- Wall blocks are used and material pallets are emptied in time and the masonry work is completed.
- Empty material pallets are loaded to the elevator and transferred to a laydown area and stocked until they are returned to the manufacturer.

Post conditions: Empty wall block material pallets are removed from the floor upon completion of the masonry work.

Scenario: Masonry subcontractor company personnel contacts the elevator operator over the phone and informs him that the elevator is assigned to masonry crew for one hour to remove the empty pallets from the 10th floor at 3 p.m. Two workers loaded 45 empty pallets to the elevator in the first round and 40 pallets in the second round. The empty material pallets are taken to the ground floor and unloaded, and the work is completed around 3.50 p.m. The subcontractor personnel then informed the site management that the empty pallets are piled up at the laydown area and ready for pick up for return to the manufacturer.

4- Use case name: Carrying the rebars to the installation area with tower crane

Primary actors: Tower crane operator, structural work subcontractor personnel

Description: This scenario describes the process of rebar installation.

Preconditions:

- The concrete of a building slab is poured and a surveying technician performed the layout of slab corners and the building core with a total station.
- Transferring the rebar from the rebar cutting and bending area to the building is performed according to the directives given to the tower crane operator via a walkie-talkie.

Transactions:

- Tower crane operator transfers iron rods from the laydown area to the production area.
- The rebars are prepared in accordance with the rebar project of the building components (i.e., columns, structural walls, slab).
- Tower crane operator follows the directives given by the ground crew via a walkie-talkie while transferring pieces of rebar and rebar cages from the rebar cutting and bending area to the building slab.

Post conditions: Rebar installation of the building components is completed at the floor.

Scenario: Tower crane operator of block A2 works coordinately with the structural works crew to transfer rebar from the rebar cutting and bending area to the rebar installation area on the 6th floor of the building in between 5 p.m. and 7 p.m. The rebar pieces that are transferred to the building are installed within the same work day.

5- Use case name: Transferring the steel components to installation area with tower crane

Primary actors: Tower crane operator, steel works subcontractor personnel

Description: This scenario describes the process of steel component transfer to the installation area.

Preconditions:

- Steel components are manufactured as ordered and delivered to site with trailers.
- Transferring the steel components from the laydown area to the building is performed according to the directives given to the tower crane operator via a walkie-talkie.

Transactions:

- Tower crane operator follows the directives given by the ground crew via a walkie-talkie to transfer steel components from the laydown area to the building.

Post conditions: Steel components brought to their installation place on the building are installed.

Scenario: Steel components are delivered to site and received by the steel construction works crew personnel. Steel crew contacts the tower crane operator from the walkie-talkie and directs the tower crane to the laydown area. One piece of steel component is securely tied and the tower crane operator transfers the steel component from the laydown area to the installation area on the 20th floor of the building. This process is repeated in between 2 p.m. and 4 p.m. until all the steel components were removed from the laydown area. Installation of the steel components that are transferred to the building is completed within the same work day.

2.4 Determining the High-Level Requirements for Data Collection Technologies to be Used at Double Shift Construction Projects

Based on the use cases developed, high-level requirements for the technologies to be used at nighttime and daytime at a double shift construction sites are elaborated in

the following paragraphs in terms of environmental (e.g., lighting conditions) and technological (e.g., minimal manual input, line-of-sight) aspects.

Working under different lighting conditions: Personal interviews and site observations showed that the activities started during the daytime might need to be completed at the nighttime. The most significant difference in between the daytime and the nighttime is the lighting conditions. Natural daylight is usually sufficient during the daytime, on the other hand, artificial lighting is needed during the nighttime work. Projectors that provide high intensity artificial light are typically used for illuminating the environment, which creates local illumination and vision decreases as one moves away from the projector. Not being affected by different lighting conditions and functioning well under both the daytime and nighttime work is the most important criteria that a data collection technology must meet. This necessitates using technologies that are not affected by weak or strong lighting conditions and eliminates the possibility of using vision-based technologies unless laser scanners or infrared cameras are the case.

Internal power source and/or need for minimal or no wiring: Considering the dynamic nature of the construction sites, systems that require long wiring are problematic in the long term. As the building rises in a relatively short amount of time and construction crews need to work at different spaces within time; wiring might cause obstructions and wires might get damaged. Therefore, technologies with internal power sources or technologies that require minimum amount of wiring is needed to be designed and installed at construction sites. While most of the sensor-based technologies have their own batteries, another option for the technologies might be to receive power from the equipment that they are attached to.

Cost-efficiency: For a technology to have low installation and operating costs is not only important to convince the site management to deploy the system in the first place, but also makes it easier to maintain the system throughout the construction. For example, laser scanners are expensive devices and require prior training and trained personnel to collect and process data. It is important for the technology to have minimum cost and to require minimum additional labor effort. There are some construction equipment that come with built-in sensors and memories to collect data and are already used in construction sites. Data collected by these sensors can be

used as they will not bring any extra cost since they are already involved in the current work flows.

Having minimal worker input and interference with the existing work flows: The current approach for activity progress monitoring is inefficient since it depends on manual data collection by a number of personnel from site based on the visual investigation of the site. Data collected in this manner is likely to be incorrect or incomplete, and thus unreliable, necessitating an automated approach for activity monitoring. Therefore, the technologies to be utilized at double shift construction sites for activity monitoring must require minimal manual input and collect data throughout the day and night shifts semi-automatically or automatically where possible. In addition, changing the work flows at construction sites is problematic since both managers and workers are not reluctant to change and to adapt to new ways of performing work. Hence, these data collection technologies must be suitable for installation on the identified equipment to be tracked and have minimal interference with the existing work flows. Existing built-in data collection systems in construction equipment must be used where possible.

Ability to track multiple activities: It is important to select technologies that are able to track multiple activities where possible. This enables an economic and feasible configuration instead of using a different tracking technology on equipment used for performing each construction activity.

Physical durability: Technologies must be robust to be used under harsh conditions of construction sites, and must be durable against difficult environmental conditions such as mud, dust, bad weather conditions, noise, etc. Therefore, technologies that can operate under open air and severe circumstances of construction sites needs to be selected.

Non-line-of-sight and long reading distance: There may not always be a clear sight in between the data collection technology and the object (i.e., equipment in this case) to be tracked. For example, when the video cameras are used for tracking the progress at site, construction vehicles or workers moving around might be standing in between the target object and the video camera at the time of recording. Also, the completed walls of a building might begin to pose an obstruction for the tasks to be

tracked that are left inside the building. Therefore, the technologies must not only have a long reading distance but also require line-of-sight for operation to ensure that the data collection is performed under all conditions at site.

2.5 Automated Tracking of Equipment for Activity Progress Monitoring

An automated approach which tracks equipment for activity progress monitoring was developed and for data collection in the developed approach, the following technologies were selected: (1) RFID technology, (2) wireless accelerometer, (3) tower crane sensors, and (4) total station. Technology selection was performed based on the high-level requirements determined in the previous section and the functional requirements of the selected technologies were identified in the following section.

RFID technology

RFID technology was selected as it is not affected by different lighting conditions and meets the requirement for minimal worker input. Also, it is possible to configure a data collection system that is cost-effective and yet efficient by using passive RFID tags. RFID technology is physically durable and resistant to mud, water, temperature changes and other severe conditions.

RFID is a non-line-of-sight technology that enables data collection without the need for a contact in between the reader and the tag and can read from relatively long distances. An RFID system that is installed on the elevator enables tracking (1) the movement of the elevator and (2) the items carried inside (Figure 2.4).

The movement of the elevator is tracked by tracking the building floor at which it stops to load and unload items and personnel. To identify the floor numbers, an RFID tag is attached on appropriate places of each building slab near the elevator mast where it can be read by the antenna. The items that need to be tracked (e.g., wall block material pallets for masonry work) also have RFID tags attached to be identified by the RFID system as the item is inside the elevator cabin.

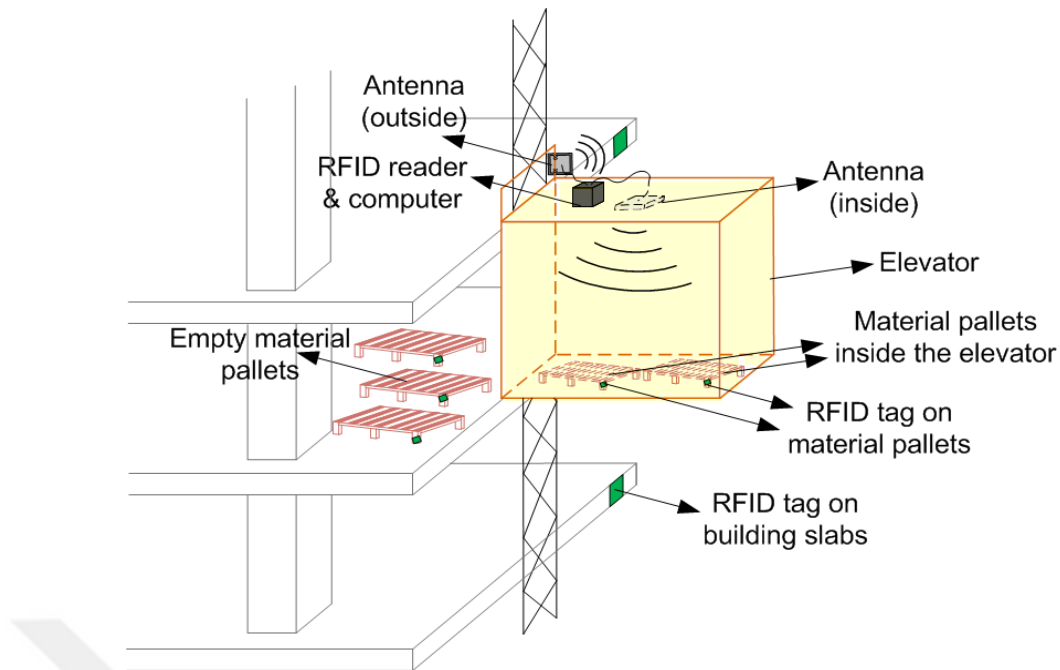


Figure 2.4 : Proposed approach for tracking the elevator movements and items inside the elevator with RFID system.

Selected RFID system

Among available RFID products, an RFID system was designed with one reader, two antennas, a computer to store collected data, and passive RFID tags. The Motorola FX7400 RFID reader operating at UHF was selected for the prototype implementation due to the need for readings with high precision and accuracy, and long reading ranges despite the metal and concrete existing in the environment (Figure 2.5). Properties of this RFID reader are summarized below (Url-1; Url-2).



Figure 2.5 : Motorola FX400 RFID reader (Url-1).

Motorola FX7400 is an EPC Class 1 Gen 2 (ISO 18000-6C) air protocol reader. EPC (Electronic Product Code) is a unique and universal identifier that is given to an object. The operating frequency of the reader is 902 MHz~928 MHz, 865 MHz~868 MHz, included in the UHF frequency. This enables performing readings up to 12 meters. The operating system of the reader is Microsoft® Windows® CE 5.0 while it has SDK (Software Development Kit) for .NET, C and JAVA languages.

Maximum four antennas can be connected to the reader. Two communication methods are available with the reader: (1) 10/100 BaseT Ethernet (rJ45) with PoE support, and (2) USB client (USB Type B). The reader provides the following network services: DHCP, HTTPS, FTPS, SSH, HTTP, FTP, telnet, SNMP and NTP. This enables controlling the reader with a web-based application and assigning static and dynamic IP addresses. The selected antenna model was MTI MT-242040 flat panel reader antenna that has 865-870 MHz frequency range. It is made out of plastic and its dimensions are 190 x 190 x 30 mm (max) (LxWxD) while it weighs 0.8 kg. Figure 2.6 shows the rear panel connections of the Motorola FX7400 series and Figure 2.7 shows the front side led indicators. Explanations of the front panel led indicators are given in Table 2.3.

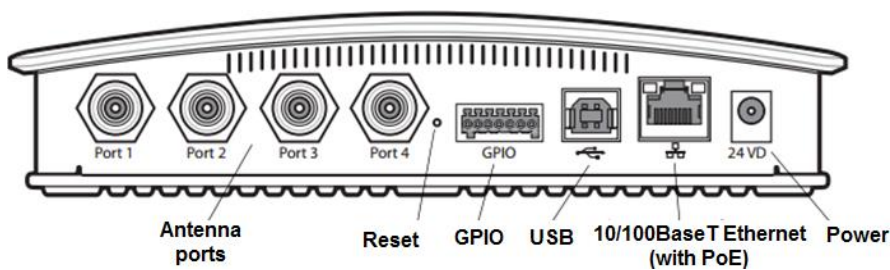


Figure 2.6 : Motorola FX7400 Series RFID reader rear panel connections (Url-2).

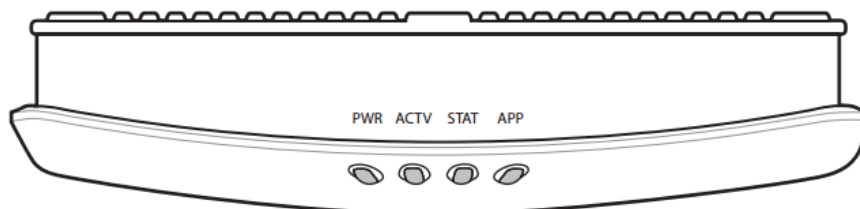
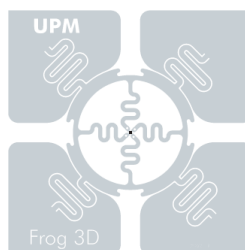


Figure 2.7 : Motorola FX7400 reader front panel led indicators (Url-1).

Table 2.3 : Common Motorola FX7400 reader led indications (Url-1).

LED	Function	Color/Status	Description
PWR	Power	Off	Reader is powered off
		Red solid	Booting
		Red flashing	Firmware upgrade
		Amber solid	Application initialization after booting
		Green solid	Reader is powered on and operational
ACTV	Activity	Off	No RF operations
		Amber Flashing	On for 500 mSec indicates another tag operation
		Green Flashing	On for 500 mSec indicates a tag is inventoried or read
STAT	Status	Off	No errors or GPIO events
		Red Solid	Firmware update failure
		Red Flashing	On for 500 mSec indicates an error in RF operation
		Green Flashing	On for 500 mSec indicates a GPI event
APP	Application	Green/Red/Amber	Controlled through RM

Passive RFID tags shown in Figure 2.8 were selected for the prototype implementation and the technical specifications of the selected tags are listed in Table 2.4.

**Figure 2.8 : Class 1 Gen 2 RFID frog tag (Url-3).****Table 2.4 : Class 1 Gen 2 RFID tags technical specifications (Url-3).**

Antenna dimensions		Electrical specifications		General characteristics of inlay	
Antenna size	50 x 50 mm	IC	Impinj Monza 4	Operating temperature	- 40 to +85 °C
Web width	60 mm	User memory	Up to 512 bit	Static pressure	<10 MPa
Die-cut size	53 x 53 mm	Operating frequency	860–960 MHz	Bending diameter	> 50 mm

These Class 1 Gen 2 tags are universal and cost effective and can be used upon various material surfaces. These tags are not affected by the light and noise in the environment. Figure 2.9 (a) shows the results of the tests performed on tags attached to plastic and corrugate surfaces, in terms of the change in the reading range with the operating frequency while Figure 2.9 (b) shows the orientation sensitivity of the tag.

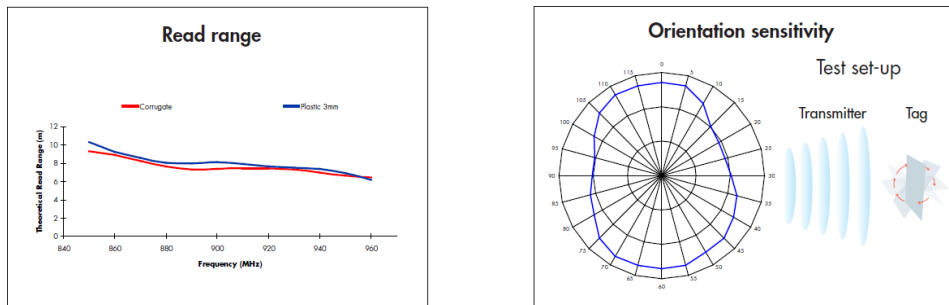


Figure 2.9 : Tests on tag's (a) read range, and (b) orientation sensitivity (Url-3).

Wireless accelerometer

A wireless accelerometer was selected as it can work under different lighting conditions, has an internal power source, requires no wiring and has minimal manual input due to automated data collection. As seen in Figure 2.10, a wireless accelerometer that is deployed on a hand drill, which is used to prepare mortar for the masonry work, tracks the idle and working times of the hand drill and for how long the hand drill is utilized. In addition to the wireless accelerometer, an RFID tag is attached to the hand drill, to identify the floor to which the elevator carried the hand drill. Therefore, the location and the duration of the masonry work are tracked.

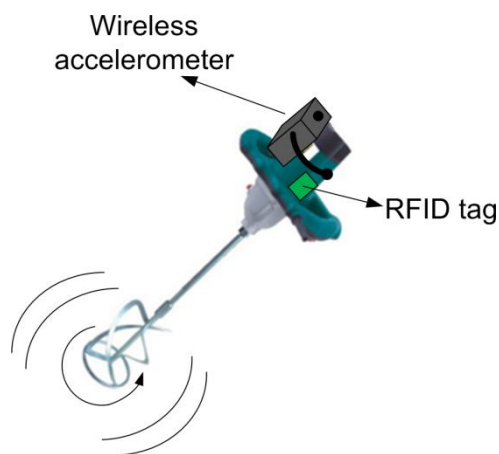


Figure 2.10 : Proposed approach for tracking the hand drill behaviour with a wireless accelerometer.

Selected wireless accelerometer components

To identify whether an equipment is working or staying idle, a 3-axis accelerometer unit (Figure 2.11 (a)) was mounted on Arduino Yún microcontroller board (Figure 2.11 (b)) and a wireless accelerometer system that will monitor the acceleration changes of the tracked equipment was developed. Accelerometers measure the acceleration of a moving or vibrating item and 3-axis accelerometer measures the changes in the acceleration of an item in x, y and z axis. Arduino is an open-source prototyping platform used for developing different projects and applications with various types of sensors (e.g., temperature, humidity).

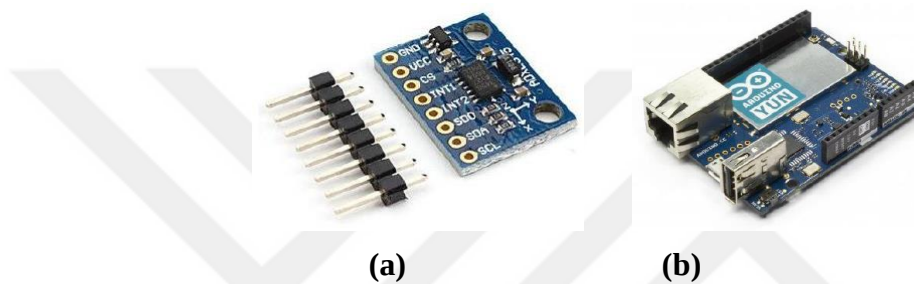


Figure 2.11 : (a) Arduino Yún microcontroller board, and (b) ADXL345 3-axis accelerometer (Url-4, Url-5).

The microcontroller board

Arduino Yún (Figure 2.12) is a board based on the Atmega32u4 microcontroller and the Atheros AR9331 microprocessor. Arduino Yún microcontroller board has a micro-SD card slot which enables on-board data storage while working offline. It also has built-in Ethernet and WiFi support, a USB-A port, micro-SD card slot, 20 digital input/output pins (of which 7 can be used as PWM outputs and 12 as analog inputs), a 16 MHz crystal oscillator, a micro USB connection, an ICSP header, and a 3 reset button (Url-6).



Figure 2.12 : Arduino Yún (a) front view, (b) rear view (Url-6).

Multiple modules with various functions, such as input and output, are located on the Arduino Yún. The dimensions of the PCB board where the Arduino modules are located is 7.3 cm x 5.3 cm, however, the board gets larger as a USB module and a micro-SD card are added. There are four screw holes that allow attaching the board to a surface. Total weight of the board is 32 grams.

The ADXL345 3-axis accelerometer

The ADXL345 is a small, low-cost (i.e., around \$5) and high resolution (i.e., 13-bit) 3-axis accelerometer with measurement capabilities up to 16 g and high vibrations up to 400MHz (Url-7). The data collected by the accelerometer is formatted as 16-bit digital output and can be accessed through either SPI protocol or I²C digital interface.

Due to its small size, it is suitable for mobile applications to measure the static acceleration of gravity in tilt-sensing applications, and dynamic acceleration that results from the motion or shock applied to it. Having a high resolution (3.9mg/LBS) enables sensitive measurements with inclination changes less than 1°. Other characteristics of the ADXL345 accelerometer are summarized in Table 2.5.

Table 2.5 : ADXL345 3-axis accelerometer characteristics (Url-7).

ADXL345 3-axis accelerometer	
Input voltage	3V - 5V
Power consumption	40uA (Sensing mode), 0.1uA (Standby mode)
Available functions	Free fall sensing Motion sensing Tap and double tap sensing
Size	3mm x 5 mm x 1 mm
Communication	SPI or I ² C

Tower crane position and load sensors

Tower crane was selected due to having existing built-in data collection system that provides a cost-efficient configuration that has no interference with the existing workflows, has the ability to track multiple activities, has an internal power source and has minimal manual input due to automated data collection. Most of the current

tower cranes have built-in systems that measure and store (1) the location of the crane boom and hook in a global and/or local coordinate system and (2) the weight of the load being lifted by the crane in real-time. Moreover, there are other sensor-based collision detection systems that are designed for enabling communication among tower cranes, which are located in close proximity to avoid dangerous situations, such as collision.

Alternatively, when such systems are not readily available on cranes, a GPS unit and a load sensor can be attached to the crane hook to determine the coordinates and the load being lifted by the crane. In the developed approach, tower crane sensors are used to track the movement and position of the tower crane in terms of the trajectory of the crane boom and the crane hook in all three axis (i.e., x, y and z coordinates) (Figure 2.13).

Also, the load carried by the tower crane is weighed and used to identify the item being carried and consequently, to identify the activity which the tower crane is used for.

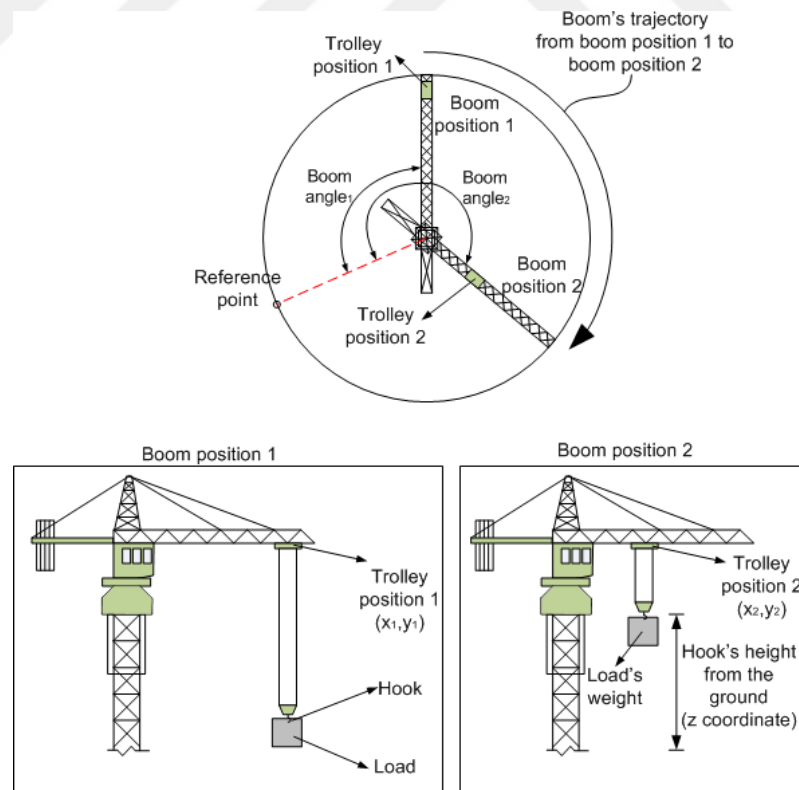


Figure 2.13 : Proposed approach for tracking the tower crane movement, position and the weight of the carried load with available tower crane sensors.

Selected tower crane sensors

As described in the vision of this PhD research, when available, feasibility of using readily available built-in data collection systems that are present on the construction equipment was investigated. Main purpose of these built-in data collection systems (e.g., on-board instruments (OBIs)) is to collect operational data regarding the health and usage conditions of the equipment. The anti-collision systems mounted on tower cranes is an example for such built-in data collection systems that can be installed on construction equipment. Figure 2.14 shows how an anti-collision system operates (Url-8). Such systems deploy several sensors on tower cranes and are principally used for identifying the interfering zones of two or more cranes for automatically detecting and preventing collisions in interfering zones.

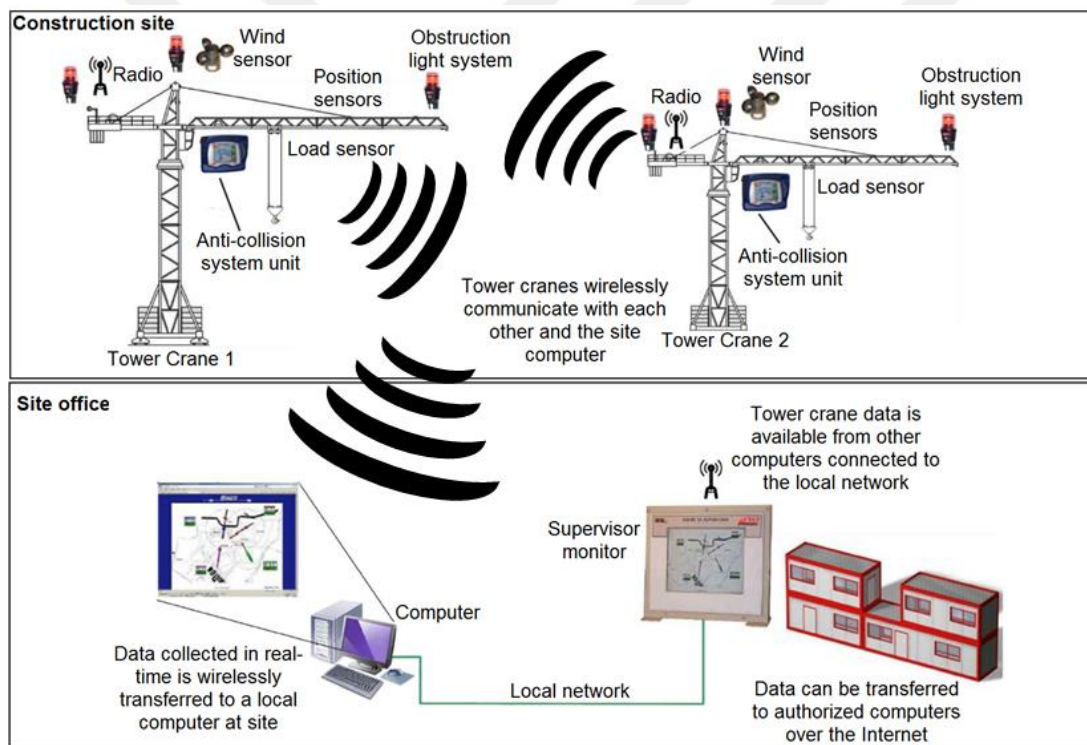


Figure 2.14 : Tower crane anti-collision system components at the production site and site office (Url-8).

In the anti-collision system at a site, multiple sensor units are mounted on the cranes. The site layout in a digital format, such as DWG, is introduced to the anti-collision system and the location of each tower crane on the site layout is entered to system. The limits to which each tower crane can move, the zones of each tower crane and the interfering zones of two or more tower cranes are defined. Tower cranes wirelessly communicate with each other using radio frequency and each time when a

tower crane is entering an interfering zone, the anti-collision system steps in to prevent the tower crane from moving further.

In the anti-collision tower crane monitoring system, multiple sensors such as anemometer, trolley position sensor, clinometer, angular position sensor, load sensor, are available and several others can be added. These sensors are connected to a central unit that includes a data logger, and a monitor inside the tower crane cabin. They are used to collect data about the angular position of the crane boom, the position of the trolley, and the load being carried by the crane at a particular time. The position information is collected in terms of the distance of the moving part of the tower crane (i.e., trolley) from the crane cabin.

Total station

Total station device that has built-in data collection capabilities was selected due to having internal power source and no need for wiring, being cost-efficient and having minimal interference with existing workflows as being currently used at site and is physically durable. Total station measurements are aimed to be tracked with the own data collection capabilities of the total station device. The total station is an instrument that is used to measure horizontal and vertical angles, and distances (Figure 2.15). It essentially composes of an electronic theodolite (used for measuring angles) and an electronic distance meter and used in multiple stages of a building construction for layout and alignment. Total station device is included in the scope of the equipment tracking vision of this research study as it provides a tracking method to monitor the progress of structural construction activities (e.g., concrete pouring, rebar installation) and it is readily available and already in use at construction sites.



Figure 2.15 : A total station used for building construction layout and alignment (Url-9).

In summary, in the developed approach: (1) movements and locations of construction equipment used for transferring (e.g., tower crane, elevator) the necessary resources (i.e., material, personnel, equipment) that are needed for an activity to be performed from one point to another at a construction site, and (2) locations and operating durations of construction equipment (e.g., total station, hand drill) used for performing an activity and the type of activity being performed are tracked with the selected technologies. Feasibility of this conceptual approach was investigated through the following steps:

- a) selection of appropriate sensor-based technologies based on the high-level requirements,
- b) identification of functional requirements for the selected technologies,
- c) development of the necessary reasoning mechanisms for data fusion and developing a prototype system,
- d) implementation of a physical prototype as a proof of concept, and
- e) performing field tests and validating the approach.

The details about the high-level requirements and technology selection are provided in this section and this is followed by the identification of the functional requirements for the selected technologies in the following section. The studies related to the third step that deals with the reasoning mechanisms for data fusion are provided in Chapter 3. Finally, the implementation of the prototype and the field tests are reported in Chapter 4 for monitoring the masonry work and monitoring the rebar and steel work.

2.5.1 Functional Requirements of the Selected Technologies

Table 2.6 reports the related equipment that is tracked with the selected technologies and the main purpose of the utilized equipment tracking approach.

Table 2.6 : List of equipment to be tracked and the selected technologies for equipment tracking.

Equipment	Selected technology for tracking equipment	Purpose
Elevator	RFID system (reader and antennas)	Tracking elevator movement and the items carried with the elevator
Tower crane	Own position and load sensors	Tracking tower crane trajectory and weight of the loads carried
Hand drill	Wireless accelerometer	Tracking the displacement of the hand drill to detect idle and working times
	RFID tag	Tracking the location of the hand drill to identify the floor where the masonry work is being performed
Wall block material pallets	RFID tag	Tracking the number and types of utilized pallets at each floor
Total station	Own built-in data collection means	Tracking the floor at which the slab concrete work has completed and rebar installation has started

As explained in the previous chapter, technologies were selected based on the determined high-level requirements. Initial tests at site were performed with the selected technologies to identify the technology-specific requirements. Following sections describe the initial tests conducted with the selected data collection technologies and the details of the identified technology-specific requirements.

2.5.1.1 RFID technology

RFID technology was selected since it is cost-effective, does not require line-of-sight, can work under different lighting conditions, has a long reading range, requires minimal manual input due to automated data collection, and is physically durable. The following functional requirements were determined based on the determined high-level requirements for the RFID system that will be installed on an elevator:

- *The components of the RFID system must take up minimum space inside the elevator cabin as possible.* As the main purpose of the elevator is to transfer personnel and other resources among the building floors, the components of the RFID system to be installed on the elevator, must not take up a lot of space inside the cabin. Especially at the beginning of working hours and at the end of the working hours the elevator is working full capacity, loaded with personnel and their tools. During the working hours, various types and

sizes of items are loaded inside the elevator, some of which almost leave no place for an extra person standing inside the cabin. Therefore, much of the components of the RFID system must be installed outside of the cabin, while only an antenna will be mounted on the inside of the elevator cabin to detect the tagged items loaded to the elevator. The ideal place for mounting the antenna inside of the cabin is the ceiling that is both out of reach of people and large-sized items. The antenna should be placed as close to the ceiling as possible to avoid dislocationing and/or malfunctioning caused by an unintended impact applied by a person or an item by hitting the antenna.

- *An antenna must be mounted on the outside of the elevator to detect the floor at which the elevator is.* The movement of the elevator will be tracked in terms of the building floors at which the elevator stops for loading and unloading items and personnel. To track the building floors, an RFID tag will be attached on each building slab. The elevator being made of metal, and the need for placing the antenna inside the elevator as close to the ceiling as possible, limit the reading range of the cabin antenna with the inner side of the elevator. This necessitates installing another antenna on the outside of the cabin, facing towards the floors of the building as the elevator climbs up and down the building facade. The tags on building slabs then will be detected by the outer antenna, and thus, the floor at which the elevator stops, will be identified.
- *To automatically detect a tagged item both inside and outside of the elevator, the reading range must be in between 20 cm and 4 m.* The antenna that will be mounted on the outside of the elevator will be positioned close to the building to be able to detect the floor tags. The minimum reading range requirement is based on this small distance (i.e., 20 cm) in between the elevator and the building facade. The maximum reading range requirement, on the other hand, derives from the geometry of the elevator cabin, which has the shape of a rectangular prism. As when a tagged item loaded to the elevator it can be as far from the antenna mounted on the ceiling of the elevator as when lying on the floor of the elevator. The longest distance diagonally measured inside the elevator is the distance from one upper end of

the elevator cabin to the other lower end on its opposite, and it is 4.1 meters. Therefore, the antenna inside the elevator must be able to detect tags from 4 meters maximum to enable automatic detection of every tagged item loaded on the elevator.

- *The outdoor antenna must be encapsulated or insulated.* The antenna installed on the outside of the elevator cabin must be physically durable and able to withstand harsh conditions such as impact (e.g., falling of an object from upper floors), rain and cold weather.

The selected RFID system that composes of a reader, two antennas and a computer was mounted on an elevator and initial tests were performed and the performance of the RFID system in terms of meeting the functional requirements were investigated. One of the antennas was mounted on the ceiling of the elevator cabin, while the other was mounted on the outside and isolated with styrofoam and thick plastic bag. Multiple number of tagged material pallets were loaded inside the elevator cabin during the tests and readings were obtained while the elevator was moving up and down, and stopping at some floors; testing the RFID system while the elevator was stationary and moving and loaded with tagged items. The inner antenna of the RFID system detected all the tags inside the elevator cabin (e.g., attached on material pallets) and the outer antenna detected all the floor tags successfully; meeting the reading range requirement that was determined as 20 cm minimum and 4 m maximum. Tests demonstrated that the selected RFID system performed well under real-life conditions and the functional requirements were met.

Initial tests showed that the tag's own adhesive may be insufficient under harsh circumstances and the tags might come off and fall out, and therefore the tags must be strongly fixed to the items that will be tracked. RFID tags attached on items may encounter harsh conditions at construction site (e.g., getting wet, heavy wind). Although the vision of this research assumes that the wall block material pallets were attached at the fabrication stage, the material pallets were needed to be tagged during the field tests. To avoid tags from falling out, the tags were additionally fixed to the material pallets with double sided-tape on the back and duct tape from the front. Although this method takes slightly longer to attach one piece of item with a tag, it worked well for keeping the tags in place.

Additionally, the need for a power supply and/or an additional battery was observed during the tests. The components of the RFID system installed on the elevator will be able to obtain power from the elevator's electric panel. However, there should be an additional battery powering the reader, the antennas and the notebook storing the RFID readings in case of a power outage in the elevator. It has been observed during the initial tests that in accordance with the health and safety measures, at the end of every working hour the elevator operator shuts down the power of the elevator and locks it to avoid unauthorized use. This necessitates an additional power source that will keep the computer and the reader functioning until the beginning of the following working hours, otherwise the computer and the reader need to be manually restarted.

When the collected data (i.e., tag IDs) that was stored in the computer was investigated, it was observed that the RFID system detected tags in its reading range numerous times as long as the tag remained inside the reading range. This necessitates performing filtering on the recorded readings as detection of a tag for one time is sufficient for decision making. Therefore, the tag readings need to be filtered both based on the antenna that it was detected by, and by removing the redundant readings of a particular tag.

2.5.1.2 Wireless accelerometer

The type of wireless sensor selected for tracking the hand drill is an accelerometer. A customized design is needed to mount the accelerometer onto the hand drill along with on-board batteries and memory. The accelerometer is suitable for use both at daytime and nighttime, as it is not affected by lighting conditions of the environment and can be configured with on-board memory and online real-time data transfer options. Following functional requirements were determined based on the high-level requirements mentioned in the previous section for the wireless sensor system that will be mounted on a hand drill:

- *The wireless sensor kit must withstand the harsh site conditions.* The accelerometer will be mounted on a hand drill to track its daily operating conditions throughout a working day. The hand drills are used for preparing mortar by mixing powder glue with water in a container and usually are

exposed to water and mortar (i.e., splashing out from the container) and receive impact as a result of aggressive use. Therefore, the sensor kit must have an encasing to be physically durable.

- *The wireless sensor kit must have enough power to operate on its own battery.* The accelerometer must include rechargeable batteries to have an internal power source. Rechargeable batteries are practical to charge at the end of every working day and the sensor will be able to operate without the need to be recharged throughout a working day.
- *The wireless sensor kit must be robust.* The accelerometer will be integrated with rechargeable batteries and with an on-board memory agent (e.g., SD card) and therefore the design will include a couple of different components. These components must not come apart while tracking the movement of the equipment. This requirement also necessitates an encasing that is light yet durable and will hold all the components together while the hand drill is working.

The wireless sensor kit was designed with the Arduino Yun microcontroller board, the ADXL345 3-axis accelerometer, batteries and an SD card. An encasing was custom designed to hold together all these components of the wireless sensor kit while measuring the movement of the hand drill and to prevent from external factors, such as water (Figure 2.16).

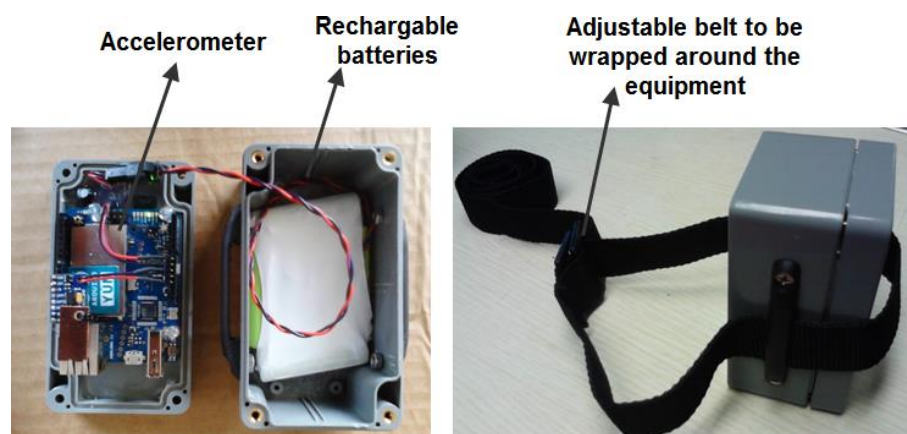


Figure 2.16 : Wireless accelerometer design: (a) inside of the encasing, (b) encasing closed.

The encasing is made out of ABS polymer plastic and the size of the encasing is 6 x 11,5 x 5,5 cm (W x L x D). This encasing ensured that the sensor kit will withstand the harsh construction site conditions and the components will not come apart while measuring vibration and movement of a hand drill.

There are three 1.2 V 2.2 Ah batteries included in the encasing that are mains-operated and rechargeable. A 5V voltage regulator was located in between the batteries and the board to keep the voltage at 5V constantly. Initial tests were conducted in a controlled environment and the current drawn by the accelerometer was measured as 0.5 mA, which is sufficient for the accelerometer to work for 4 hours non-stop. This meets the requirement for the accelerometer to work on its own battery throughout the day.

The tests showed that when the I2C protocol is used, less power is consumed and therefore the I2C protocol was preferred. The accelerometer was tested with a vibration motor in a controlled environment where the motor was given power within 10 seconds intervals and the measurements of the accelerometer were examined in terms of correctly identifying the stationary and moving conditions. The results demonstrated that the collected data by the accelerometer was able to detect the movement with 100% accuracy.

2.5.1.3 Sensors for tracking tower crane position and load

Sensors are used to track the movement and position of the tower crane (i.e., trajectory of the crane boom and the crane hook coordinates), as well as the the load carried by the crane. The following functional requirements were determined for the sensors that are used to track the movement of a tower crane, based on the high-level requirements described in the previous section:

- *The location from which the tower crane lifts a load and the location to which the tower crane lowers a load must be identified.* To automatically identify the type of activity that the tower crane is performing without worker input, the locations where the tower crane starts to lift a load and where it lowers the load will be detected. The reason is that the construction sites are divided into multiple zones for different utilization purposes (e.g., construction area, laydown area, roads, production plants). Therefore, the position of the crane will hint the type of activity that it is performing.

- *The weight of the load carried by the tower crane throughout a lifting activity must be identified.* Knowing the locations at which the load is lifted and lowered may not be sufficient to automatically identify the type of the load being transferred, and thus, the activity performed by the crane may not be detected. Therefore, the load weight must also be measured and this information should be integrated with the starting and ending point of a lifting activity to determine what item(s) is being carried, and thus, what activity is being performed.
- *The tower crane sensors must have on-board storage capabilities.* Typically a tower crane is utilized by multiple trades throughout a working day and the tasks performed for different trades show different characteristics. Therefore, the trajectory of the tower crane boom and the load carried by the crane must be measured to identify different works performed by different trades. Data collection that is performed in real-time must be stored in an on-board data storage unit. Due to the dynamic environment of construction sites, an uninterrupted network connection (e.g., local area network, 3G) might not always be available. Therefore an internal memory for data storage is needed for the times when there is no network connection.
- *Wireless data transfer should be provided.* To enable minimal manual input and minimal interference with the existing work flows, the data stored on-board should be transferred wirelessly. This will eliminate the need to for the crane operator to manually create a copy and transfer the data stored on-board to a remote computer every working day.

To evaluate the efficiency of the data collected from the anti-collision system for the purpose of this study, initial tests were performed at site and the collected data is investigated. The most important functional requirement that this system needs to meet is determining the position of the tower crane when it lifts a load and lowers a load. The anti-collision system calculates the angular position of the crane boom relative to a predefined reference point, where the angle of the crane boom is 0 at the reference point and increases in the anticlockwise direction. The tests demonstrated that the angular position of the crane boom and the position of the trolley in terms of distance from the cabin can be used to determine the 2D position (i.e., x and y coordinates) of the tower crane on the site layout plan at a given time. By combining

the position information with the load data; the 2D location of points at which the tower crane started and ended a specific lifting activity were identified. To obtain the depth of the hook at the time of lifting and lowering (i.e., z coordinate), an additional depth sensor or a separate GPS unit need to be mounted on the hook. However, budget and logistic constraints dictated that the anti-collision system sensors were used for the field tests and the prototype as is. Therefore, the anti-collision system sensors were able to meet the requirements for determining where the lifting activity of a tower crane starts and ends in 2D, instead of 3D. However, the high level requirements point out the need for detecting the position of the crane, and similarly the initial tests showed that when a load is lifted from the ground and lowered on a building floor, the z coordinate of the crane hook needs to be detected to identify to which building floor the load is transferred. This shortcoming of the existing data collection system was overcome by manually recording to which building floor the tower crane carried loads during the field tests. On the other hand, the sensors fully met the requirement for identifying the load carried by the crane within a lifting activity.

The anti-collision system tested, collects data from each sensor every 2 seconds and stores the data in CSV format into an SD card located in the central unit in real-time, meeting the on-board data storage requirement in case when wireless connection is not available. Also, the movements and positions of each tower crane are visualized on a local computer screen in real-time. Other operational information, such as operating conditions of the sensors and the tower cranes, is available to the supervisor personnel through the wireless network of the construction site, meeting the wireless data transfer requirement. Other connected computers in the local network and computers on the Internet can remotely access the tower crane data in real time if authorized.

To conclude, the primary functional requirement that this system needs to meet is determining the position of the tower crane when it lifts a load and lowers a load. The existing anti-collision system only provides 2D information and to collect crane's position in the z coordinate, the building floor which the tower crane carried loads to was manually recorded during the field tests.

2.5.1.4 Total Station device

Based on the determined high-level requirements in the previous section, the following functional requirement was determined for the total station devices for tracking the completion of concrete pouring activity of a building slab, and thus indicating the beginning of rebar production activity on that particular building floor:

- *On-board data storage capabilities and data storage in multiple formats.*

Total station devices are already in use in construction sites for building construction layout and alignment before the beginning and after the completion of certain activities, such as concrete pouring. This provides a cost-efficient solution for data collection. Since total stations have built-in sensors that collect data about the position of the survey (x, y and z), and therefore, no additional means of data collection is necessary for tracking the movement and position of the total station device. The only requirement determined for the total station device is to provide on-board data storage option and compatibility with multiple data storage formats so that the collected data can be used for purposes different than surveying only (i.e., activity tracking).

During the initial tests, the feasibility of the data collected by the total station device was investigated in terms of providing information about the completion of structural work at a particular floor and starting of the rebar installation at the upper floor. The total station device calculates the coordinates of unknown points based on the references of known points and provides the x, y, and z coordinates of the measured points. Layout of a multiple number of points are realized within one measurement period. The initial tests demonstrated that among the collected coordinates, knowing only the z coordinate is sufficient to know the floor at which the structural works are performed. Therefore, the total stations were sufficient to obtain the date of the data collection and the completion of concrete pouring activity at a particular building floor. Also, the tested total station have on-board data storage capacity and the provide the option to transfer the collected layout and alignment data to computer in different formats (e.g., txt, ncn); meeting the requirement for automated data collection and on-board data storage.

2.6 Conclusions

Current conventional methods for progress monitoring are problematic as they are based on manual data collection from visual site investigations and paper-based notes. Errors and missing data entrance are likely to occur during manual data collection and entrance to a computer. Progress is estimated by the site personnel based on their personal experience and this usually do not reflect the real conditions. The findings show that the progress of activities cannot be effectively tracked especially at large-scale construction sites, where different subcontractor crews and trades are working simultaneously.

To implement the proposed activity monitoring approach that is based on equipment tracking, the following activities were selected: (1) masonry work, (2) rebar installation, and (3) steel component transfer to installation area. Also, the following equipment were selected to be tracked with sensor-based technologies and data collection systems that are readily available at site: elevator, tower crane, hand drill, wall block material pallets, and total station. Tower crane, elevator, hand drill and wall block material pallets are used for tracking the progress of the masonry work, while the tower crane and total station is used for tracking the rebar installation progress. Finally, tower crane is used to monitor the progress of the steel component installation by tracking the steel component transfer to installation area.

The following high-level requirements for the technologies to be used at nighttime and daytime at a double shift construction site were determined by using the use case method: (1) working under different lighting conditions, (2) internal power source and/or need for minimal or no wiring, (3) cost-efficiency, (4) having minimal worker input and interference with existing work flows, (5) ability to track multiple activities, (6) physical durability and (7) non-line-of-sight and long reading distance.

Based on the high-level requirements sensor-based technologies were selected and technology-specific requirements were identified for each technology selected. A passive RFID system for tracking the elevator and the materials (i.e., brick) that were carried by the elavator was selected and implemented on an elevator to perform initial tests. The selected RFID system was able to meet the requirements related to the reading range and installation configuration based on to the geometry of the elevator and distances from the tagged items. Also, new requirements were identified

during the initial tests, such as the need for additional power supply and a better method to fix the tags to objects, as well as the need to filter redundant tag readings.

A wireless sensor kit was designed to be installed on a hand drill to track the idle and working times of the hand drill. A 3-axis accelerometer was mounted on a microcontroller board along with batteries and an SD card. These components were located in an encasing that will keep the components together while attached on the hand drill and enable working on its own batteries as indicated in the identified requirements.

Technology specific requirements were also determined for the sensors that will track the position of the tower crane and the loads (e.g., wall block material pallets for masonry work, pieces of rebar and steel components) carried by the crane. The feasibility of the anti-collision system sensors were investigated as these sensors were already present on the tower crane at the construction site where the initial field tests and the prototype implementation was conducted. The tests demonstrated that the angular position sensor on the crane boom and the position sensor on the trolley provided the tower crane position on the site layout plan in 2D (i.e., x and y coordinates) at a given time. When this positioning information was combined with the load sensor data; the 2D location of points at which the tower crane started and ended a specific lifting activity were identified. Although the functional requirement was determined to identify the crane boom and hook position in 3D, the anti-collision system was decided to be used as is, budget and logistic constraints were against obtaining a new sensor that detects the hook's coordinate. To collect crane's position in the z coordinate, the building floor which the tower crane carried loads to was manually recorded during the field tests. However, in the future, this process can be automated by mounting a depth sensor or a separate GPS unit on the crane hook to receive the depth of the hook (i.e., z coordinate) at the time of lifting and lowering.

Finally, for the total station device that will be used to track the beginning of rebar production activity at a particular floor of a building, no additional means of sensor-based tracking was deemed necessary. The built-in data collection capability of the total station device was investigated. The functional requirements were determined as to have on-board data storage capability and ability to store data in different formats. The initial tests demonstrated that these requirements are met by a regular total station device that are in use in most of the construction sites.

Based on the identified functional requirements and selected technologies, the reasoning mechanisms for data fusion and a prototype system were developed. The physical prototype was implemented as a proof of concept, and field tests were performed to validate the proposed activity monitoring approach. Details of the data fusion reasoning mechanisms are provided in the following chapter. Implementation of the prototype and the related field tests for monitoring the masonry work and rebar installation work, as well as the demonstration of the developed data fusion approach for the steel component transfer to installation area are reported in Chapter 4.



3. DEVELOPMENT OF REASONING MECHANISMS FOR DATA FUSION

The previous chapters described the vision of a sensor-based approach to track the construction equipment for automated monitoring of construction activities and presented the activities and related equipment to be tracked, including the selection of tracking technology. This chapter provides the details of the reasoning mechanisms utilized for data fusion which is needed to integrate data from the selected technologies and other resources. Based on the data fusion reasoning mechanisms reported in this chapter, a prototype was developed and implemented in the field experiments that were conducted at a double shift residential project. Details of the prototype implementation are provided in the following chapters of this thesis.

3.1 Background Research

This section reviews the related work in the literature in terms of (1) the data collection technologies utilized for progress monitoring and equipment tracking purposes, and (2) data fusion models and data fusion studies in the construction management domain.

3.1.1 Data collection technologies utilized in progress monitoring and equipment tracking

Several automated field data collection technologies have been utilized by the researchers in construction management studies for automated project control and monitoring purposes. These technologies can be categorized in three groups: (1) vision-based, (2) sensor-based and (3) hybrid (i.e., combination of different types of technologies).

Vision-based methods and technologies (i.e., image processing, laser scanning, photogrammetry, videogrammetry) were used in measuring the progress and productivity of construction work (Cheok et al., 2000; Hashash et al., 2005; Memon et al., 2005; Trupp et al., 2005; El-Omari and Moselhi, 2008; Kim and Kano, 2008;

Choi et al., 2008; Golparvar-Fard 2009a; 2009b; 2009c; 2010; 2012; Bosche et al., 2009; Ibrahim et al., 2009; Gong and Caldas, 2009; Zhang et al., 2009; Son and Kim, 2010; Ranaweera et al., 2012; Turkan et al., 2012a; 201b; Yang et al., 2012). For example, in a recent use of laser scanning for progress tracking purposes, researchers demonstrated the use of 3D laser scanning (i.e., LADAR) for automated progress tracking of concrete and steel buildings (Turkan et al. 2012a; 2012b). 3D point clouds and the 4D model of the project were registered in the same coordinate system which enabled recognizing as-built building components, progress estimation and schedule updates (Turkan et al., 2012a). In another study, daily progress photographs taken at site are superimposed on 4D as-planned models to measure the physical progress (i.e., % complete) of the building structure and the façade and to identify and visualize progress discrepancies (Golparvar-Fard et al. 2009a; 2009c). Vision-based technologies were also used for equipment tracking, mostly to track excavators and dump trucks used in earthwork activities as these jobsites provide clear sightlines and the equipment is more recognizable (Heydarian et al., 2012; Rezazadeh Azar et al., 2013). Previous work shows that the researchers did not investigate the usage of vision-based technologies for monitoring the performance of nighttime construction work. Major reason behind this is the shortcomings of vision-based technologies when used at poor lighting conditions (e.g., nighttime). While some vision-based technologies, such as laser scanners and 3D camera ranging, are viable for use at night; laser scanners are costly and 3D camera ranging is known to have short-range distances, low spatial resolutions and lower accuracies (Zhu and Brilakis, 2009; Dai et al., 2012). The visibility issues and the occlusion of objects observed at sites, along with the effects of bad weather conditions and weak lighting on the performance of vision-based technologies, make vision-based technologies less preferable for use at night (Güven and Ergen, 2014). Recent studies look for solutions to overcome the occlusion problem of vision-based data collection technologies (Lin et al., 2015); however, more studies are needed to demonstrate the feasibility of vision-based technologies to be used for monitoring the nighttime work.

Sensor-based technologies (e.g., UWB, RFID, GPS, OBIs), on the other hand, have the potential to be used both at daytime and nighttime (Güven and Ergen, 2014). Several sensor-based technologies have been successfully used in localization and tracking of almost all types of construction resources that can physically be tagged

(e.g., workers, materials, components and equipments) (Kannan and Vorster, 2000; Teizer and Castro-Lacouture 2007; Song et al., 2006; Ergen et al., 2007a; 2007b; Grau and Caldas, 2009; Cheng et al., 2011; Pradhan and Akinici, 2012a). Also, in a recent effort, UWB positioning technology were used as a means of progress tracking of piping activities (Shahi et al., 2013; 2014). Researchers also explored different types of sensor-based technologies to collect data regarding the productivity and safety of workers (Joshua and Varghese, 2011; Cheng et al., 2012; 2013). For equipment tracking purposes, GPS technology have successfully been used either individually or integrated with RFID technology (Navon and Shpatnitsky, 2005; Su and Liu, 2007; Lu et al., 2009; Pradhananga and Teizer, 2013). A group of researchers demonstrated the use of GPS in equipment tracking in road construction where the collected data were converted into project performance indicators, such as progress, productivity and cost (Navon and Shpatnitsky, 2005). In one of the recent studies, researchers focused on automatic spatio-temporal analysis of equipments used in earthmoving operations (i.e., skid steer loader) using GPS data (Pradhananga and Teizer, 2013). Cyclic activities (i.e., loading, hauling, unloading and returning of equipment) were automatically identified and analyzed using GPS data, and the amount of hauled material was estimated considering the capacity of the equipment for productivity analysis (Pradhananga and Teizer, 2013).

Other researchers have also shown the applicability of the combination of RFID and GPS positioning technologies, for tracking the productivity of backhoes used in a drainage pipe installation project (Su and Liu, 2007), and the mixer trucks used for delivery of concrete (Lu et al., 2009). RFID technology alone was also used for tracking the hauling units (i.e., trucks) used in the earthwork activities (Montaser and Moselhi, 2012) and buck hoists during a window replacement project on a high-rise construction site (Costin et al., 2012). Transportation of material (i.e., glass) and workers was performed via buck hoists, and RFID assisted in understanding the movement of workers, lifts or hoists, material carts, and glass throughout the project (Costin et al., 2012). Further analysis regarding the cycle times of the buck hoists were performed for understanding the usage details of the resources (i.e., wait times, peak times, underutilized times). Other researchers also demonstrated the use of built-in data sources (e.g., OBI, built-in performance monitors) for the purpose of collecting data regarding the performance of equipments (e.g., trucks, tower cranes)

(Kannan and Vorster, 2000; Sacks et al., 2005; Pradhan and Akinci, 2012). In one of these studies, the primary data source for collecting productivity information was the built-in performance monitors of mobile cranes (Sacks et al., 2005) that collected and showed information such as the position and the lifted weight on the monitors of the crane. Researchers showed that such information can be used to understand the construction progress. Other types of sensors were used to understand the variation of the excavator body orientation with respect to time to measure the productivity of earthmoving activities and the collected information was used for simulations (Akhavian and Behzadan, 2012). The major limitation of the sensor-based tracking technologies is the need for tagging every item that needs to be tracked, which can be costly in large construction areas (Brilakis et al., 2011a; Golparvar-Fard et al., 2009).

There are studies in which different types of technologies were used together (e.g., vision-based with sensor-based) for progress and productivity monitoring, and equipment and labor tracking purposes (Cheng and Chen, 2002; Teizer and Castro-Lacouture, 2007; Weerasinghe and Ruwanpura, 2009; El-Omari and Moselhi, 2011; Cheng and Teizer, 2013). In an earlier study, a combination of barcodes, GIS and video recording was used for progress monitoring of prefabricated structural components (Cheng and Chen, 2002). Several data collection technologies such as barcoding, RFID, 3D laser scanning, photogrammetry, and pen-based computers were used in another study (El-Omari and Moselhi, 2011). It was envisioned that the users will contribute to decision making process of project managers by making comments, taking records and snapshots while moving around the construction site with a tablet. Another group of researchers studied on the safety aspect of labor and other type of resource tracking (Teizer and Castro-Lacouture, 2007; Cheng and Teizer, 2013). In the earlier study, UWB technology was used together with 3D range imaging cameras for the purpose of generating a 3D representation of the construction site near real time. It was aimed to detect hazardous areas and determine potential collisions between laborers and equipment, while calculating productivity metrics and related safety indicators (Teizer and Castro-Lacouture, 2007). The latter study combined sensors, laser scanning and virtual reality technologies for collecting the location of resources (i.e., worker, equipment, material) for facilitating activity monitoring and safety applications in real-time (Cheng and Teizer, 2013). A study combined infrared cameras and unidirectional microphones attached on workers for

productivity monitoring of tools used in construction (Weerasinghe and Ruwanpura, 2009; 2010). The microphones located on workers and around site, were used to identify the type of tool from its sound (e.g., carpentry work such as nailing with nail gun or hammer, sawing) while the thermal images obtained via infrared cameras were used to recognize if the worker is idle or not. The collected data were used to measure the tool time and productivity of a given work within a specific time period. This research was one of the studies that demonstrated the idea of tracking construction activities by monitoring the equipment used in the execution of these activities.

The previous studies on automated progress monitoring at construction sites only focused on monitoring of daytime work using several automated field data capture technologies and there has been no attempt to monitor both the daytime and nighttime work. Although it has been demonstrated that the construction activities could be monitored based on the identified locations of the equipment used in performing the activities (Sacks et al. 2005), most of the related studies focused on equipment that is used in earthmoving and excavation activities, and a few studies tracked the equipment used in building construction (Gong and Caldas 2009; Costin et al. 2012; Yang et al. 2012). Moreover, in the building-related studies, only the crane and buck hoist movements were tracked during transporting material and workers to determine the productivity of the performed activities. Besides, some construction equipment have built-in performance monitors that show information related to the work that the equipment is performing. For example, built-in monitors located inside the tower crane cabins show the weight of the lifted equipment and the operating location on a map in real-time. Such means of data collection have the potential to provide information about the progress of activities; however, studies on utilizing built-in monitors and data collection systems for activity progress monitoring are limited. Overall, the potential of equipment tracking for progress monitoring in building construction has been overlooked in the literature.

3.1.2 Data fusion models

Different data fusion models were created in different domains to describe a process for fusing data from multiple sources. Among these, the Joint Directors of Laboratories (JDL) data fusion process model developed by US Department of

Defense is a generic model originally developed for military applications, and aimed to define the basic components of the data fusion processes of different disciplines and to assist in communications about data fusion applications (Hall and McMullen, 2004). The JDL model is in widespread use and there are evolved versions and extensions of the model that focus on its different aspects (Liggins et al., 2009). The original JDL model comprises of five levels of data fusion:

- (1) Level 0 (i.e., source preprocessing) dealing with preprocessing of raw data from sensors and databases,
- (2) Level 1 (i.e., object refinement) dealing with estimating the state of an entity,
- (3) Level 2 (i.e., situation refinement) dealing with the assessment of relationships among entities and with the environment,
- (4) Level 3 (i.e., impact assessment) dealing with predictions and estimations based on current situation,
- (5) Level 4 (i.e., process refinement) dealing with the monitoring of the ongoing fusion process to be able to use the most useful set of information sources (Liggins et al., 2009; Hall and McMullen, 2004).

The fusion performed at Level 0-1 are called low level data fusion, Level 2-3 are the high level data fusion and Level 4 is a meta process (Hall and McMullen, 2004, Razavi and Haas, 2010).

Other models are created to describe a general framework for data fusion and provide different perspectives of viewing the data fusion process, such as Dasarathy's functional fusion levels model (Dasarathy, 1994), Omnibus model (Bedworth and O'Brien, 1999) adapted from Boyd's (1996) decision loop model, TRIP model developed by Kessler and Fabien (2001) (Hall and McMullen, 2004). Among these, Dasarathy's model is another commonly known data fusion model (Dasarathy, 1997). In this model, data fusion is characterized based on the inputs and outputs of the model and fusion steps are defined under three levels:

- (1) sensor fusion dealing with raw sensor data,

(2) feature fusion dealing with extracting attributes from sensor data,

(3) decision fusion dealing with integrating data obtained from the first two fusion levels. Dasarathy's data fusion model and other developed data fusion models are a subset of the JDL fusion model, focusing on its different sections (Pradhan, 2009). Therefore, the steps of the Dasarathy's data fusion model can be mapped into the levels of the JDL data fusion model.

3.1.3 Data fusion studies in construction management domain

Data fusion research studies in the construction management domain have a variety of purposes, such as tracking and locating construction materials and equipment (Song et al., 2006; Ergen et al., 2007; Grau and Caldas, 2009; Razavi and Haas, 2010; Vasenev et al., 2011), productivity monitoring (Kannan and Vorster, 2000; Gong and Caldas, 2010; Pradhan and Akinci, 2012), progress monitoring (El-Omari and Moselhi, 2008; Bosche et al., 2009; 2013; Golparvar-Fard et al., 2009c; Shahi et al., 2013; 2014; Kim et al., 2013; Han and Golparvar-Fard, 2015), quality control and safety (Cheng et al., 2012; 2013), and object recognition and reconstruction in construction by visual data fusion (Zhu and Brilakis, 2010; Kuipers et al., 2014). Literature review revealed that the existing data fusion studies in the construction management domain fused data from different data sources providing data either (1) at overlapping time frames, or (2) at different time frames (Figure 3.1). Most of the existing data fusion studies are included in the former group and the details of the studies in each group are provided in the following sections.

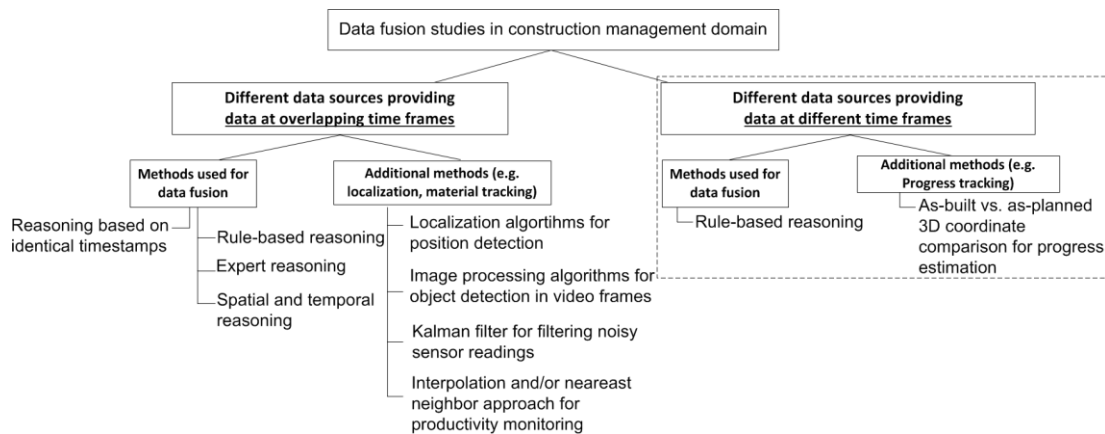


Figure 3.1 : Methods used by the data fusion studies in the construction management domain.

Fusing different data sources providing data at overlapping time frames

In this group of studies, researchers developed several reasoning mechanisms for fusing data. Reasoning based on identical timestamps is either used individually or coordinately with other reasoning methods to fuse the data collected from different data sources at the same (overlapping) time frames (Table 3.1).

Developing reasoning mechanisms for data fusion: The preferred data fusion method by the studies in the literature to combine data collected from different data sources at overlapping time frames was to develop reasoning mechanisms (e.g., expert reasoning, rule-based reasoning) related to the problem at hand. The utilized data fusion approaches utilized by the studies in the literature are summarized in Table 3.1 and can be grouped as given in the following paragraphs.

Table 3.1 : Data fusion approaches utilized in studies that fused different data sources providing data at overlapping time frames.

Reference to the study	Data source	Method for data fusion	Results
Vasenev et al., (2014)	- GNSS trajectory data for equipment - Expert knowledge on how the equipment works	- Expert reasoning	Filtering noisy sensor data and removing outliers from the construction equipment trajectories
Cheng et al., (2013a; 2013b)	- PSM - UWB - Video camera	- Rule-based reasoning - Reasoning based on identical timestamps	Identifying types of tasks performed by the workers and locations of unsafe actions
Song et al., (2006) Ergen et al., (2007) Grau and Caldas, (2009) Razavi and Haas, (2010)	- GPS - RFID	- Reasoning based on timestamps	Tracking location of construction materials and other resources
Gong and Caldas, (2009)	- Video camera	- Rule-based reasoning	Identifying different states of a crane (e.g., working, idle)
Kuipers et al., (2014)	- RFID - Video camera	- Reasoning based on timestamps	Identifying the types of visitors occupying a particular building space at a particular time from their IDs
Pradhan and Akinci, (2012)	- OBI - Weather data	- Spatial and temporal reasoning	Predicting the temperature and the payload productivity using interpolation and nearest neighbor methods.

Reasoning based on identical timestamps: Studies that utilized this method take advantage of different data sources collecting data at overlapping time frames, therefore different data sources can be fused by matching the identical timestamps. This method is either used as the sole data fusion method or it was combined with other reasoning mechanisms for fusion. For example, researchers performed tests in a controlled environment and collected physical data from workers with PSM and location data with UWB to identify the type and location of activities (e.g., load-lifting, walking, bending) performed by workers (Cheng et al., 2013a; 2013b). The tests were recorded with a video camera and the researchers synchronized the times of the UWB and PSM sensors based on the video camera time for fusing the data collected via these technologies. In another couple of studies, GPS and RFID data was fused by matching the timestamps of GPS location readings and RFID tag ID readings when tracking construction material and other resources (Song et al., 2006; Ergen et al., 2007; Grau and Caldas; 2009; Razavi and Haas, 2010). In another case, the overlapping locations of the recordings of the video cameras viewing a building space and RFID reads of visitor IDs moving around that space were matched based on the same timestamps to identify the types of visitors who occupy a particular building space at a particular time (Kuipers et al., 2014).

Expert reasoning: A group of researchers used expert knowledge to filter noisy sensor data and remove outliers from the construction equipment (e.g. excavator, dozer) trajectories obtained from Global Navigation Satellite System (GNSS) (Vasenev et al., 2014). Via the user interface developed by the researchers, the expert is able to filter the outliers in the collected GNSS data, based on his/her domain knowledge. This method depends on the expert's priori knowledge and expectations about how a specific equipment can move during construction (e.g., speed and rotation limits) and what the equipment is used for (e.g., hauling) when determining whether the outlier data is a result of the actual movement of the equipment or is it because the GNSS data was erroneous at that point.

Spatial and temporal reasoning: Pradhan and Akinci (2012) developed spatial and temporal reasoning mechanisms to fuse spatial (e.g., weather and soil database) and temporal (e.g., time cards) data sources for calculating the productivity in road excavation projects. It was suggested to fuse two data sources based on either timestamp or spatial location synchronization and interpolation and nearest neighbor approach was utilized for data synchronization (Pradhan and Akinci, 2012).

Rule-based reasoning: This is a commonly used approach in multiple data fusion studies with various purposes. For instance, when tracking the movement of precast components in a storage yard, Ergen et al., (2007) utilized an RFID system and a GPS unit to determine the piece of component that is moved from one stack to another. RFID system continuously recorded data and collected the tag IDs that are available in the test environment. A rule-based reasoning approach was used and the component that has been moved was determined by reasoning that the tag ID that appears the most in the tag readings is significantly higher for the piece being carried by the gantry crane. In another study, researchers developed a model that is based on domain knowledge to enable a computer to interpret the video frames of crane movements like a human being and to identify different conditions of a crane (Gong and Caldas, 2009). Rules are defined in the model to first identify three different states of the crane (i.e., waiting, idle, working). Then the change from one state to another is identified (i.e., idle started to working), and the time spent for each activity is determined based on the scenarios developed for possible states and movements of the crane.

In another study, researchers utilized rule-based reasoning for identifying the type and location of a particular activity performed by workers (Cheng et al., 2013a; 2013b). Physical data, such as heart rate and bending angle, and location of workers were used to identify the type and location of activities (e.g., load-lifting, walking, bending) performed by the workers. First, heart rate and bending angle (i.e., posture) thresholds were determined for particular tasks (e.g., load lifting, walking, bending). Then, measurements of heart rates and bending angles were taken with Physiological Status Monitoring (PSM) while the workers performed several tasks, and these were combined with location data obtained from the UWB to differentiate between multiple types of activities (e.g., load-lifting, walking, bending). The locations at which workers perform unsafe actions while working were determined by comparing the measurements with the determined threshold values.

Additional methods used for specific purposes of the study: In addition to the data fusion methods used for combining data from different data sources, further algorithms were used in these studies for the specific purposes (e.g., localization, material tracking) of the study (Figure 3.1). For example, studies that aimed to perform localization of construction resources utilized localization algorithms for detecting the position of the object of interest (Song et al., 2006; Grau and Caldas,

2011; Razavi and Haas, 2011; Cheng et al., 2013a; 2013b). Different filtering methods (e.g., Kalman filter) for removing outliers and noisy data from the sensor readings (Cheng et al., 2013a, 2013b) and several image processing methods and techniques were used to identify objects (e.g., building elements, workers) from the video frames and/or images for object detection purposes (Kuipers et al., 2014).

Fusing different data sources providing data collected at different time frames

Only one study is included in the second group. In this study, rule-based reasoning mechanisms were developed for fusing data obtained from different data sources that provide data collected at different time frames (Table 3.2).

Table 3.2 : Data fusion approach utilized in the study that fused different data sources providing data collected at different time frames.

Reference to the study	Data source	Method for data fusion	Results
Shahi et al., (2014)	- UWB - Laser scanner	- Rule-based reasoning	By fusing the UWB location data and laser scanner object recognition data, the progress of a pipeline project is estimated

Developing reasoning mechanisms for data fusion: Shahi et al., (2014) identified rule-based reasoning and defined logical statements to fuse laser scanner object recognition results with UWB material tracking data for pipeline projects. In this approach, the installed pipe information that is retrieved from UWB were double-checked with the installed pipe information which is collected by the laser scanner. In the first step, by looking at the magnitude of the error values that show the deviation of installed critical pipes from their as-planned locations; the status of the pipes (e.g., delivered, installed at correct location, installed at wrong location) is identified using fuzzy set of error values. This is then compared with the percentage of the pipes detected in the environment by the laser scanner, and different conclusions are made for each corresponding logical statement. For example if a critical spool is identified as being installed at wrong/different location via UWB, while more than 50% of spools in the same segment with the critical spool are detected at their as-planned locations by the laser scanner; then it is concluded that the pipeline was installed in the correct location. Although one critical spool is not

installed on its designed location, whole pipeline is deemed as installed at correct location (Shahi et al., 2014).

Additional methods used for specific purposes of the study: For the progress estimation purpose of the same study, as-built and as-planned locations of the pipes were compared and the results were used for earned-value calculations where conclusions were made based on expert opinion that identified the contributions of each activity category (e.g., delivery, installation, welding) on the total construction progress for a piping project (Shahi et al., 2014).

In summary, the literature review showed that the data fusion studies in the construction management domain developed their own data fusion methods and approaches for the specific needs of the problem they are dealing with and a generalized approach for data fusion for construction industry applications have not been developed. There are adaptations of the existing data fusion models (e.g., JDL and Dasarathy's model) from other fields to the construction domain and some researchers described their fusion strategies based on the JDL model. The first study to adapt the JDL functional model to civil engineering applications is performed by Haas (2006). Following that, Razavi and Haas, (2010) developed a modified data fusion model based on JDL model to be used in location estimation in construction resource applications. More recently, Shahi et al., (2014) developed a high level data fusion methodology that corresponds to the levels 1-4 of the JDL model and mainly contributed by managing the process of data fusion at various levels through workflows within the model. On the other hand, Kiziltas et al. (2006) used Dasarathy's model for defining the system architecture for the process of fusing data collected from multiple sources to generate integrated project histories to support estimator's decision making.

Pradhan et al., (2011) developed a query capture language to capture dynamic user queries and presented a query-based data processing model to support data fusion for construction productivity monitoring. Pradhan and Akinci (2012b) also described a generic data fusion formalism built on a planning-based approach for construction productivity monitoring to fulfill the need for a generic formalism for fusing data from multiple sources to support different construction management tasks. Same researchers described the type of data sources that are generally needed to perform construction management tasks (e.g., productivity monitoring, cost estimation) as

either spatial (e.g., design drawings, survey data, building information models, point-cloud models) and temporal (e.g., time-cards, weather, schedule) and provided the necessary reasoning mechanisms to fuse these data sources (Pradhan and Akinci, 2012a; 2012b). A taxonomy of reasoning mechanisms was developed to fuse a pair of spatial and temporal data sources to support construction productivity monitoring in road excavation projects.

The data fusion approach developed in this study to fuse the data collected from construction equipment for monitoring the progress of activities in double shift construction sites is built on this existing taxonomy of reasoning mechanisms created by Pradhan and Akinci (2012). A new non-spatiotemporal data source (i.e. physical properties) was added to the existing taxonomy and the related reasoning mechanisms were described to perform construction activity tracking applications in double shift construction sites.

3.2 Developed Data Fusion Approach

This section describes the necessary reasoning mechanisms for data fusion developed for tracking construction activities in double shift residential construction sites based on the data collected from sensor-based technologies deployed on several construction equipment. The data fusion reasoning mechanisms developed in this chapter was used to develop a prototype was that was tested in field experiments at a double shift residential project. In this section, the reasoning mechanisms were explained using the sample data collected during the field experiments.

The reasoning mechanisms for processing data obtained from each sensor were developed by extending the taxonomy of reasoning mechanisms that was developed by Pradhan and Akinci (2012) mainly to fuse a pair of spatial and temporal data sources to support construction productivity monitoring in road excavation projects.

In their study, researchers categorized data sources that are available for construction productivity monitoring as: (1) spatial (e.g., design drawings, survey data, building information models, point-cloud models) and (2) temporal (time-cards, schedule), and data fusion was performed using either space (i.e., spatial) or time (i.e., temporal) information.

However, the type of data sources defined and the reasoning mechanisms described in the previous study was not sufficient for the automated activity monitoring

purpose of this study that is based on equipment tracking. Therefore, a new non-spatiotemporal data source category was proposed in this study for construction activity monitoring, and the existing taxonomy of reasoning mechanisms was extended accordingly. Data interpretation step was added for interpretation of the non-spatiotemporal data sources used in construction activity tracking applications. Also, rule-based reasoning step was added to the data merging step of the existing taxonomy. Following sections provide the details for the extensions made to the taxonomy of reasoning mechanisms described by Pradhan and Akinci (2012). The details of the prototype implementation based on the developed reasoning mechanisms are provided in the following chapters of this thesis.

3.2.1 Data fusion process of this study

This section provides the details of the data fusion approach that was developed to fuse (1) data obtained from several construction equipment via sensor-based technologies and (2) project related information, such as quantity takeoffs, schedules and site reports. The data will be fused in a complementary and supporting fashion for monitoring the progress of construction activities. Figure 3.2 shows the data fusion process developed in this PhD study.

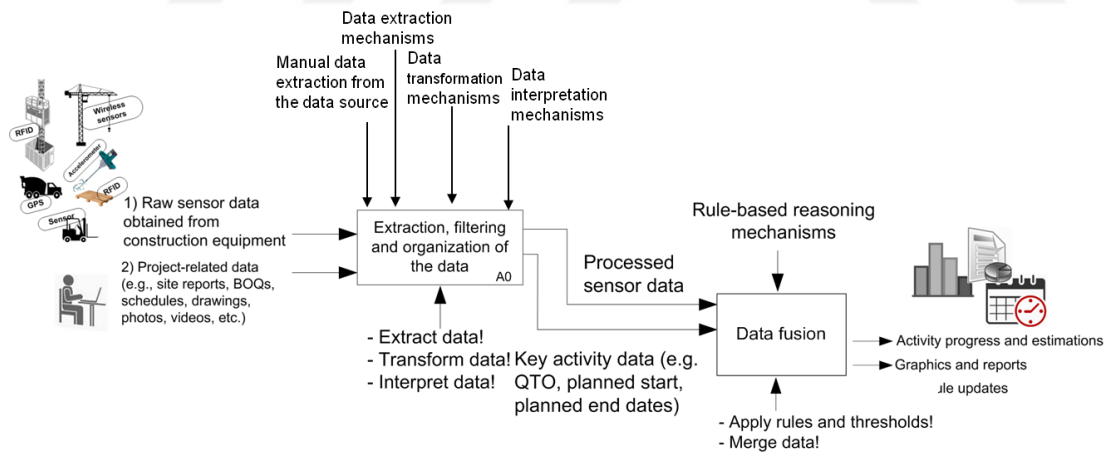


Figure 3.2 : Data fusion process for activity progress monitoring based on equipment tracking.

The developed data fusion approach fuses data obtained from different data sources that are fragmented in nature and provide data at different time frames. In the developed data fusion approach, data input is provided by:

1. Sensors installed on construction equipment or other means of data collection readily available on the equipment:

- RFID technology,
- Wireless accelerometer,
- Position and load sensors on tower crane,
- Total station device,

2. Data sources related to the project

- project quantity takeoffs,
- project schedule,
- site reports,
- expert inputs at some points.

In the first step, raw sensor data related to the location, utilization and trajectory information about the tracked equipment needs to be processed (data extraction, transformation and interpretation). Similarly, necessary key information needs to be extracted from the project documents (e.g., quantity takeoff of a particular work, and planned start and end dates) so that the sensor data and the project information can be fused based on the developed data fusion approach. Processing of the raw sensor data is accomplished by the data extraction, data transformation and data interpretation mechanisms developed for sensor-based data, and the details of these mechanisms are provided in the following sections. On the other hand, the extraction of the key information from the project documents is performed manually. The extracted key information about the project (e.g., quantity takeoff, planned start and end dates of activities) are fused with the processed sensor data that include information about the actual progress data of related activities using the rule-based reasoning mechanisms developed in this study. Results are used to calculate activity progress estimations, graphics and reports showing these estimations and schedule updates by comparing the actual and planned start and end dates for the monitored activities.

3.2.2 Extension of data source categories

Pradhan and Akinci (2012) provided a generalized categorization of data sources that are available for construction productivity monitoring as (1) spatial (e.g., design drawings, survey data, building information models, point-cloud models) and (2) temporal (time-cards, schedule). The researchers developed a taxonomy of reasoning

mechanisms to fuse a pair of spatial and temporal data sources for construction productivity monitoring, using either space (i.e., spatial) or time (i.e., temporal) information.

The type of data sources defined and the reasoning steps described in the previous study was not sufficient for the automated activity monitoring purpose of this study that is based on equipment tracking. Therefore, a new non-spatiotemporal data source category was proposed in this study for construction activity monitoring, and the existing taxonomy of reasoning mechanisms was extended. This new type of data source category, physical property data source, measures and/or collects the physical properties (e.g., weight, motion, volume, color, texture, physical shape, material) of entities (e.g., material, human, equipment), regardless of the time and space of the data collection. Three types of reasoning mechanisms, namely (1) data extraction, (2) data transformation and (3) data merging, described for the existing reasoning mechanisms that were previously defined for spatial and temporal data sources, were modified to represent the non-spatiotemporal data sources used in construction activity tracking applications. The extended version of the taxonomy of reasoning mechanisms is given in the following section.

3.2.3 Data collection with the prototype

Developed data fusion approach was implemented at a pilot construction site in Istanbul, with a physical prototype that was implemented as a proof of concept. The project is a reinforced concrete residential project with 24 building blocks being constructed and work is performed in two shifts. Field tests were performed for validating the developed approach in terms of determining the progress of (1) masonry work and (2) rebar installation at a double shift building construction project.

Masonry work

For monitoring the progress of the masonry work, (1) position and load sensors available on a tower crane, (2) a passive RFID system deployed on an elevator, (3) a wireless accelerometer mounted on a hand drill, and (4) wall block material pallets tagged with RFID tags, were tracked. The tower crane position and load sensors were used to collect data while the tower crane is carrying wall block material pallets to a building floor to identify the amount of material brought to a building floor. The

passive RFID system, that was selected and implemented based on the high-level requirements determined in Chapter 2, was deployed on the elevator. An RFID reader, and two antennas (i.e., one inside and one outside the elevator cabin) were installed to detect the tagged components being carried with the elevator and the building floors at which the elevator loads and unloads items. A wireless accelerometer that was attached on a hand drill was used to track the working times of the hand drill. Also, a passive RFID tag was attached to the hand drill to identify the floor at which the masonry work is performed. Finally, wall block material pallets that are used to deliver Autoclaved Aerated Concrete (AAC) masonry blocks were tagged with passive RFID tags upon their arrival to site. After their utilization, emptied material pallets are removed from the floors with the elevator and loaded on trailers and returned to the manufacturer. Number and types of utilized material pallets were detected when the empty material pallets are loaded on elevators.

Rebar installation work

For monitoring the progress of the rebar installation, (1) total station, and (2) position and load sensors available on a tower crane, were tracked. The total station is used for layout and alignment at different stages of the construction before the beginning and after the completion of certain activities, such as concrete pouring. Therefore, the data collected with the total station is used to identify the time of completion of the structural work at a particular floor and the time of beginning of the rebar installation at the upper (i.e., current) floor. As it is detected that the rebar installation has started, the tower crane position and load sensors, were used to collect data while the tower crane is used to transfer the pieces of rebar from the rebar cutting and bending area to the building floor to identify the amount of rebar brought to a building floor for installation.

The next sections elaborate how the developed reasoning mechanisms are applied on the data collected from these sensor-based technologies through the field tests for determining the progress of the selected activities.

3.2.4 Reasoning mechanisms developed for data fusion

The taxonomy of reasoning mechanisms is given in Figure 3.3 and the new steps that are defined in this study are shown in a dotted box. Details of the extended version of the taxonomy of reasoning mechanisms are explained in the following sections.

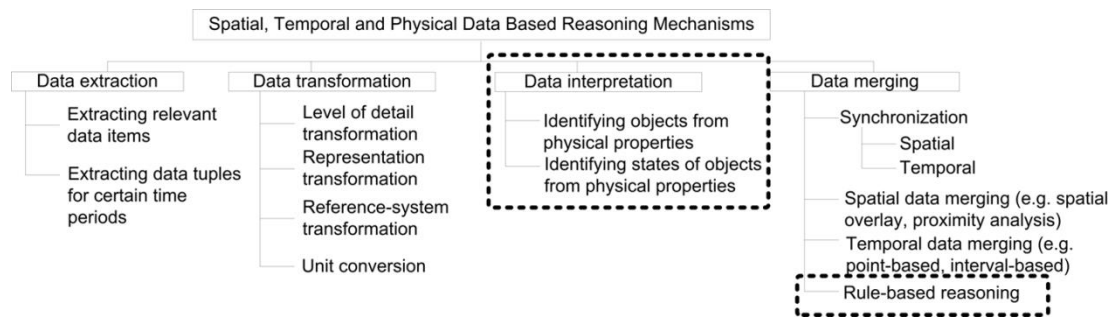


Figure 3.3 : Data fusion reasoning mechanisms for construction activity tracking (extended Pradhan and Akinci's (2012) study).

3.2.4.1 Data extraction

In this step, the relevant data is extracted from a sensor-based data source. In this study, data extraction is applied on the (1) RFID data collected from the elevator, (2) data obtained from tower crane position and load sensors, (3) wireless accelerometer data collected from the hand drill, and (4) total station data.

Pradhan and Akinci (2012) has defined two types of data extraction steps: (a) extracting relevant data items and (b) extracting data tuples for certain time periods. The former is extracting only a number of relevant data items among a list of all available data items. For example, data items related to the position of the tower crane and the load it is carrying are extracted from the available data items collected by the tower crane sensors to understand the type of activity performed by the crane and unnecessary data items, such as the wind speed, are eliminated. The latter is extracting a group of data items (i.e., data tuples) for an intended time period. A data source can contain a group of data items (i.e., data tuples) that are collected and stored on a timely basis (e.g., daily, hourly). Among this group of data items, only a subset of data items that belong to a certain time period might be necessary and the rest of the data items might not be needed for data fusion. For example, only the data tuples related to the load lifting activities of the tower crane are extracted, and data tuples belonging to other time periods when the tower crane is idle, are eliminated.

Extracting relevant data items and extracting data tuples for certain time periods were defined in the existing taxonomy of reasoning mechanisms for spatial and temporal data sources. They are also applicable to non-spatiotemporal data sources, which is defined in this thesis.

3.2.4.2 Data transformation

Once the relevant data items and data tuples for certain time periods are extracted from the data sources, next step is the data transformation. This is the process to change the data from one state to another. For spatial and temporal data sources, Pradhan and Akinici (2012) defined four types of data transformation:

- Unit conversion of a data item (e.g., changing temperature unit from Centigrade to Fahrenheit),
- Level of detail transformation, which is transforming data from a finer level of detail to a coarser level of detail (e.g., from minute to daily data) (i.e., data aggregation) and vice versa (i.e., data decomposition)),
- Representation transformation (e.g., converting from one spatial representation (e.g., line, point) to another, or from one temporal representation (e.g., point, interval) to another),
- Reference-system transformation (i.e., converting a reference system of a data source (e.g., global) to another (e.g., local)).

3.2.4.3 Data interpretation

Data interpretation mechanism is not currently included in the existing version of the taxonomy of reasoning mechanisms described for spatial and temporal data source. However, it was observed in this study that interpreting the data obtained from physical properties data source was necessary before applying the data merging. The following additions were made to the existing taxonomy of reasoning mechanisms under the data interpretation, as shown in Figure 3.3:

- Transformation of physical properties into objects: Physical properties that can be measured with sensors (e.g., weight, volume) can be used to infer objects. For example, the weight of an object (e.g., carried by the tower crane) can be used to understand what the object is (i.e., rebar).
- Transformation of physical properties into states of objects: Physical properties (e.g., motion) can be transformed into states of objects (e.g., moving or static). For example, the vibration of a hand drill can be used to deduce if the object is idle or working.

3.2.4.4 Data merging

Data merging is the final step to fuse two or more data sources. In the existing taxonomy of reasoning mechanisms, two types of data merging methods were described (Pradhan and Akinci, 2012): (1) spatial (e.g., spatial overlay, proximity analysis), and (2) temporal (e.g., point-based, interval-based). Additionally, researchers proposed two new synchronization method to fuse spatial and temporal data sources for construction productivity monitoring: nearest neighbor and interpolation. These methods aimed at overcoming the challenges with two data sources having different time stamps or spatial locations, and providing data at different frequencies.

In addition to the data merging approaches that are defined within the existing taxonomy of reasoning, this study suggested adding a new data merging step that combines spatial, temporal and non-spatiotemporal data sources and that is the rule-based reasoning (Figure 3.3). As explained in the review of data fusion studies in construction management domain, developing a reasoning mechanism specifically designed to solve the problem at hand, is a commonly used data fusion approach in data fusion studies. Therefore, the rule-based reasoning data merging method was added to the existing taxonomy.

3.2.5 Application of the reasoning mechanisms

The extended taxonomy of reasoning mechanisms was applied on the data collected during the field experiments. This chapter provides the details of the reasoning mechanisms applied on the data collected through the field experiments with (1) tower crane position and load sensors, (2) RFID system installed on the elevator, (3) wireless accelerometer deployed on the hand drill, and (4) total station device.

3.2.5.1 Data extraction

Data extraction from tower crane sensors

In this step, relevant data items and data tuples for certain time periods are extracted for determining the position of the tower crane and the load it is carrying, to identify the type of activity that the tower crane is performing.

First, relevant data items were pulled out from the tower crane position and load sensors. The tower crane sensors provide eleven data items such as date, time, load

weight, load rate, wind speed and error code. Among these data items, the following seven data items are relevant for understanding the tower crane movements, shown in Table 3.1:

- date,
- time,
- slewing position (in degrees),
- trolley position (in meters),
- hook position (in meters),
- load weight (in tons),
- power off (Boolean)

Date and time indicate the time instant for collection of the relevant data items. The slewing angle, trolley position and the hook position are related to the position of the tower crane boom, trolley and hook at that time instant. Load weight is the weight value measured at that time instant while the power off data item shows whether the tower crane is on or off. Other data items (e.g., wind speed) are eliminated as they are not relevant for understanding the position of the tower crane and the load it is carrying.

In addition to that, data instances are extracted for certain time durations (i.e., load lifting activities). Tower crane sensors store data that is collected every two seconds. However, only the load lifting activities of the tower crane are needed, and the instances when the tower crane is not carrying a load or is idle, are unnecessary. Table 3.3 is a data instance sample illustrating a load lifting activity that is extracted among the list of data items recorded in a particular day. A load lifting activity is identified via the load values: in the extracted data instances, the load weight value is zero at the beginning and gradually increases in time and equals to zero as the tower crane unloads the weight. Figure 3.4 illustrates the tower crane part movements for the sample lifting activity data given in Table 3.3.

Table 3.3 : Sample extracted tower crane data.

Date	Time	Slewing position (°)	Trolley position (m)	Hook position (m)	Load weight (t)	Power OFF
15.05.2015	15:57:25	278	38.7	00.0	0.0	0
15.05.2015	15:57:27	278	38.6	00.0	0.1	0
15.05.2015	15:57:29	278	38.6	00.0	0.5	0
15.05.2015	15:57:31	278	38.7	00.0	0.8	0
15.05.2015	15:57:33	278	38.6	00.0	1.1	0
15.05.2015	15:57:35	278	38.7	00.0	1.2	0
15.05.2015	15:57:37	278	38.6	00.0	1.4	0
15.05.2015	15:57:39	278	38.7	00.0	1.4	0
15.05.2015	15:57:41	278	38.7	00.0	1.4	0
15.05.2015	15:57:43	278	38.7	00.0	1.4	0
15.05.2015	15:57:45	278	38.6	00.0	1.4	0
15.05.2015	15:57:47	278	38.6	00.0	1.4	0
15.05.2015	15:57:49	278	38.7	00.0	1.4	0
15.05.2015	15:57:51	278	38.3	00.0	1.3	0
15.05.2015	15:57:53	277	38.6	00.0	1.4	0
15.05.2015	15:57:55	275	38.6	00.0	1.4	0
15.05.2015	15:57:57	274	38.6	00.0	1.4	0
15.05.2015	15:57:59	273	38.6	00.0	1.4	0
15.05.2015	15:58:01	272	38.6	00.0	1.4	0
15.05.2015	15:58:03	271	38.6	00.0	1.4	0
15.05.2015	15:58:05	270	38.6	00.0	1.1	0
15.05.2015	15:58:07	269	38.6	00.0	1.4	0
15.05.2015	15:58:09	268	38.6	00.0	1.4	0
15.05.2015	15:58:11	266	38.6	00.0	1.4	0
15.05.2015	15:58:13	265	38.6	00.0	1.4	0
15.05.2015	15:58:15	264	38.6	00.0	1.4	0
15.05.2015	15:58:17	263	38.6	00.0	1.4	0
15.05.2015	15:58:19	262	38.5	00.0	1.4	0
15.05.2015	15:58:21	261	38.5	00.0	1.4	0
15.05.2015	15:58:23	260	38.5	00.0	1.4	0
15.05.2015	15:58:25	260	38.5	00.0	1.4	0
15.05.2015	15:58:27	259	38.6	00.0	1.3	0
15.05.2015	15:58:29	258	38.6	00.0	1.3	0
15.05.2015	15:58:31	258	38.6	00.0	1.3	0
15.05.2015	15:58:33	257	38.6	00.0	1.1	0
15.05.2015	15:58:35	257	38.6	00.0	1.1	0
15.05.2015	15:58:37	257	38.6	00.0	0.7	0
15.05.2015	15:58:39	257	38.6	00.0	0.0	0

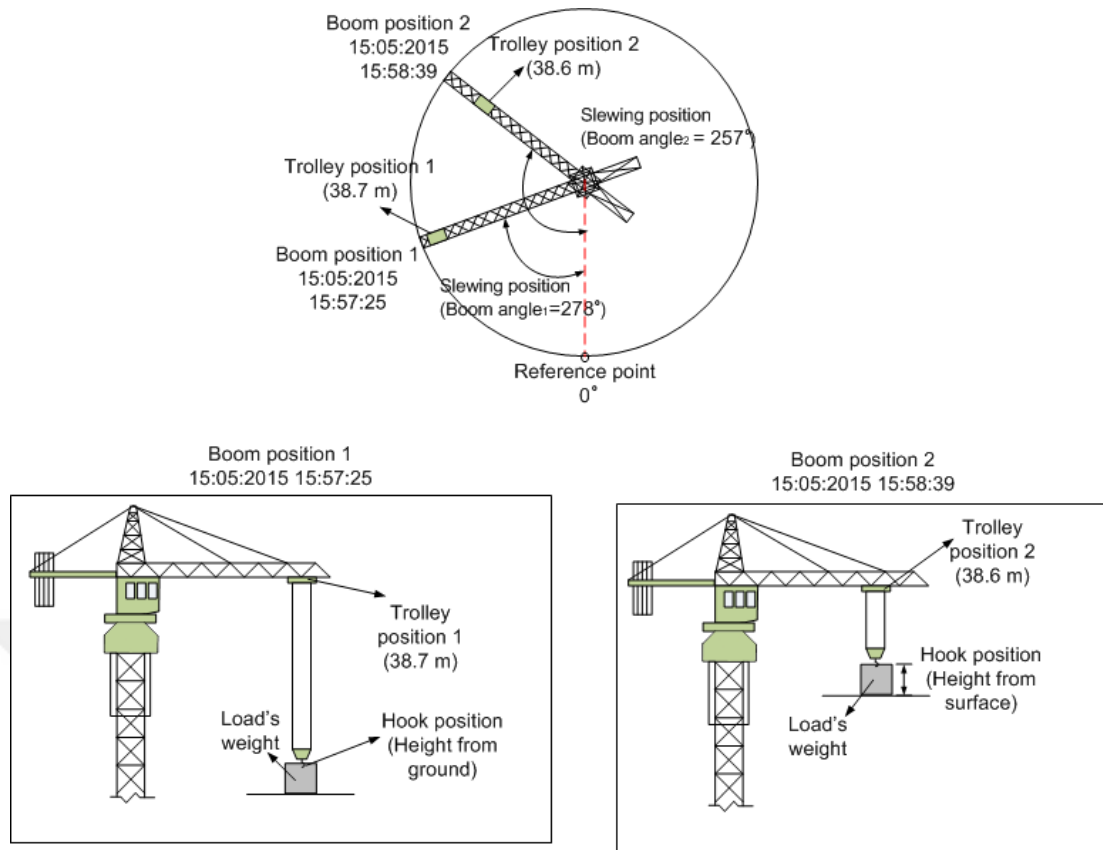


Figure 3.4 : Tower crane part movements: (a) slewing position change of the crane boom from the plan view, and (b) position change of the trolley.

The relevant data items are extracted automatically and a rule-based reasoning is performed for extracting the data tuples for the intended time periods (i.e., load lifting activities). This reasoning is based on the site observations and interviews that were conducted and the main steps are given as follows

- First, to identify the load lifting activities of tower crane from the idle times or other types of movements of the tower crane, the precondition is that the tower crane is operating (i.e., Power OFF = 0) throughout the activity (Figure 3.5).
- Start of a activity is then determined with a change in the load weight value from zero to a value greater than zero (i.e., Load weight = 0 at t_0 and Load weight > 0 at t_1).
- In addition to the load weight change, the slewing position and the trolley position of the tower crane is checked. Safety regulations necessitate that the crane operators are assisted through a walkie-talkie by pointer personnel located at the ground level to direct the operator to prevent hitting incidents

where the operator's field of view is blocked. During the site visits, it has been observed that in the beginning of a weight lifting, in accordance with the directions coming from the ground, crane operator keeps the position of the crane boom and the trolley static for a short time to avoid hitting to a worker or to another object with the load while the load is levitated from the ground. According to the site observations, the wait time before the crane's slewing position change is assumed to be four seconds, and if the trolley is not moving more than 0.5 meters back and forth, the trolley is assumed to remain static. Based on these assumptions, rules have been defined to identify the movements of both the crane boom and the trolley during a load lifting:

- The slewing position of the crane is checked to identify the instances when it remains static (i.e., not moving more than two degrees clockwise or counter clockwise) for the first four seconds (i.e., in between t_1 and t_5).

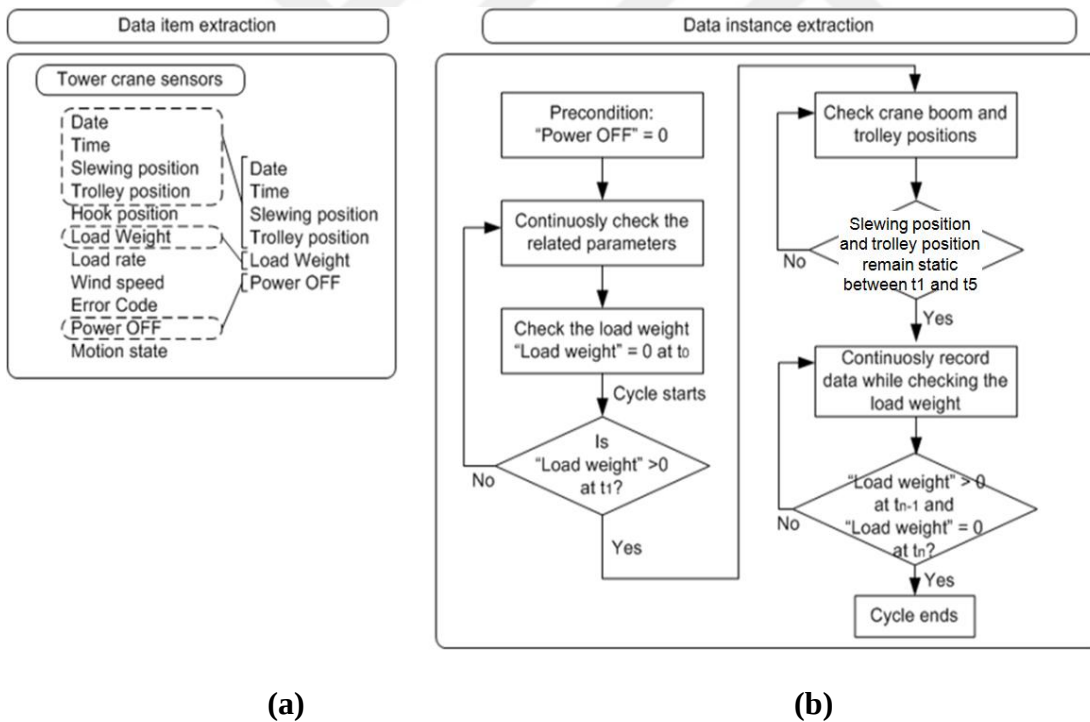


Figure 3.5 : (a) Extracting relevant data items, and (b) method for extracting data instances that identify a load lifting activity from tower crane sensor data.

- At the same time, the position of the trolley is also checked to remain static (i.e., not moving more than 0.5 meters back and forth) for the first 4 seconds (i.e., in between t_1 and t_5).

- To identify when the lifting activity ends, the load weight value is checked again to see it decreased from a value greater than zero to zero (i.e., Load weight > 0 at t_{n-1} and Load weight = 0 at t_n).

Data extraction from RFID

Data extraction was applied on the readings of the RFID system installed on the material and personnel elevator to identify the material pallets being unloaded from the elevator from other movements of the elevator. RFID system can read 800 tags per second, and the data items recorded include (Table 3.3):

- the unique RFID tag ID,
- antenna number by which the tag is detected,
- the timestamp of the reading.

All data items were extracted since they all are relevant.

The reasoning mechanism for data instance extraction was developed based on the experimental setup. While antenna number 1 is the one installed inside the elevator cabin, and the antenna number 2 is the one installed on the outside of the elevator cabin. The elevator travels up and down on the building facade throughout each working day and in the meantime, antenna number 2 detects the floor tags attached on each building floor. The reasoning mechanism developed for data instance extraction for RFID readings aims to differentiate the material pallet carrying event from the other movements of the elevator:

- It first detects when the antenna number 1 reads a tag; indicating a tagged component (i.e., empty material pallet) is inside the elevator cabin (Figure 3.6).
- Starting from this very first incident of reading by antenna number 1, all readings are taken until the last tag ID is detected by antenna number 1.
- At the same time, the readings of antenna number 2 is also monitored to determine the floor number from which the material pallets are loaded and brought down to the ground floor.

Table 3.4 : Sample RFID data.

Tag ID	Antenna number	Timestamp
BDBD01FF1101000000020964	1	2015-06-30 15:22:38.703
BDBD01FF1101000000020913	1	2015-06-30 15:22:38.718
BDBD01FF1101000000020892	1	2015-06-30 15:22:38.718
BDBD01FF1101000000020993	2	2015-06-30 15:22:38.718
BDBD01FF1101000000020921	1	2015-06-30 15:22:38.734
BDBD01FF1101000000020967	1	2015-06-30 15:22:38.734
BDBD01FF1101000000020000	1	2015-06-30 15:22:38.734
BDBD01FF1101000000020964	1	2015-06-30 15:22:38.734
BDBD01FF1101000000020954	1	2015-06-30 15:22:38.75
BDBD01FF1101000000020913	1	2015-06-30 15:22:38.75
BDBD01FF1101000000020927	1	2015-06-30 15:22:38.75
BDBD01FF1101000000020930	1	2015-06-30 15:22:38.75
BDBD01FF1101000000020968	1	2015-06-30 15:22:38.75
BDBD01FF1101000000020908	1	2015-06-30 15:22:38.859
BDBD01FF1101000000020939	1	2015-06-30 15:22:38.859
BDBD01FF1101000000020944	1	2015-06-30 15:22:38.89
BDBD01FF1101000000020914	1	2015-06-30 15:22:38.89
BDBD01FF1101000000020892	1	2015-06-30 15:22:38.89
BDBD01FF1101000000020003	1	2015-06-30 15:22:38.89
BDBD01FF1101000000020909	1	2015-06-30 15:22:38.89
BDBD01FF1101000000020891	1	2015-06-30 15:22:38.89

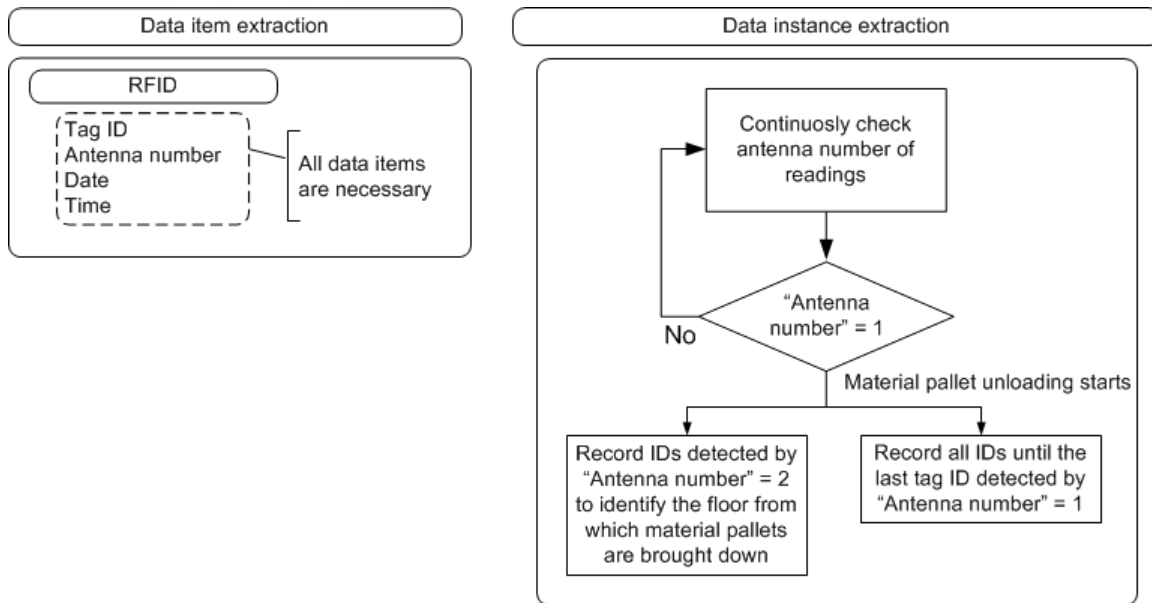


Figure 3.6 : (a) Extracting relevant data items, and (b) extracting data instances that identify elevator's material pallet carrying event from RFID data.

Data extraction from wireless accelerometer

Similar rule-based approach was applied to accelerometer readings to identify among the different states of the hand drill (i.e., working or idle) (Figure 3.7). Table 3.2 shows sample raw data obtained from the 3-axis accelerometer installed on the hand drill and it consists of (1) date-time, (2) accelerations in x, y and z directions, and (3) active/passive value (i.e., activity and inactivity).

Table 3.5 : Sample accelerometer data.

Date-time	x	y	z	Active/Passive
15/08/15-13:11:58	-165	177	-79	inactivity
15/08/15-13:11:59	-33	246	15	inactivity
15/08/15-13:12:00	-30	242	-3	inactivity
15/08/15-13:12:01	-33	277	-77	inactivity
15/08/15-13:12:02	-10	252	-99	inactivity
15/08/15-13:12:03	17	372	8	activity
15/08/15-13:12:04	79	326	-14	activity
15/08/15-13:12:05	56	252	-51	activity
15/08/15-13:12:06	19	247	88	activity
15/08/15-13:12:07	5	251	17	activity
15/08/15-13:12:08	133	182	81	activity
15/08/15-13:12:09	-28	71	170	activity
...	...	...	...	...
15/08/15-13:12:50	-257	198	-266	activity
15/08/15-13:12:51	-188	114	-151	activity
15/08/15-13:12:52	-133	52	-191	activity
15/08/15-13:12:53	-174	511	-106	activity
15/08/15-13:12:54	-130	172	-196	inactivity
15/08/15-13:12:55	-97	193	-70	inactivity

Among these data items, date-time and 3-axis acceleration values are extracted. The sensor itself classifies a change in one of the three axis as there is a movement and assigns "activity" value to active/passive column. For the purpose of the study, this classification was not taken into account and the different states of the tracked equipment was calculated using a different method. The acceleration values for each of the three axis were compared with the previous corresponding values and the change that exceeds the threshold was deemed as there is activity. Comparison with the previous values at a point in time was calculated with the below equation (3.1):

$$\sqrt{(X_2-X_1)^2 + (Y_2-Y_1)^2 + (Z_2-Z_1)^2} \quad (3.1)$$

To distinguish a working state (i.e., hand drill being used for preparing mortar) from a position change (e.g., equipment moved from one place to another), it is checked whether the acceleration values continue to show "activity" for the following 15 seconds.

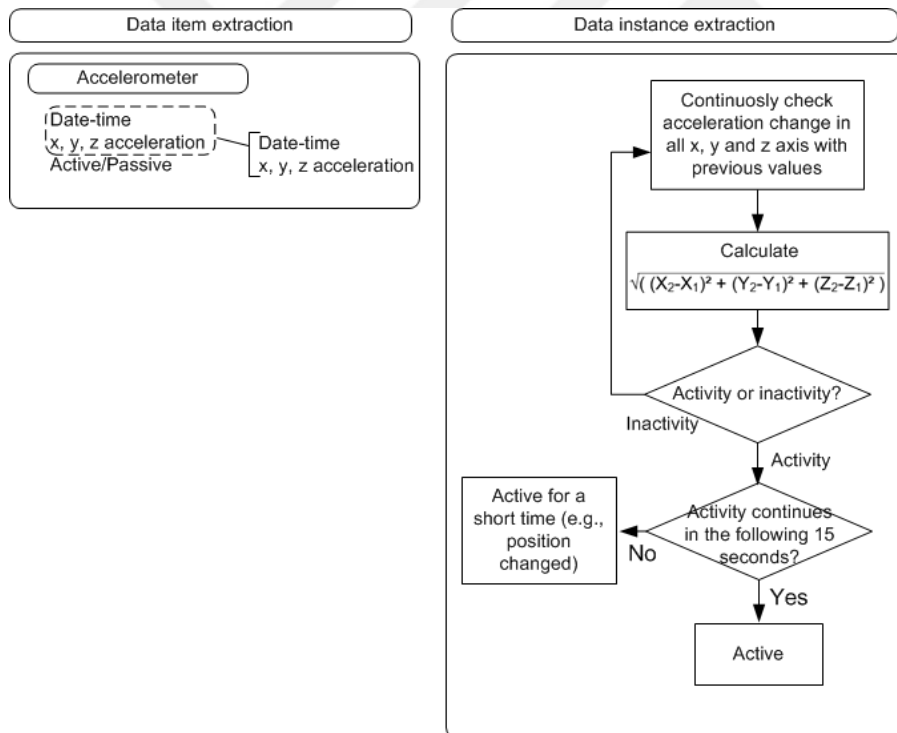


Figure 3.7 : (a) Extracting relevant data items, and (b) method for extracting data instances that identify different states of the hand drill from the accelerometer data.

Data extraction from total station

Table 3.6 shows a sample total station data collected during building construction layout and alignment and the format of the collected data.

Table 3.6 : Sample total station data.

Point number	Z coordinate
1	159.7575
2	159.7664
3	159.7429
...	...
96	159.7517
97	159.7446
98	159.8269
99	159.7527

Data storage is performed in many file formats, and a naming convention that shows the date of the data collection and the elevation of the floor at which the layout has been performed is used when giving the file a name (e.g., 20152702_159.75_layout.txt). The elevation and date information are extracted from the total station data.

3.2.5.2 Data transformation

Data transformation for the tower crane sensors

Load weight: The load weight data item is transformed in terms of the level of detail. As can be seen from Table 3.1, different load weight values are obtained for a load during a typical load lifting activity. This is mainly due to the fact that data collection is performed in very short time intervals (i.e., 2 sec). Other various factors include the effect of the change in the environment, such as wind, within a lifting activity and the effect of the tower crane movement itself on the load being carried, such as turning the load, upwards and downwards movements, affect on the amount of the load being measured. Therefore, the weight load value seems to change throughout a lifting activity and lots of load weight values are obtained even for a short lifting activity. After a lifting activity is determined through data instance extraction, data aggregation (i.e., level of detail transformation) is applied on the load data to calculate one representative value of the load weight. Median of all the load weight values of a lifting activity is calculated as the weight of the load being carried.

Location: The load being carried from one place to another is important since weight is a descriptive physical property that can be transformed into objects, in other words, weight of an object can be used to understand what the object is (e.g., rebar,

formwork, material pallets). When the weight of the load itself may not be enough to identify the object being lifted (e.g., objects with the same weight stored closely), the weight loading and unloading points become important. When used together with the weight information, one can infer the beginning and ending points of tower crane movements from its slewing position and trolley position data items (Figure 3.4). Different areas are assigned to different purposes (e.g., production area, laydown area, roads) in a construction site layout. Slewing position (i.e., tower crane boom angle for a reference point) of the tower crane boom at the beginning of a lift, along with the trolley position (i.e., distance of the carriage from crane cabin) at the beginning of a lift can be used to understand where the weight is loaded. The same applies when inferring to the lowering location of the load. This type of transformation refers to representation transformation as the angle and distance information are transformed into location information. A reference system transformation is applied on this location information to identify the corresponding locations of weight loading (e.g., rebar production area) and unloading points (e.g., building slab) in the site layout plan of the construction site.

Time interval: Another representation transformation is applied on the weight loading time point (e.g., lifting activity start time, 15:57:27) and unloading time point (i.e., lifting activity end time, 15:58:37) to calculate the duration of a lifting activity (i.e., 70 seconds). This is an example for time points transformed into time intervals.

Data transformation for the accelerometer

Time interval: Timestamps that represent the working times and idle times of the hand drill are combined and transformed into time intervals that show the total working time intervals and total idle time intervals, respectively.

Data transformation for RFID

Location of reading: A reference-system transformation is applied on RFID data, as the antennas are used to identify whether the reading is performed inside the elevator cabin (i.e., antenna #1) or outside (i.e., antenna #2) the elevator cabin.

Data transformation for total station

Building floor: Elevation information stored in the coordinate format is transformed into building floor information to identify the building floor at which the layout was

performed (e.g., elevation: 159.75 m corresponds to 19th floor) by applying a reference-system transformation.

After the transformation is completed to convert data items and instances into the necessary versions and states, next is the data interpretation step, and finally, data merging is performed.

3.2.5.3 Data interpretation

Data interpretation for the tower crane data

Transforming physical properties into objects: As the median of all the load weight values of a lifting activity is calculated, the weight value of the load being carried is determined. This is used to infer the type of object being lifted with the tower crane (e.g., rebar, material pallet), not only in monitoring the masonry work but also in other activity monitoring applications that involves data collection with the tower crane.

Transforming physical properties into object states: Type of data transformation applied on the accelerometer data exemplifies the transformation of physical properties into states of objects. The data instances that are identified to show the active times of the hand drill within a daylong data, are used for distinguishing the different states of the equipment being tracked (i.e., working or idle).

3.2.5.4 Data merging

Multiple types of data sources that are necessary for this study are used to collect data from field at different times and act in a complementary fashion. Additionally, project documents, such as quantity takeoffs and schedules, are used to evaluate the activity being monitored is ahead or behind the planned schedule. Data extraction and data transformation steps are applied on the collected data and the data merging steps are performed for monitoring the progress of activities based on the collected data. Details of the prototype implementation are given in Chapter 4, however, the details of the data fusion steps implemented for each selected activity type are explained in this chapter.

Data merging for monitoring the masonry work

The progress of the masonry work is obtained by collecting data from (1) tower crane sensors, (2) RFID system on elevator, and (3) wireless accelerometer on hand drill. These data sources are involved in the data collection process sequentially, and the data provided by these data sources complemented each other. Additionally, the amount of work to be completed (i.e., quantity takeoff) and the planned start and end dates for the masonry work activity are obtained from related project documents. Figure 3.8 is the IDEF0 diagram that shows how the developed reasoning mechanisms are applied for tracking the progress of masonry work.

Steps for data extraction, transformation and interpretation

1. The wall quantity takeoff and the planned start and end dates for the masonry work at the particular floor are manually extracted from the related documents.
2. Transfer of necessary material (e.g., wall blocks, glue) to the floor at which the masonry work is to be performed is the first step to complete. Data collected by the tower crane sensors are received and based on the predefined data extraction rules, relevant data items and data tuples are extracted from the tower crane data. This enables identifying the load lifting activities of the tower crane.
3. For each of the identified load lifting activities, median of the load weight data item is calculated and a load value is obtained. This enables identifying that the loads lifted by the tower crane are wall block material pallets and the number of wall block material pallets carried in each load lifting activity.
4. The angular position of the crane boom and the position of the trolley at the time of load lifting (e.g., laydown area) and load lowering (e.g., building) are transformed into the corresponding locations on the site layout.
5. After the necessary wall block material is brought to the floor, accelerometer data is taken into account. The records of the accelerometer is used to identify the displacement of the hand drill throughout a day. The behaviour of the hand drill is used to transform this physical property of the hand drill (i.e., being in motion) into a state of the hand drill (i.e., working), to identify the time instances that the hand drill is working.

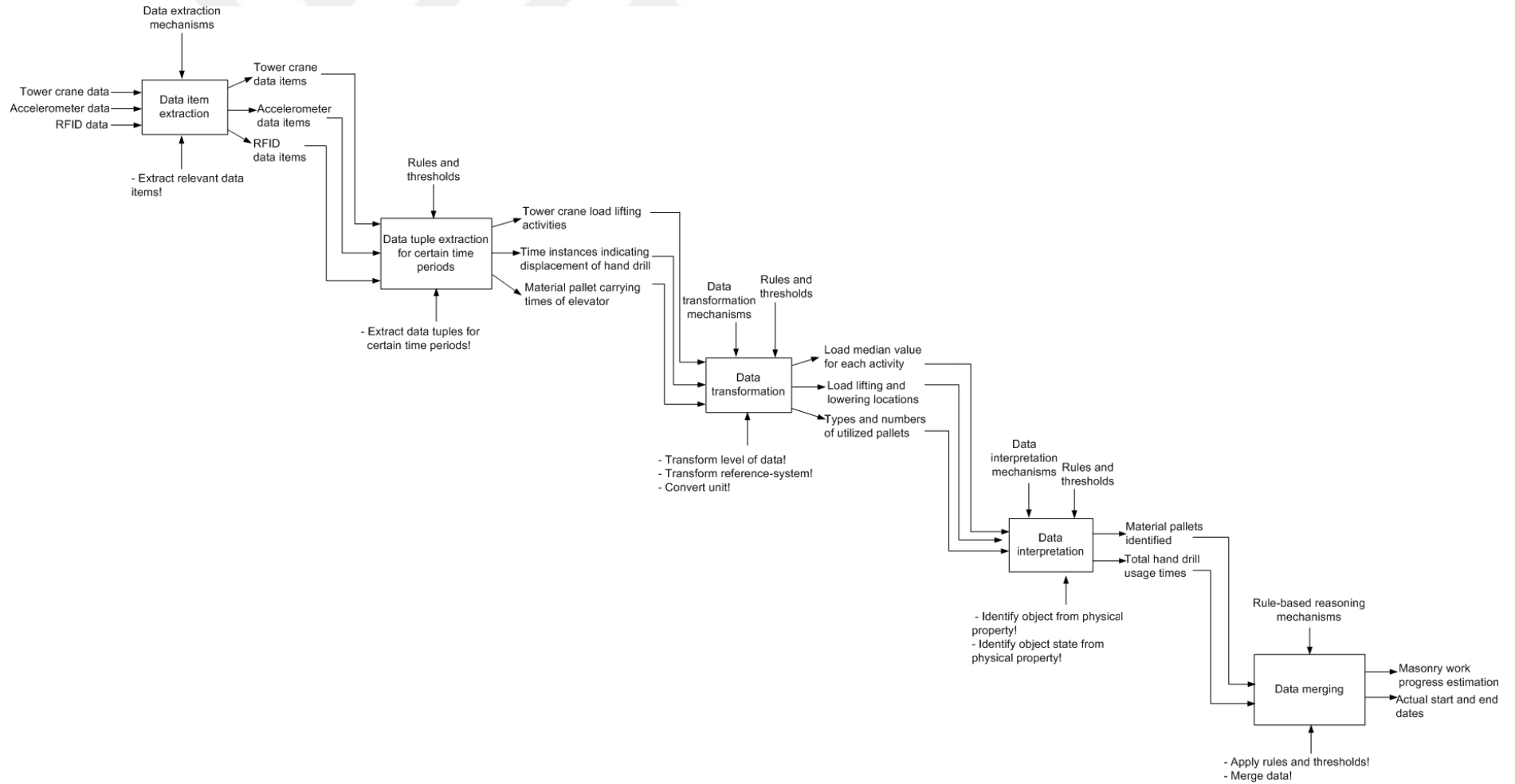


Figure 3.8 : IDEF0 diagram for applying the developed reasoning mechanisms for tracking the progress of masonry work.

6. The identified working time instances are then transformed into time intervals, and used for identifying the start and end dates of the masonry work at a floor.
7. During the masonry work, material pallets are utilized gradually, and empty pallets are stored at the floor and at the end of the work, the empty pallets are taken down with the elevator to be returned to the manufacturer for reuse. RFID system detects the ID of the tags in the environment and identifies whether the detected ID belongs to a material pallet or not, based on the location of the reading performed (i.e., inside or outside of the elevator cabin). The tag IDs are used to determine the number and types of utilized material pallets at a particular floor.

Obtained information

- The progress of the masonry work is calculated by applying data extraction and data transformation steps on the data collected from different data sources as explained in the previous paragraphs. First output is the amount of material transferred to the floor and this is calculated from the data obtained from the tower crane sensors.
- Second output is the identification of the dates of the masonry work performed at the floor and that is obtained from the accelerometer data.
- Third output is the identification of the number and type of material pallets utilized at the floor and the amount of work completed, and these are calculated from the RFID readings.

Activity progress estimations and schedule comparisons

- By comparing the amount of utilized material with the amount of material transferred to the floor, the percentage of masonry work completed is calculated. Also, the developed approach compares the progress estimation (i.e., percentage of work completed) with the masonry work quantity takeoff to determine the necessary material to complete the remaining work.
- The planned start and end dates for the masonry work at the particular floor is obtained from the schedule and it is compared with the actual start

and end dates obtained from the accelerometer records. Therefore, the performance of the masonry work is identified as being either behind or ahead of the schedule.

Data merging for monitoring the rebar installation work

The progress of the rebar installation work is obtained by collecting data from (1) tower crane sensors, and (2) total station. Also, the rebar quantity takeoff and the planned start and end dates for the rebar installation are obtained from related project documents. Figure 3.9 is the IDEF0 diagram that shows how the developed reasoning mechanisms are applied for tracking the progress of rebar installation.

Steps for data extraction, transformation and interpretation

1. The rebar quantity takeoff and the planned start and end dates for the rebar installation at the particular floor are manually extracted from the related documents.
2. Layout data collected with total station is extracted to obtain the "z" elevation and date of the performed layout. Based on the site observations and general practice, it is assumed that the day of the layout is the day when the rebar installation started at the floor and the day before the layout is when the concrete pouring of that floor slab was performed. If the concrete pouring activity is delayed for some reason, then the following layout activity is delayed, as well.
3. "z" elevation is transformed into building floor information and the floor at which the rebar installation is being performed is obtained.
4. Tower crane sensors record the positions and the loads carried by the tower crane while the tower crane is used for transferring material and other items (e.g., rebar) to the floor at which the structural works are being performed. Relevant data items and data instances are extracted from the tower crane sensors and the load lifting activities of the tower crane are identified.
5. For each of the identified load lifting activities, median of the load weight data item is calculated and a load value is obtained. This enables identifying that the loads lifted by the tower crane are rebar.

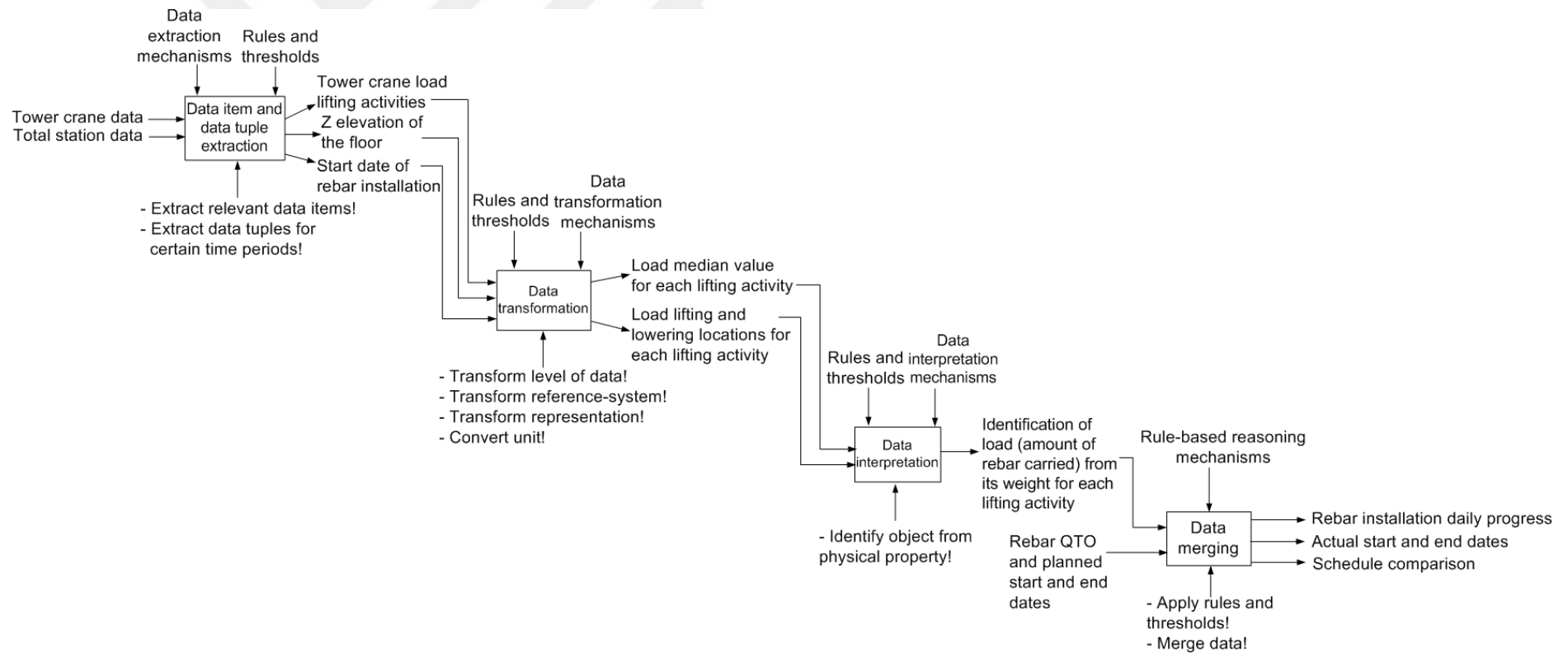


Figure 3.9 : IDEF0 diagram for applying the developed reasoning mechanisms for tracking the progress of rebar installation.

6. The angular position of the crane boom and the position of the trolley at the time of load lifting (e.g., rebar cutting and bending area) and load lowering (e.g., building) are transformed into the corresponding locations on the site layout. Finally, the amount of rebar transferred in each load lifting activity are calculated.

Obtained information

- First output is the identification of the start date of the rebar installation and this is obtained from the total station data.
- Second output is the amount of rebar transferred to the floor and this is calculated from the tower crane sensor data.

Activity progress estimations and schedule comparisons

- The total time of the tower crane assigned for the rebar installation is calculated to determine the productivity of the rebar installation work. Also, the progress of the rebar installation is estimated (i.e., percentage of completed work) based on the amount of rebar (in tons) transferred from the rebar cutting and bending area to the building, by comparing (1) the total amount of rebar installed calculated from the tower crane data, with (2) the rebar quantity takeoff, obtained from the related project document. Based on the site observations, it is assumed that the transferred rebars are installed within the same working day.
- The planned start date for the rebar installation at the particular floor is compared with the date obtained from the total station data. Whereas, the planned end dates for the rebar installation is compared with the data obtained from the tower crane sensors and the performance of the rebar installation is determined.

Data merging for monitoring the steel component transfer to installation area

Steel component transfer to installation area is tracked through the data obtained from the tower crane sensors and this information is combined with the steel component quantity takeoff to estimate the progress in steel component installation. Figure 3.10 is the IDEF0 diagram that shows how the developed reasoning mechanisms are applied for tracking the progress of steel component installation.

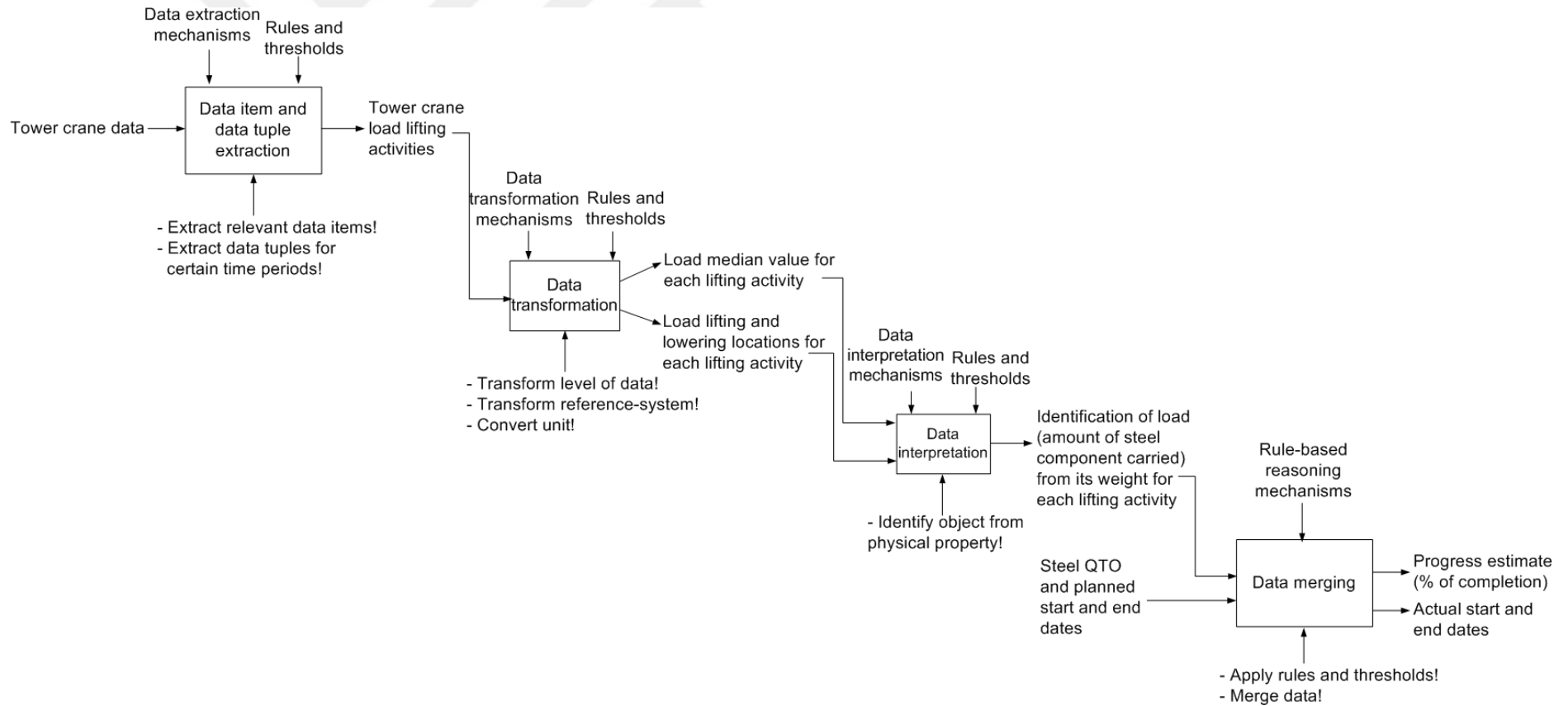


Figure 3.10 : IDEF0 diagram for applying the developed reasoning mechanisms for tracking the progress of steel component transfer to installation area.

Steps for data extraction, transformation and interpretation

1. Steel quantity takeoff and the planned start and end dates for the steel work at the particular floor are manually extracted from the related documents.
2. Tower crane sensors record the positions and the loads carried by the tower crane while the tower crane is used for transferring steel components. As in the previous cases, relevant data items and data instances are extracted from the tower crane sensors and the load lifting activities of the tower crane are identified.
3. For each of the identified load lifting activities, median of the load weight data item is calculated and a load value is obtained. This enables identifying that the loads lifted by the tower crane are steel components.
4. To identify the transfer of a steel component from the laydown area to the floor, the angular position of the crane boom and the position of the trolley at the time of load lifting (e.g., laydown area) and load lowering (e.g., installation point on building) are transformed into the corresponding locations on the site layout.

Obtained information

- First output is the identification of the start and end dates of the steel component transfer to installation area and this is obtained from the tower crane sensors.
- Second output is the weight of the steel components transferred to the floor and this is calculated from the tower crane sensor data.

Activity progress estimations and schedule comparisons

- By evaluating the total weight of the steel component (in tons) transferred from the laydown area to the installation point on the building, the progress of the steel work is estimated (i.e., percentage of completed work) by comparing the total amount of steel (in tons) to be used in the project.
- The planned start and end dates for the steel component transfer to installation area at the particular floor is compared with the actual start and end dates obtained from the tower crane sensors.

3.3 Conclusions

Previous studies in the construction management domain utilized multiple types of data collection technologies for automated progress monitoring of activities and equipment tracking purposes. However, no attention was given to monitor both the daytime and nighttime work and instead the existing studies focused on monitoring of the daytime work only. Also, equipment tracking were performed for large construction equipment mostly for monitoring the earthmoving and excavation activities and the potential of equipment tracking for progress monitoring in building construction has been overlooked. This study aims to fill this gap by tracking equipment used in building construction to monitor progress of activities in both daytime and nighttime work.

The findings of the data fusion literature review, on the other hand, showed that there are typically two types of data collection was performed for data fusion: (1) fusing different data sources providing data at overlapping time frames, and (2) fusing different data sources providing data collected at different time frames. The methods applied for data fusion in these studies were examined and it was concluded that in each data fusion study a customized approach was developed to solve the data fusion problem at hand. A generalized approach for data fusion for construction industry applications have not yet been developed.

On the other hand, Pradhan and Akinci (2012) developed a taxonomy of reasoning mechanisms to fuse a pair of spatial and temporal data sources to support construction productivity monitoring in road excavation projects using either space (i.e., spatial) or time (i.e., temporal) information. The data fusion approach developed in this study to fuse the data collected from construction equipment for monitoring the progress of activities in double shift construction sites is built on this existing taxonomy of reasoning mechanisms. However, since the data sources defined and the reasoning steps described in the previous study were not sufficient for the purpose of this study; a new non-spatiotemporal data source (i.e., physical property) was proposed for construction activity monitoring, and the existing taxonomy of reasoning mechanisms was extended.

Physical property data source was defined as the new data sources that measure and/or collect the physical properties (e.g., weight, volume, color, texture, physical

shape, material) of entities (e.g., material, human, equipment), regardless of the time and space of the data collection. Three types of reasoning mechanisms, namely (1) data extraction, (2) data transformation, and (3) data merging, were already described in the existing reasoning mechanisms for spatial and temporal data sources. A new step was added to the existing taxonomy, named data interpretation, for interpretation of the non-spatiotemporal data sources used in construction activity tracking applications. Two types of data interpretation were defined and implemented in this study: (1) transformation of physical properties (e.g., weight) into objects (e.g., brick, rebar), and (2) transformation of physical properties (e.g., velocity) into states of objects (e.g., moving or static). Also, a new data merging step, named rule-based reasoning, that is applicable to all types of data sources was added to the existing taxonomy.

The rule-based reasoning approach was utilized for the developed data fusion approach in this study, and this chapter provided the details of the development of the necessary reasoning mechanisms for data fusion and how the reasoning mechanisms are applied on the field experiment data. Based on the data fusion reasoning mechanisms developed in this chapter, a prototype was developed and implemented in field experiments that were conducted at a double shift residential project. Details of the prototype implementation are provided in the following chapters of this thesis.



4. FIELD TESTS FOR MONITORING THE MASONRY WORK AND REBAR INSTALLATION AND DEMONSTRATING THE MONITORING OF STEEL COMPONENT TRANSFER TO INSTALLATION AREA

This chapter focuses on the development of a physical prototype that meets the functional requirements identified in the previous chapters for tracking masonry work, and provides the details of the design and implementation of the prototype at a construction site. Field experiments were conducted to monitor the masonry work at a double shift construction site in Istanbul to demonstrate the technical feasibility of the developed approach. One building block at the construction site was used as the test set-up (Figure 4.1).

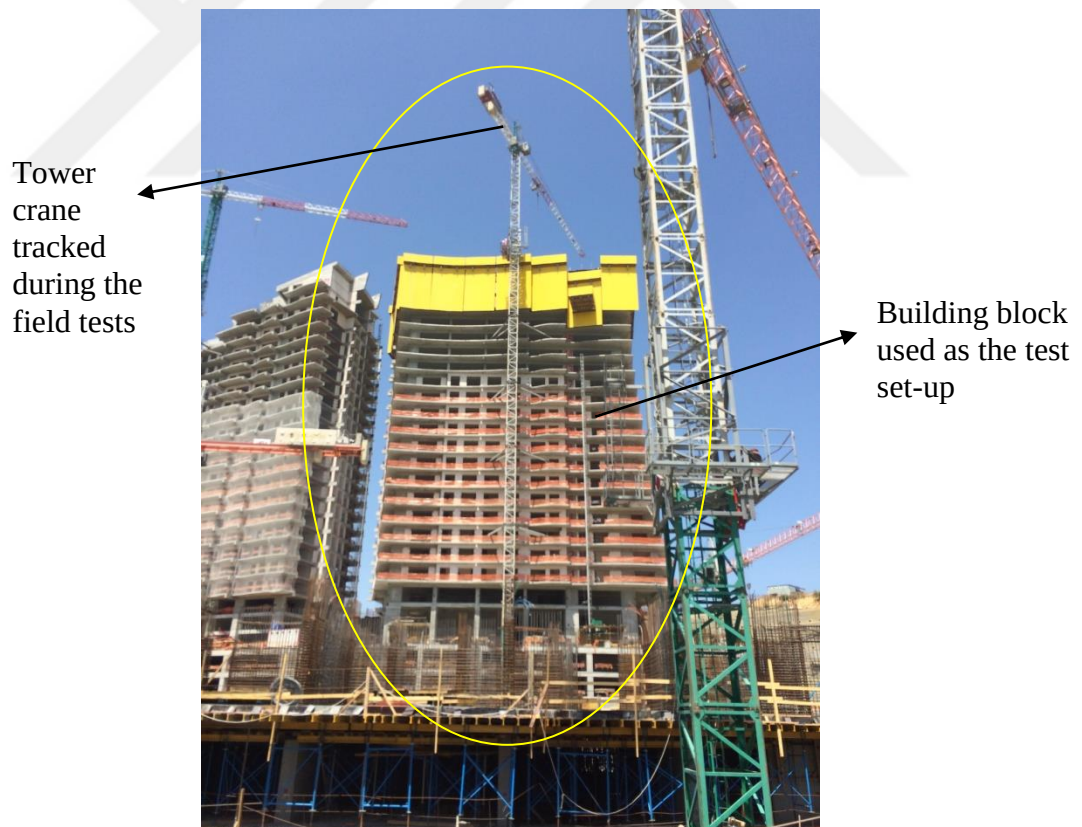


Figure 4.1 : Building block where the field tests were performed.

The construction project at which the field experiments were conducted (henceforth termed "Site 1") was a residential project consisting of 24 building blocks. The total

construction area is 320,000 m², and includes 4,039 apartments and 642 residence that were built in four stages. Approximately 50 subcontractors actively worked in this project. Construction work was performed in two shifts and the preparation for the next day's activities and/or completing the unfinished activities of the day shift were performed during the night shifts. This chapter provides the field experiments on monitoring the masonry work in one building with the sensor-based approach for three month.

4.1 Masonry Work Case Study: Current process

Based on the observations at Site 1, the current process of the masonry work is as follows: The ordered amounts of the Autoclaved Aerated Concrete (AAC) masonry wall blocks are delivered to site on trailers (Figure 4.2) and stored at the laydown areas (Figure 4.3). Packing unit of AAC wall blocks are the pallets that are made of timber.



Figure 4.2 : A trailer delivering the AAC pallets to site.



Figure 4.3 : AAC pallets stocked at the laydown area.

AAC pallets are transferred to the floor at which the masonry work is performed by a tower crane and the masonry crew is ready to start working at that floor. Workers prepare mortar by mixing the specified amount of AAC glue with water using the hand drill using the special AAC mixing tip attached to the hand drill (Figure 4.4). It is suggested to stir the mixture in a low-speed until no air bubble is left in the mixture. The prepared glue must be used within approximately 4-5 hours and must not be used by re-adding water (Url-10).

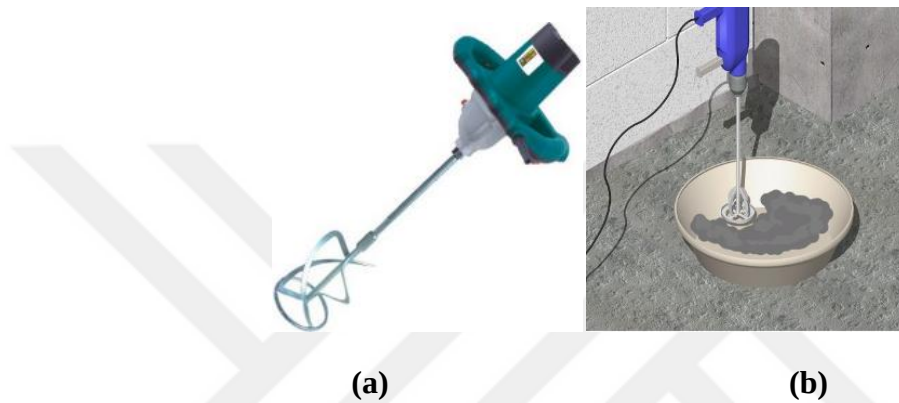


Figure 4.4 : (a) Hand drill and the AAC mixing tip, (b) preparation of AAC glue with the hand drill (Url-10).

As the AAC blocks are used for masonry production at the floors, empty pallets are stored at floors and finally loaded on an elevator and taken down to the ground floor for reuse by the manufacturer (Figure 4.5).



Figure 4.5 : Empty pallets loaded on the elevator and removed from the floor.

Manufacturer may even apply a penalty for the pallets that are not returned due to being lost or broken. AAC blocks are available in multiple sizes and weights, and to determine the amount of masonry work that can be performed with a particular type of AAC block, the type needs to be identified. The dimensions and the number of AAC units included in a packing depends on the size of the AAC units (e.g., packing size is 60x25x10 cm for 10 cm AAC units, and 60x25x15 cm for 15 cm AAC units). Product specifications determine the number of AAC units included in one pallet, the weight of the pallet and the area of masonry that can be built with one pallet of AAC blocks and the corresponding volume (Table 4.1). To obtain these specifications, a AAC masonry unit supplier was contacted (Yesil, 2014). The supplier stated that the lifting weight of a pallet changes, depending on many factors such as humidity, and can be calculated approximately. For instance, approximate weight of a pallet of 10 cm AAC units is about 770 kg, and one pallet includes 90 wall units and 13.5 m² masonry can be built with it.

Table 4.1 : Packing specifications of AAC wall units.

Dimensions (Height 150 cm)	Number of AAC units in a pallet	Corresponding volume (m ³ /pallet)	Corresponding area (m ² /pallet)	App. weight of a pallet (kg)
60 x 25 x 9	90	1.21	13.5	690
60 x 25 x 10	90	1.35	13.5	770
60 x 25 x 12.5	72	1.35	10.8	770
60 x 25 x 15	60	1.35	9	770
60 x 25 x 20	42	1.26	6.3	720
60 x 25 x 25	36	1.35	5.4	770
60 x 25 x 30	30	1.35	4.5	770

4.1.1 Proposed approach for tracking masonry work progress

The steps for monitoring the masonry work are explained in the following paragraphs. It is assumed that the AAC pallets are tagged with passive RFID tags by the manufacturer at the fabrication stage. Additionally, passive RFID tags were attached to each floor of the building and to the hand drill. Data obtained from the position and load sensors on the tower crane, the RFID system deployed on the elevator of the building and the wireless accelerometer installed on the hand drill are collected to monitor the progress of the masonry work. Table 4.2 reports the data to

be collected from each construction equipment to be tracked and the project related data source (i.e., quantity takeoff documents and schedule), and summarizes the tracking approach developed for monitoring the progress of the masonry work.

Table 4.2 : Tracking approach developed for monitoring the progress of the masonry work.

Data collected from	Tracking method	Data collected	Data used and results obtained	Integration of results
Tower crane	- Angular position, trolley position and load sensors (on tower crane)	(A) Load weight in each load lifting activity (ton) (B) Angular position of the crane boom (degree) (C) Position of the trolley and the depth of the hook (m)	(A)+(B)+(C) = Total amount of AAC pallets brought to the floor	$\frac{[(A) + (B) + (C)]}{[(D) + (E)]} =$ Total amount of material delivered/ total amount of material utilized = Percentage of completion (%)
Elevator	-Passive RFID tags (on building floors) -Passive RFID tags (on AAC pallets) - RFID reader (on the elevator) - Antennas (inside and outside the elevator cabin)	(D) Floor ID (E) Pallet ID	(D) = Floor at which the elevator stopped for unloading empty AAC pallets (D) + (E) = Type and number of AAC pallets utilized at the floor	
Hand drill	- Passive RFID tag (on hand drill) - Accelerometer (on hand drill)	(F) Equipment ID (G) Hand drill working times	(F) = Time and date of hand drill daily working times	(D)+(F) = The floor at which the hand drill is used (D)+(F)+(G) = Actual start and end date of masonry work at the floor
Project related data sources	- Manual data extraction from related documents	(H) Wall quantity takeoff (m ²) (I) Planned start and end dates	(H) = Total amount of masonry work (m ²) (I) = Planned start and end dates for masonry work	(H) - [(D) + (E)] = Amount of material needed to finish the masonry work (I) vs. (H) = Planned vs. actual date comparison

The steps of the masonry work are illustrated in Figure 4.6. In the first step, AAC pallets are transferred from the laydown area to the floor by the tower crane (Figure 4.6). As the pallets are being transferred, tower crane sensors collect and store the tower crane movement, position and load data (Table 4.2). Tower crane load lifting activities are identified among all tower crane movements. From the load sensor of the tower crane, first the weight of the load being carried is identified for each load lifting activity. Then, the tower crane angular position and trolley position sensors are used to identify the location from where the load is lifted (i.e., laydown area) and the location where it is lowered (i.e., building). This information is combined with the load information to identify that the carried load is an AAC pallet.

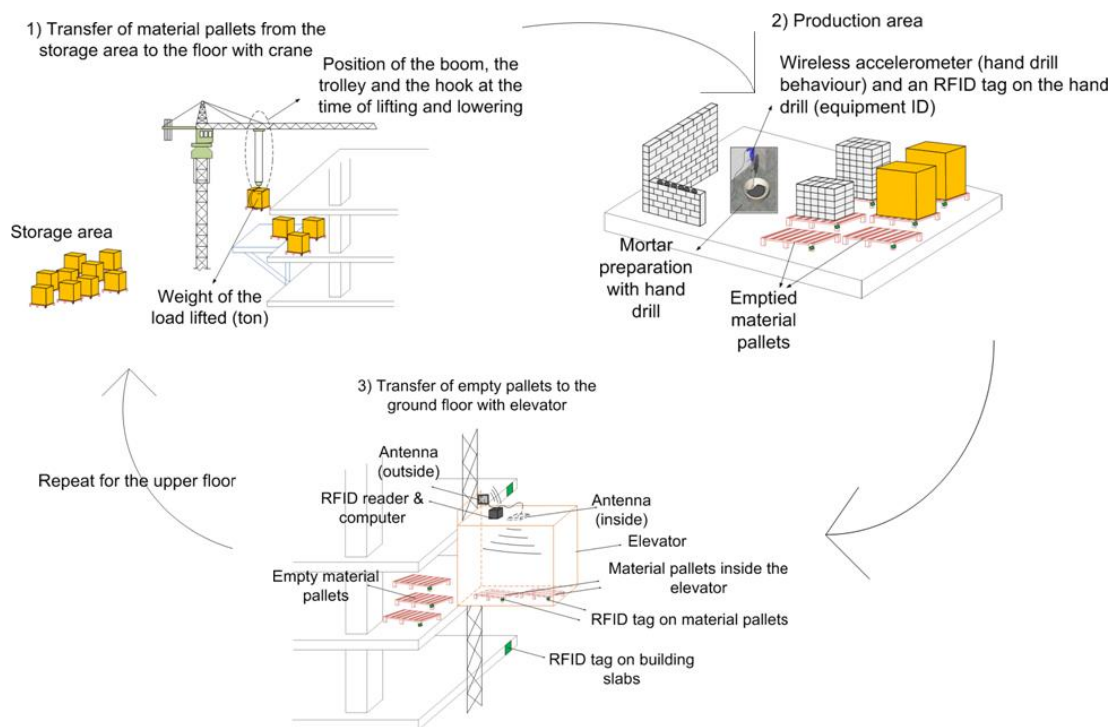


Figure 4.6 : Steps of the masonry work.

In the ideal case when different sizes of AAC blocks are stacked in separate groups standing away from each other; the type of the AAC pallet can be identified by determining the location from which the pallet is lifted (i.e., angular position of the crane boom and the trolley position transformed into location information). However, most of the times construction sites lack storage spaces that are large enough to group and stack different sizes of AAC pallets away from each other. In that case, all pallet lifting activities start almost from the same point, and therefore, in addition to the position information of the crane boom and trolley, the weight of the pallet is necessary to identify the type of pallet being lifted. Another option is to read

the IDs of the tags on the AAC pallets at the laydown area with a hand-held RFID reader before the pallets are transferred from the laydown area to the floor to identify the type of pallets that are soon to be transferred to the floor. This has not been performed during the prototype implementation due to the associated extra labor costs, however, an assumption was made that this step has been performed.

The floor to which the AAC pallets are transferred with the tower crane can be determined from the depth of the crane hook at the time of lowering the load. The result obtained from the tower crane sensors is the total amount of AAC pallets brought to the floor (Table 4.2).

Second step is performing the masonry work (Figure 4.6). Mortar preparation is necessary to start the masonry work. Mortar preparation is performed a couple times throughout a working day, using the hand drill to mix the AAC glue with water. As the hand drill is taken to the production floor with the elevator, RFID system that is deployed on the elevator is used to track the floor at which the hand drill gets off the elevator. Also, an accelerometer is mounted on the hand drill to track the hand drill's working times, and therefore the date when the masonry work started at a particular floor and the date when it ended are obtained from the accelerometer data (Table 4.2). As the masonry work continues, the AAC blocks are utilized and pallets are emptied, and empty pallets are stored at the floor.

Third step is to remove the empty pallets from the floor with the elevator (Figure 4.6). The number and types of the utilized AAC pallets are obtained from the RFID readings when the empty pallets are loaded to the elevator (Table 4.2). This tracking approach enables determining the actual start and end dates of the masonry work performed at a particular floor, and the percentage of completion of the masonry work by comparing the amount of material brought to the floor with tower crane and the amount of material utilized at the floor.

4.1.2 Prototype system design

The prototype system was designed based on the functional requirements identified and the selected sensor-based technologies described in Chapter 2. The following sections provide the details of the prototype system design and technology implementation at Site 1, where the field experiments were performed.

Selected RFID technology

Available RFID solutions were investigated and the necessary RFID hardware was obtained from a company named Borda Technology Ltd. The obtained hardware included one RFID reader (Motorola FX740), two antennas (MTI MT-242040), a notebook, a 12V 40Ah additional power supply and a modem used as a bridge in between the computer and the reader (Figure 4.7). An "active reader passive tag" system was designed and installed on an elevator that serves the building at which the field tests were performed in Site 1.

Passive RFID tags, shown in Figure 4.8, were attached on items that are aimed to be tracked (i.e., one hand drill and all AAC pallets). Figure 4.9 shows the tag attached on the hand drill, and Figure 4.10 shows the tagged AAC pallets before the packaging is unwrapped, and after the blocks are utilized and the pallets are emptied. Also, passive RFID tags were attached to the slab of each building floor (Figure 4.11).

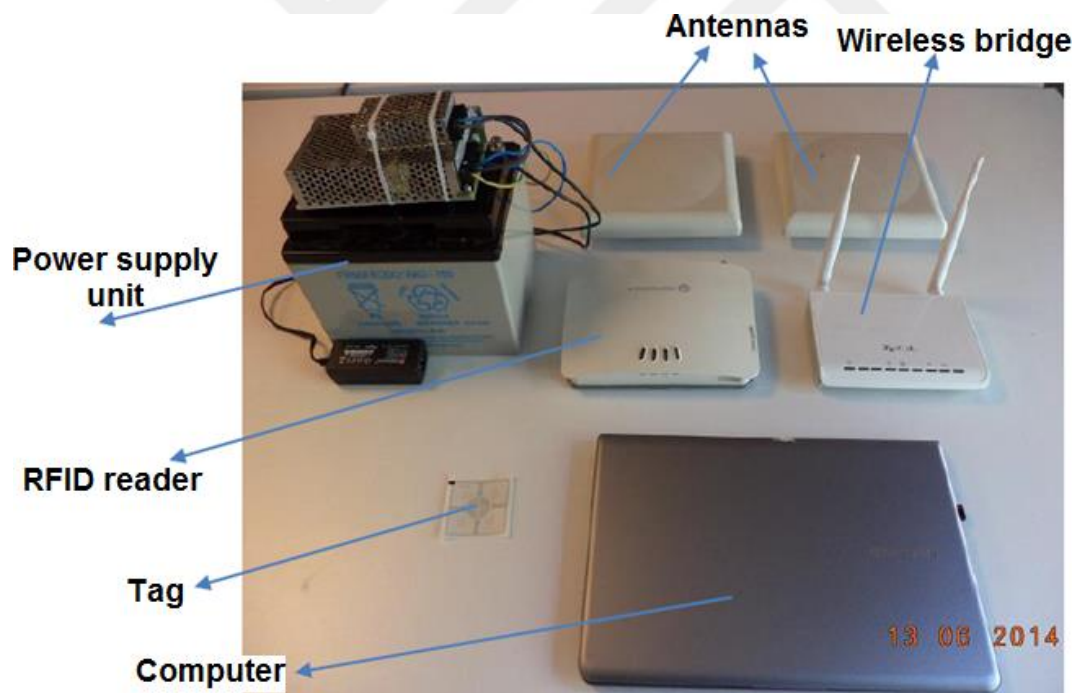


Figure 4.7 : Components of the RFID system.

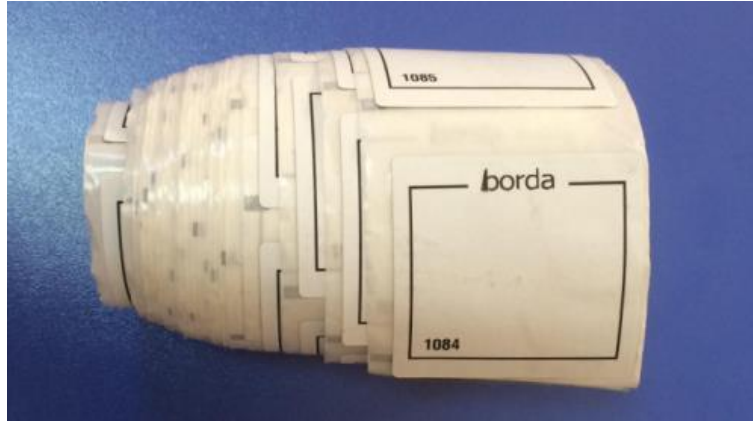


Figure 4.8 : Passive RFID tags.



Figure 4.9 : RFID tag on the hand drill.



Figure 4.10 : RFID tags on AAC pallets before the unwrapping of packaging, and after the AAC blocks are utilized and pallets are emptied.



Figure 4.11 : RFID tag on the floor slab.

As determined by the functional requirements, one antenna was mounted on the inside and the other antenna on the outside of the elevator. The inner antenna (i.e., antenna number 1), shown in Figure 4.12, was aimed to detect the tagged items loaded on the elevator, such as the AAC pallets and the hand drill.

Antenna inside
the elevator
cabin

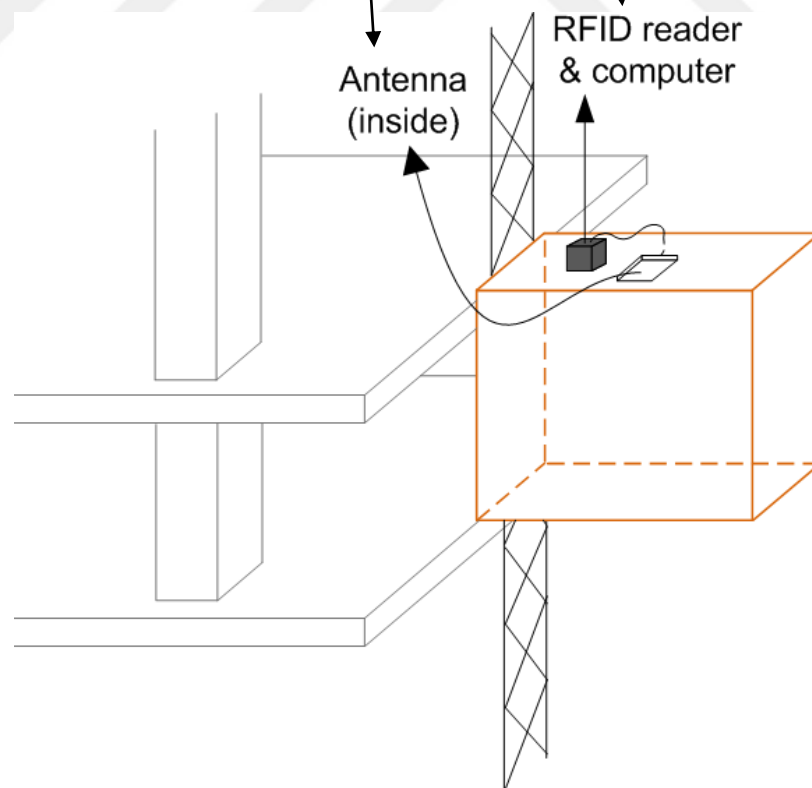


Figure 4.12 : Inner antenna, antenna 1, mounted on the center of the ceiling of the elevator cabin.

On the other hand, the outer antenna (i.e., antenna number 2) was mounted on the outside of the elevator cabin, facing towards the building, to track the movements of the elevator by detecting the floor at which the elevator stops for loading and/or unloading (Figure 4.13). Therefore, the system has a fixed reader design on the inside of the elevator, and a mobile reader design on the outside of the elevator.

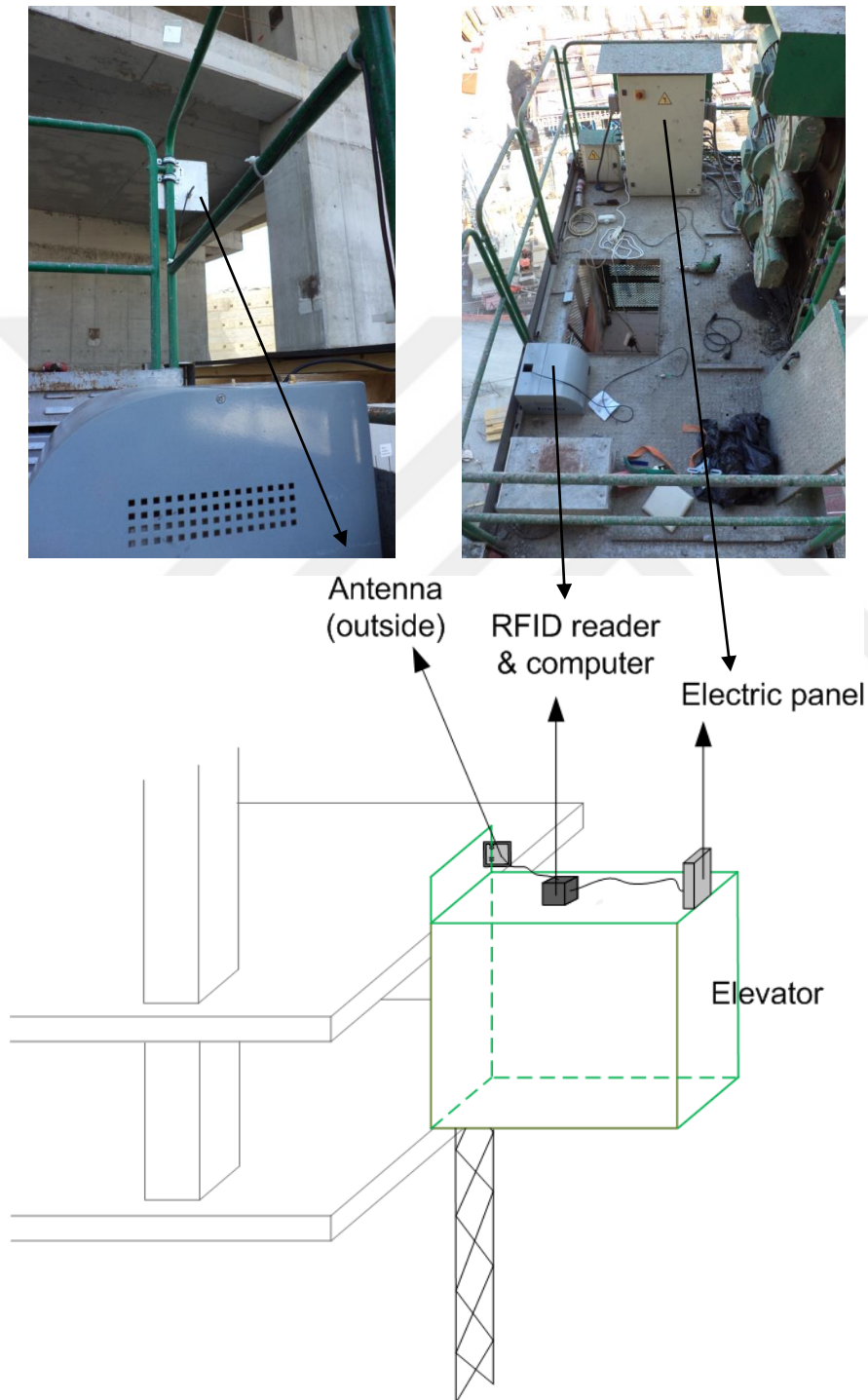


Figure 4.13 : Outer antenna, antenna 2, mounted on the outside of the elevator cabin, facing towards the building.

In addition to integrated with a microcontroller board and an accelerometer was located on the hand drill, as explained in Chapter 2, Section 2.5.1.2 (Figure 4.14).

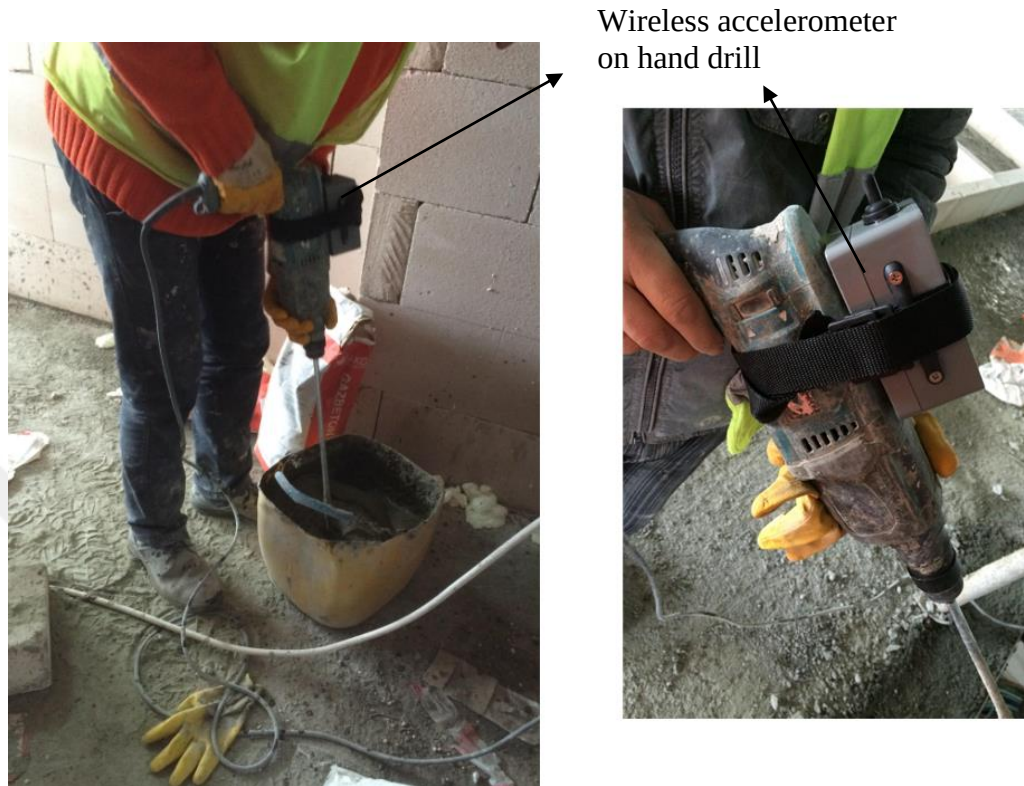


Figure 4.14 : Custom designed wireless accelerometer kit located on hand drill.

Sensors on the tower crane

Sensors for tracking the tower crane movements (i.e., angular position sensor, trolley position sensor and load sensor) were already installed on the tower crane that serves the building at which the field tests were performed in Site 1. The tower crane sensors were used as part of the anti-collision system, as explained in Chapter 2, Section 2.5.1.3. Figure 4.15 shows the illustration for the data storage method of the anti-collision system. Data collected from the tower crane sensors are stored in an SD memory stick inside the data logger that is located in the central unit, and the SD memory stick is used for data transfer to local computer(s).

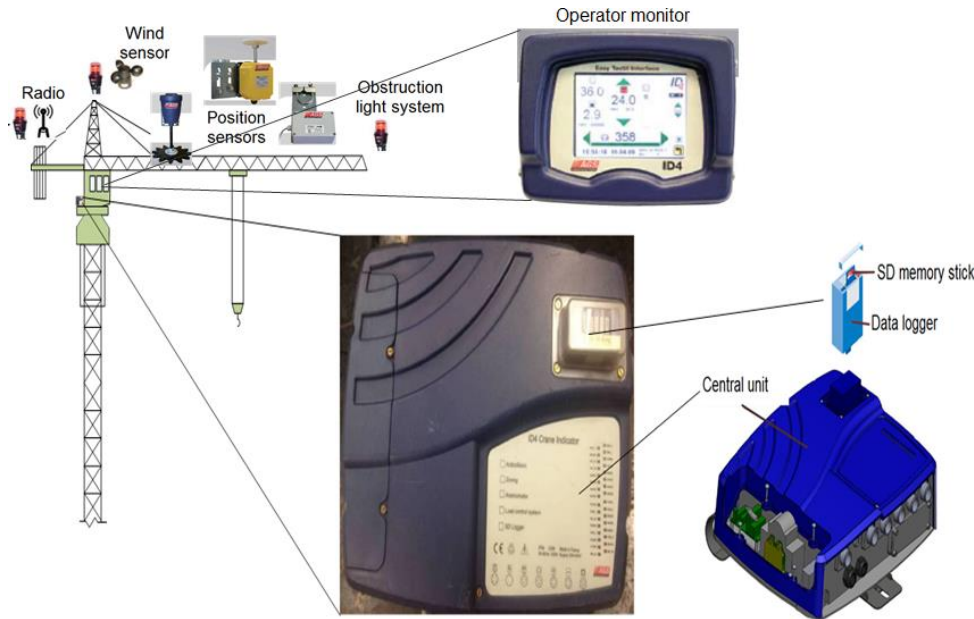


Figure 4.15 : Anti-collision system cenral unit box located near the crane cabin, data logger and SD memory stick, and operator monitor inside the cabin.

4.1.3 Prototype implementation

Following sections explain the developed approach in detail. The flow diagram for the monitoring process of the masonry work is divided into three parts in Figure 4.16, 4.17 and 4.18.

The tracking process begins with the delivery and receipt of AAC pallets and continues with the transfer of AAC pallets to floors and utilization of AAC pallets for building walls. The tracking process ends with the return of the emptied AAC pallets to manufacturer for reuse. Three data sources are used in the tracking of masonry work: tower crane position and load sensors for tracking the amount and type of material delivered to a floor, wireless accelerometer on a hand drill to track the daily utilization of the hand drill to track the start and end dates of the masonry work, and RFID system installed on the elevator to track the amount of material utilized at a floor. The technologies selected for data collection perform data collection and storage in real-time and wireless data transfer is also available. However, during the prototype implementation, collected data was stored on an SD card or to the internal memory of the data collection technologies and then manually transferred to a local computer. In the case of tower crane, this was due to the security restrictions applied by the site management, whereas for the RFID and

wireless accelerometer, this was due to the lack of a continuous wireless connection at site.

Before starting the tracking process, the AAC pallets were tagged with RFID tags at site although in the research vision, it was assumed that the AAC pallets are tagged by the manufacturer at the fabrication stage. Different groups of tags were used to represent different types (i.e., sizes) of AAC blocks. A database is prepared to keep a list of tag numbers that are assigned to pallet types. When empty pallets are removed from the floor using the elevator, RFID system on the elevator detects the tag numbers and identifies the type of material from the corresponding tag number in the database. Another option is to store the type of material information in the memory of tags. However, this would necessitate utilizing a hand-held RFID reader with writing options or an RFID tag printer if the writing will be performed using a computer. However, both the hand drill and the building floors were tagged at once and these tags were used throughout the tests.

Steps of the field test are provided in the following paragraphs:

Delivery of AAC pallets to floor

This section provides the steps for transferring the AAC pallets from the storage area to the floors, as illustrated in Figure 4.16.

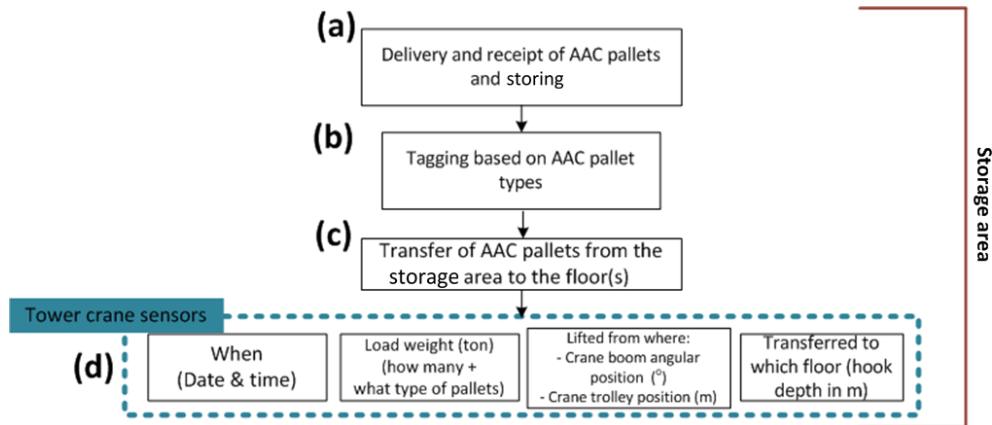


Figure 4.16 : Tracking of masonry work flow diagram (Part 1).

- **Delivery of AAC blocks to site:** AAC wall blocks are delivered to site on trailers and received by the personnel in charge (Figure 4.16-a).
- **Tagging of AAC pallets:** AAC pallets are tagged (Figure 4.16-b).

- **Transfer of AAC pallets to floors:** Tower crane transfers the AAC pallets from the storage area to the floors (Figure 4.16-c).
- **Information about the AAC pallets transferred with tower crane:** Data collected by the tower crane sensors are used to identify the number and types of AAC pallets delivered to the floors (Figure 4.16-d):
 - **Time of material delivery:** The time of AAC material pallet delivery to the floor is identified from the timestamps of tower crane sensor records.
 - **Number of AAC pallets delivered to the floor:** First, the number of lifting activities of the tower crane performed in between the AAC pallet storage area and the building floor are identified. The weight of the load carried in each lifting activity is then used to determine the number of pallets (i.e., one or two pallets are lifted at a time) transferred to the floor in each lifting activity.
 - **Types of AAC pallets (size of AAC blocks) delivered to the floor:** It was assumed that the IDs of the tags on the AAC pallets are read at the laydown area with a hand-held RFID reader before the pallets are transferred from the storage area to the floor to identify the type of pallets that are soon to be transferred to the floor.
 - **The floor information:** Since a depth sensor was not included in the existing sensor configuration on tower crane, the floor information was manually tracked during the field experiments.

Mortar preparation and masonry work

This section provides the steps for bringing the hand drill to the floor and starting the masonry work, as illustrated in Figure 4.17.

- **Bringing hand drill to the floor:** Hand drill is brought to the floor at which the masonry work is performed by the masonry crew with the elevator (Figure 4.17-e) and the masonry work starts (Figure 4.17-f).
- **Tracking the hand drill:** Several timestamps for the hand drill that is detected by the RFID system are considered to identify the floor at which the hand drill is used:

- **Detection of hand drill arriving to the floor:** When the hand drill is loaded on the elevator, RFID system starts to detect the tag ID of the hand drill repeatedly as long as the hand drill remains on the elevator (i.e., until the elevator stops at a floor and hand drill is taken out of the elevator at floor). The next time that the hand drill ID is detected by the RFID system is not until the hand drill is loaded on the elevator at the end of working day. A similar process occurs when the hand drill is put on the elevator leaving the floor: RFID system repeatedly detects its ID until the hand drill is taken out of the elevator off at the ground floor. The timestamp when the hand drill ID is detected for the very first time at the beginning of the working day, is named “timestamp A”, and the timestamp when the hand drill ID is detected for the last time in this continuous reading, is named “timestamp B”. This is the time interval that the hand drill was at the particular floor throughout a working day. Therefore, each day, accelerometer data recorded after the timestamp B should be taken into account (Figure 4.18).

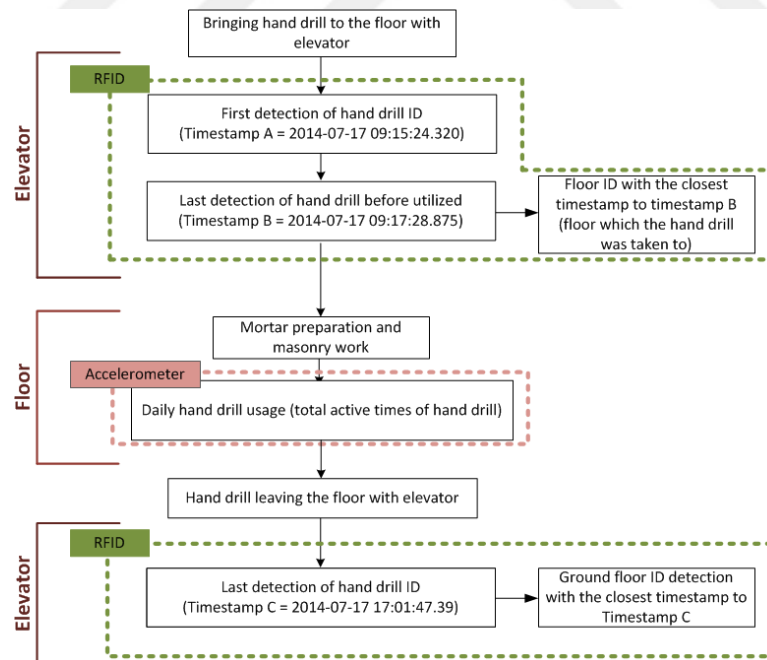


Figure 4.17 : Tracking of masonry work flow diagram (Part 2).

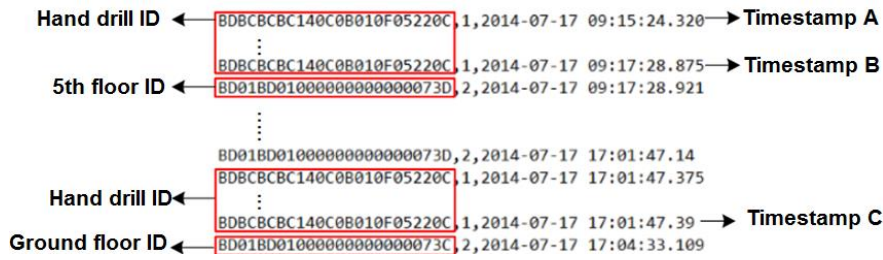


Figure 4.18 : Timestamps (1) when hand drill is first detected (A), (2) when hand drill arrived at the floor (B), (3) when hand drill is last detected (C).

- **Detection of the floor to which the hand drill is brought:** The last floor ID that is detected close to the timestamp B is the floor that the hand drill is brought to. For example, 5th floor ID is detected at closest to the timestamp B in Figure 4.18.
- **Detection the hand drill leaving the floor:** The timestamp when the hand drill ID is last detected by the RFID system at the end of the working day is named “timestamp C”. This timestamp is created when the hand drill is taken out of the elevator at the ground floor. The floor ID that is detected close to the timestamp C, is the ground floor ID in the example given in Figure 4.18.
- **Determining hand drill usage:** Hand drill usage time is determined since the time spent in between timestamp B and timestamp C is the period at which the accelerometer records will be examined to identify the working times of the hand drill at a floor (Figure 4.18 and Figure 4.19).

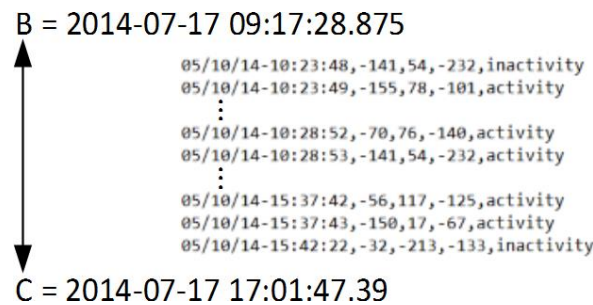


Figure 4.19 : Time interval searched for the working times of a hand drill (i.e., between timestamp B and C).

Removing empty pallets from floor

This section provides the steps for removing the utilized pallets from the floor, as illustrated in Figure 4.20.

- Removing the empty pallets from the floor:** Last step of the tracking process is to remove the emptied pallets from the floor by loading the pallets to the elevator and taking the pallets down to the ground floor for return to manufacturer (Figure 4.20-h). When tracking the empty pallets there is a process similar to the tracking of the hand drill:
 - As the masonry work continues, empty AAC pallets are stacked at the floor, and at an available time, loaded on the elevator to be removed from the floor and taken down to the ground floor. As when the pallets are loaded on the elevator, RFID system detects the pallet IDs.
 - The floor ID that is detected while the empty pallets are being loaded to the elevator, is the floor at which the pallets are utilized and the masonry work is performed.

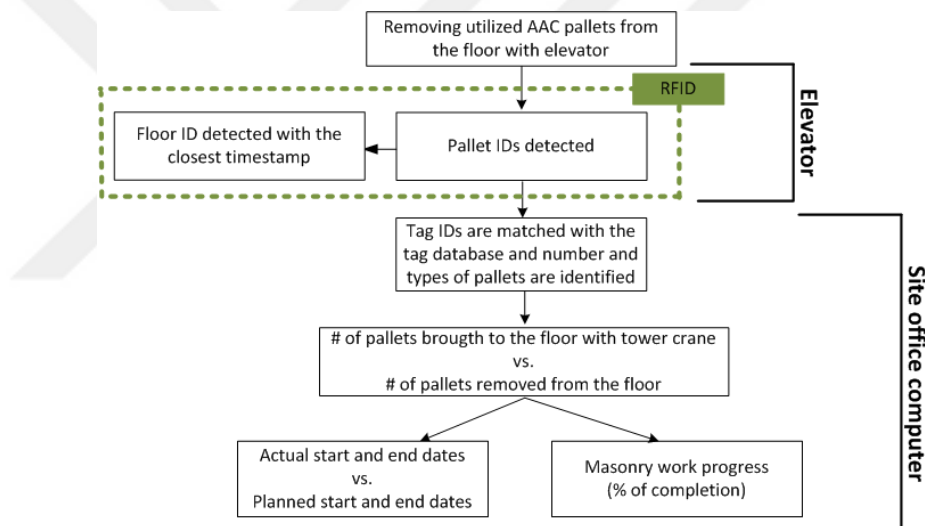


Figure 4.20 : Tracking of masonry work flow diagram (Part 3).

- As long as the pallets remain inside the elevator until all the empty pallets are loaded on the elevator and all are unloaded at the ground floor, pallet IDs are detected repeatedly by the RFID system several times, creating redundant readings. The redundant readings are filtered since detecting a pallet ID inside the elevator once is sufficient to identify that the pallet is emptied and eventually removed from the floor. After no longer pallet IDs are detected by the RFID system, the readings are filtered to remove the redundant readings and number and types of pallets are identified by matching the tag IDs with the tag database (Figure 4.21).

- As the identified tag IDs are matched with the tag IDs listed in the database; the types (i.e. sizes) of each emptied pallet are determined. The amount of material utilized at the floor is then calculated by considering the sizes and the numbers (i.e., how many of what type is used) of pallets (Figure 4.20-i). Finally, the amount of material delivered to the floor with tower crane, and the amount of material utilized at the floor calculated from the RFID readings are compared and the percentage of completion for the masonry work at that floor is calculated. Additionally, the amount of material utilized is compared with the quantity takeoff.

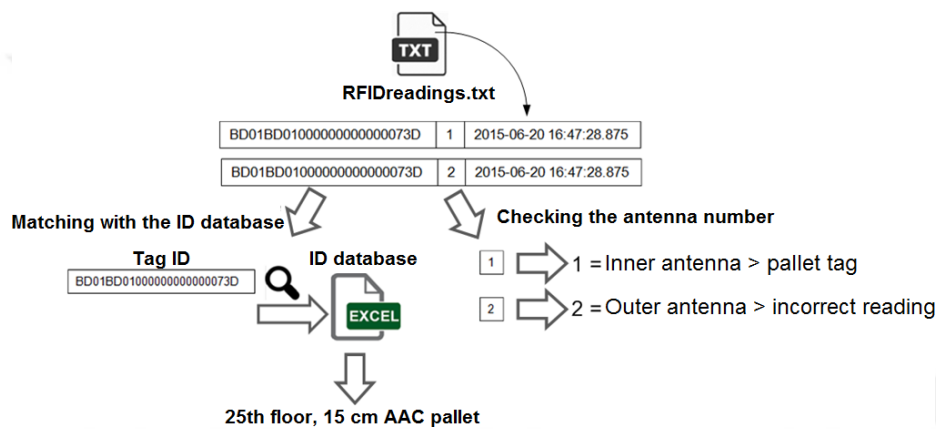


Figure 4.21 : Matching the tag IDs detected in the RFID readings with the tag database.

4.1.3.1 User interfaces

The user interfaces implemented for the prototype enabled data collection and processing. Following sections describe the details of the user interfaces developed and used for the prototype implementation.

RFID system user interface

This section provides the details of the user interface developed to perform readings with the RFID system to collect data from RFID tags.

Connecting to the RFID reader

An application was developed utilizing Motorola's Java libraries to connect with the Motorola FX7400 RFID reader to read data from RFID tags and store the collected data in a text file in CSV format. This development was performed in Microsoft Windows XP Home Edition operating system and with JAVA programming

language in NetBeans development environment (Figure 4.22), necessitating JDK installation to run the program on a computer.

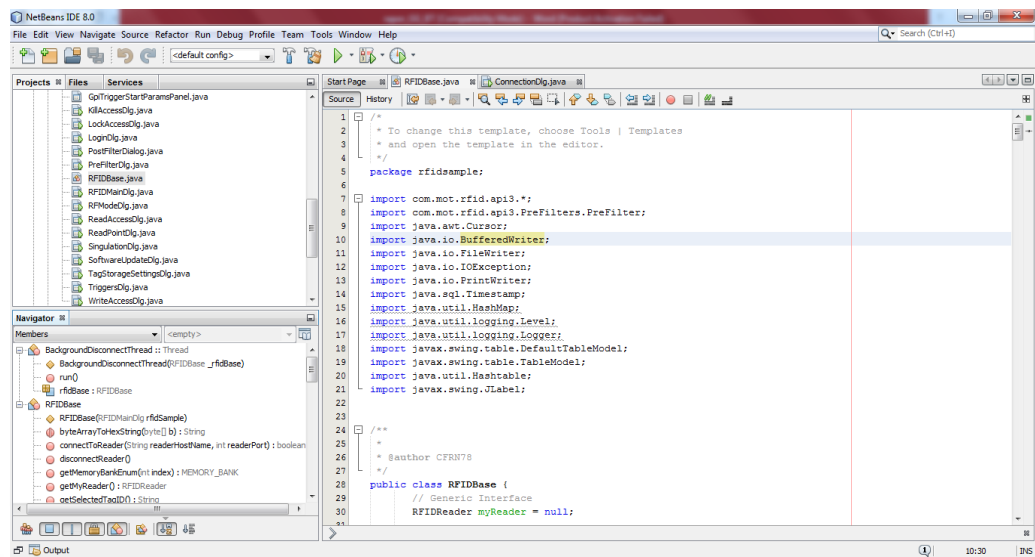


Figure 4.22 : Program development environment NetBeans.

The program starts with the offline window given in Figure 4.23 when it is first compiled. This window includes tabs and buttons that enable running specific functions of the reader on the upper side of the window and the remaining part of the window lists the information about the detected tags. Red icon on the lower right hand side of the window indicates that the program is not connected to the reader.

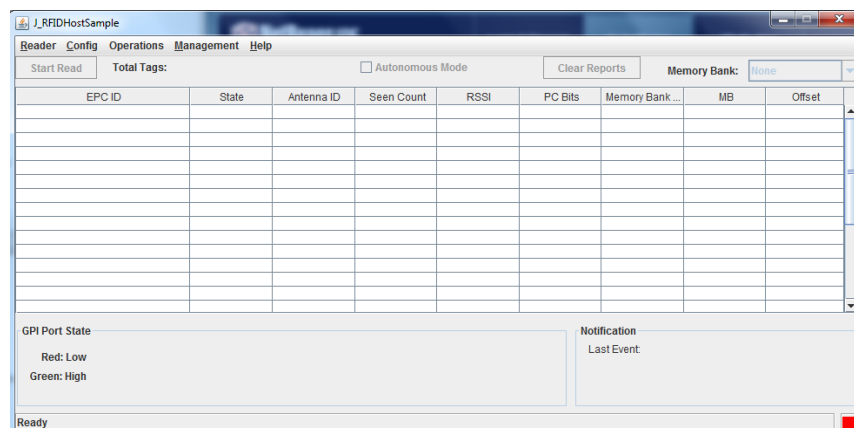


Figure 4.23 : Offline version of the user interface of the prototype application for RFID system.

Figure 4.24 shows the "Reader" tab that enables connecting with the reader and its functions. When the "Connection" function is selected, the "Connect" window opens up, as seen in the Figure 4.25. This window asks for user input about the IP address of the reader and the Port number. Correctly entering these inputs and hitting the

"Connect" button enable connecting to the reader and perform readings with default settings. Before connecting, login information must be entered through the "Management" tab. Static IP was assigned “192.168.1.10” to the reader and the same IP was entered to the "Connect" window, while the default Port number is used as "5084".

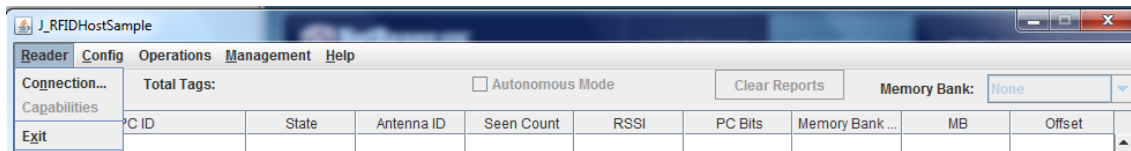


Figure 4.24 : User interface "Reader" tab.

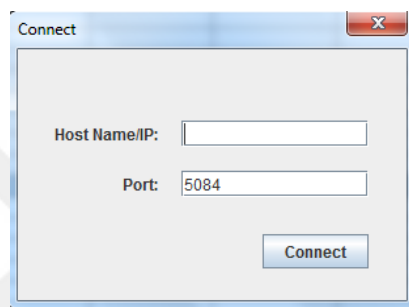


Figure 4.25 : User interface "Connect" window.

Figure 4.26 shows the "Management" tab and its functions, such as login/logout, update, reboot. When selected, “Login/Logout” tab displays the "Login" window that asks for login information (Figure 4.27-a). First option is to select the reader type from the drop-down menu (Figure 4.27-b). Since the type of the reader utilized in this study is FX7400, "FX" is selected from the list. The login window asks for the IP information, and as mentioned before, static IP address that was determined as “192.168.1.10” is entered. Then the user name and password is asked and the Motorola FX7400 reader's default values are entered as “admin” and “change”, respectively.

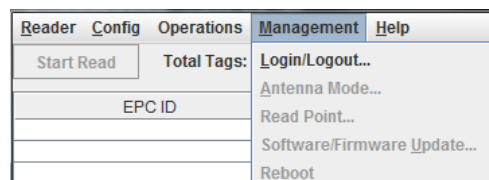


Figure 4.26 : User interface "Management" tab.

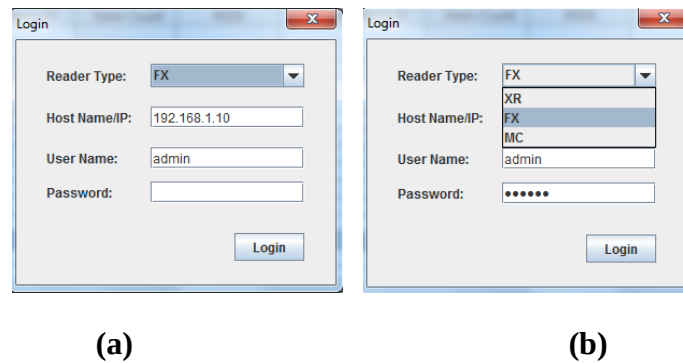


Figure 4.27 : (a) "Login" window, and (b) selecting reader type from "Reader Type" drop-down menu.

After entering the correct information and connecting from the "Connect" window, the window shown in Figure 4.28 displays. Lower right hand corner of the window is green, and the "Function Succeeded" is displayed on the lower left hand corner, both indicating that the connection to the reader succeeded. "GPI Port State" panel provide information about the general input/output ports on the reader. First icon is the input port and the second is the output port and while the red icon indicates logic 0, green icon indicates logic 1. When the connection is succeeded, "Start Read" and "Clear Reports" buttons are active.

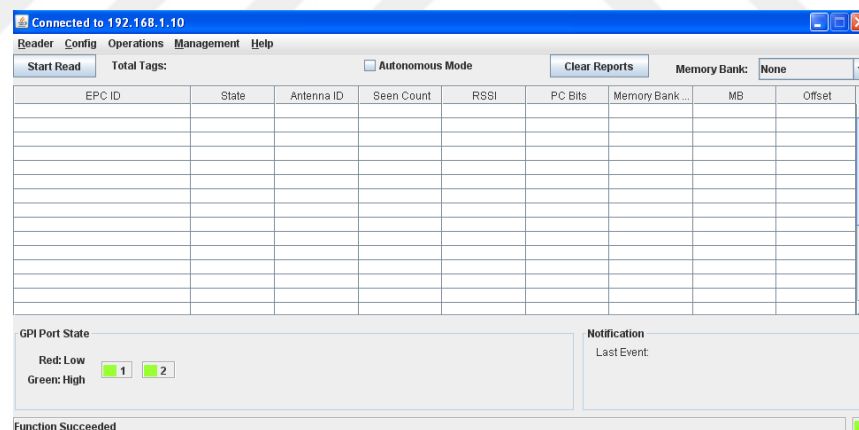


Figure 4.28 : User interface connection status.

Reading the RFID tags

"Start Read" button in Figure 4.29 initiates the tag reading process and the list is filled with tag information in accordance with the reading order. "EPC ID" is the tag's ID in hexadecimal format. "State" column indicates the tag's status, and as no status information is written in tag's memory, this column is filled "None". "Antenna ID" is the number of the antenna by which the tag is detected. "Seen Count" column stores the number of times the tag is detected by the reader. "RSSI" column stores the

signal strength received from the tag and “PC Bits” column reads the "Memory Bank" of the tags, which is the tag ID.

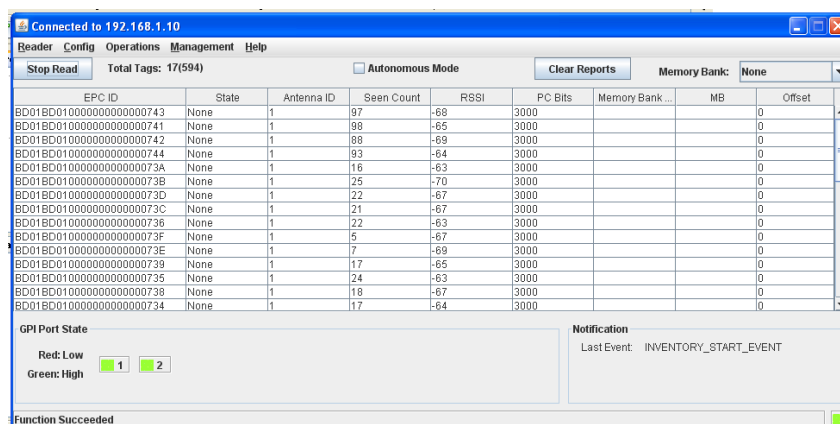


Figure 4.29 : User interface at the time of tag reading.

If additional information is stored in the memory of tags, such as descriptive information about the equipment that the tag is attached to, or the type of material pallet and floor information, then the displayed information will change accordingly. “MB” and “Offset” columns display the external storage area of tags and its offset, if available. When the “Stop Read” button is hit, the reader stops detecting tags. “Clear Reports” button is used to clear all the listed readings. If this "clear reports" function is enabled at the time of ongoing readings, the window shown in Figure 4.28 is displayed for a second, and then the program continues to read tags, restarting the enumeration from 1. If the "Clear Reports" function is enabled when the reader is not detecting tags, then the window returns to its former state.

Figure 4.30 shows the "Notification" panel where the user is notified about the program. This panel displays the latest event under “Last Event” line. For example, if the latest event of the reader was to start reading tags, then “INVENTORY_START_EVENT” is displayed. Similarly, when the “Stop Read” function is enabled and tag reading is terminated, it is displayed as “INVENTORY_STOP_EVENT” (Figure 4.30).

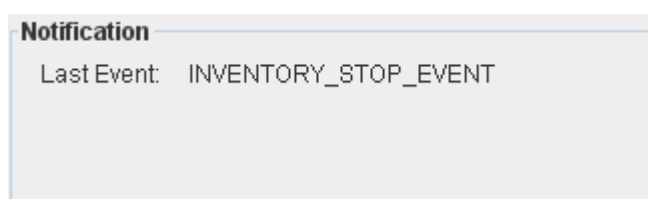
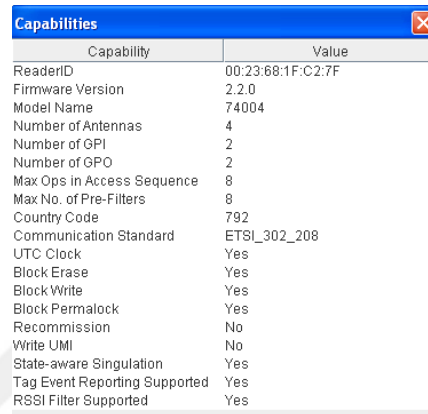


Figure 4.30 : User interface notification panel.

Reader settings and configuration

“Capabilities” function under the "Reader" tab displays the window in Figure 4.31 which lists the capabilities and general properties about the reader. As can be seen from the list, the reader has four antenna ports, two GPI and GPOs, maximum 8 pre-filters and many other properties. The last function under the “Reader” tab is “Exit” that is used to exit the program.

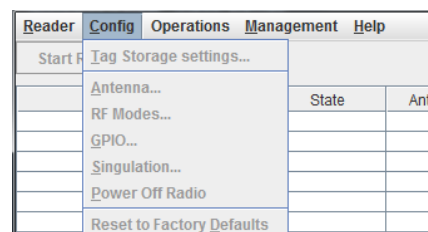


The image shows a window titled "Capabilities" with a table listing various properties of the reader. The table has two columns: "Capability" and "Value".

Capability	Value
ReaderID	00:23:68:1F:C2:7F
Firmware Version	2.2.0
Model Name	74004
Number of Antennas	4
Number of GPI	2
Number of GPO	2
Max Ops in Access Sequence	8
Max No. of Pre-Filters	8
Country Code	792
Communication Standard	ETSI_302_208
UTC Clock	Yes
Block Erase	Yes
Block Write	Yes
Block Permalock	Yes
Recommission	No
Write UMI	No
State-aware Singulation	Yes
Tag Event Reporting Supported	Yes
RSSI Filter Supported	Yes

Figure 4.31 : "Capabilities" window listing the general properties of the reader.

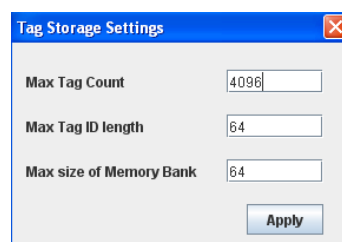
“Config” tab, next to the "Reader" tab, includes the functions, shown in Figure 4.32, that enable changing the configuration settings of the system components. When the “Tag Storage settings” function is selected, the “Tag Storage settings” window is displayed, which lists the available tag configuration settings (Figure 4.33). First row determines the maximum tag count, while the second row determines the maximum tag ID length and the third determines the maximum size of memor bank.



The image shows the "Config" tab of the user interface. It has a menu bar with "Reader", "Config", "Operations", "Management", and "Help". The "Config" menu is open, showing options: "Start", "Tag Storage settings...", "Antenna...", "RF Modes...", "GPIO...", "Singulation...", "Power Off Radio", and "Reset to Factory Defaults". To the right, there is a table with columns "State" and "Ante".

	State	Ante

Figure 4.32 : User interface "Config" tab.



The image shows a window titled "Tag Storage Settings" with three input fields and an "Apply" button.

Max Tag Count	4096
Max Tag ID length	64
Max size of Memory Bank	64
Apply	

Figure 4.33 : Tag storage settings window.

Figure 4.34 is the "Antenna" configuration window that is displayed when the "Antenna" option is selected from the "Config" tab. "Receive Sensitivity (dB)", "Transmit Power (dBm)" and "Transmit Frequency" values of antennas can be changed from this window.

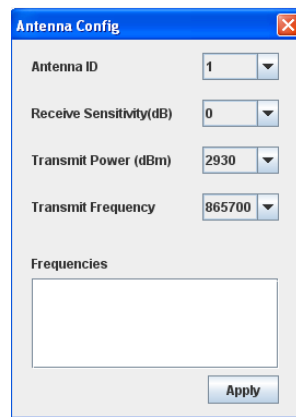


Figure 4.34 : Antenna configuration settings window.

Figure 4.35 displays the "GPIO settings" window for enabling settings related to the general-purpose input/output ports.

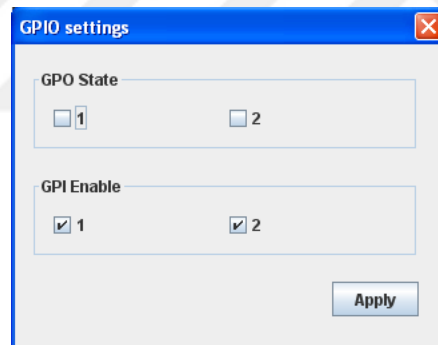


Figure 4.35 : General-purpose input/output port settings.

Connecting the reader from Web

The reader can be connected from a Web browser. This type of connection is especially important for performing the initial settings of the reader. The initial settings of the reader utilized in this study was performed using the Google Chrome web browser's 36.0.1985.125 m version. The host address is entered to the web browser to connect to the reader, and this address is written in the back of the reader (e.g., <http://fx74001fc27f>). The reader can also be connected by entering its IP address, as well. Initial settings were made by connecting the reader from its host address, and then the static IP that was determined as 192.168.1.10, was used for

later connections. Reader login page displays as in Figure 4.36. Similar to the previously mentioned “Login” window (Figure 4.27-a) “User Name” is entered “admin” and “Password” is entered “change” to connect to the reader.

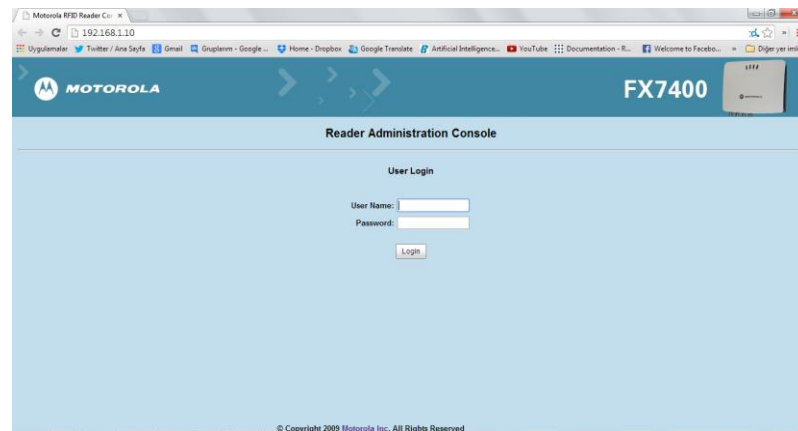


Figure 4.36 : Reader "User Login" page.

"Home" page is displayed when the reader is connected over a Web browser (Figure 4.37). This page displays the reader's version, host name, IP address, and serial number. Left hand side of the page is the menu that includes the reader properties, while the right hand side includes the “Help” menu.

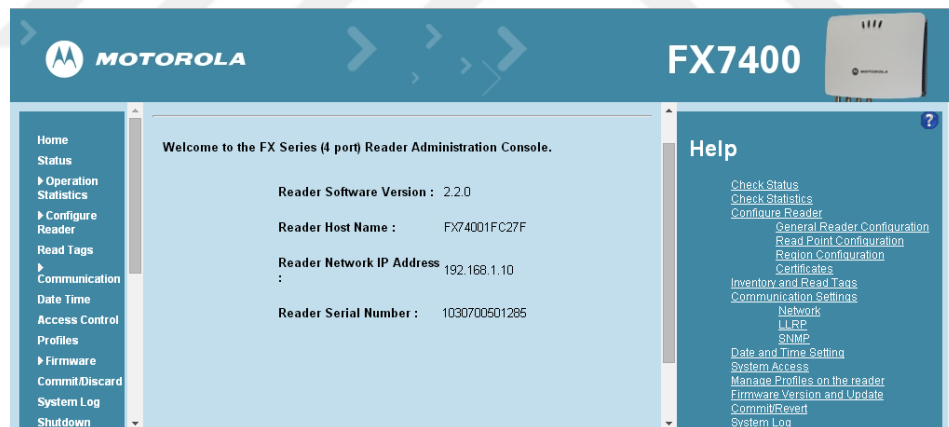
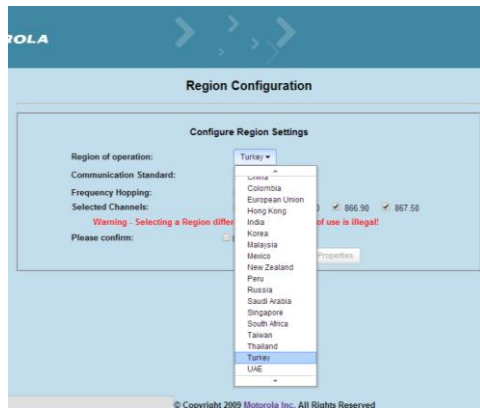


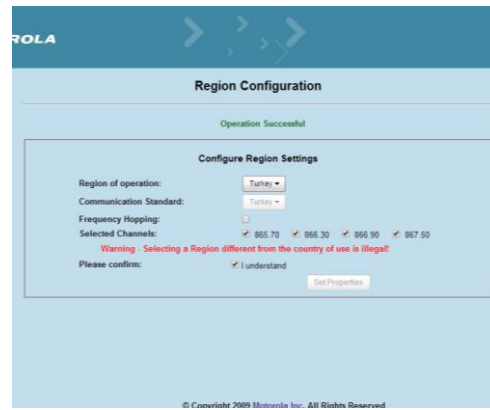
Figure 4.37 : Reader "Home" page.

Reader settings

Initial settings of the reader is performed over the web browser by listing the options under the “Configure Reader” tab from the menu. “Region Configuration” under the “Region” tab enables setting the region of operation (Figure 4.38). “Region of operation” is selected “Turkey” from the drop-down list. Different frequency bands are allowed in different regions therefore the available frequency channels are selected and confirmed in this page.



(a)



(b)

Figure 4.38 : Region configuration settings (a) region selection, (b) operation succeeded.

“System Time Management” page is displayed by selecting the "Date Time" tab from the menu (Figure 4.39) to perform the time settings by selecting "(GMT +02:00) Athens, Bucharest, Istanbul" under the “Time Zone” drop-down menu. This is an important setting to ensure that the readings are recorded with correct date and time information.

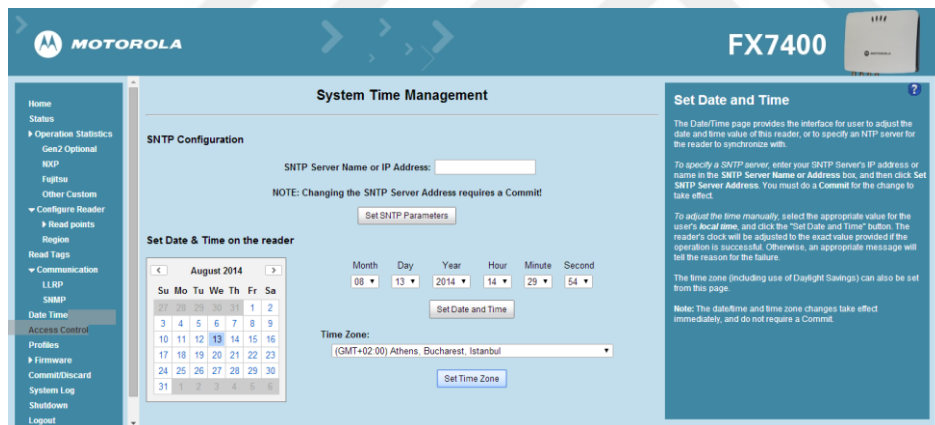


Figure 4.39 : System time management settings page.

To set the reader communication parameters, "Communication" is selected from the menu and “Reader Communication Parameters” page opens up (Figure 4.40). For the developed program to connect to the reader over the static IP, “Obtain IP Address via DHCP” option is marked as “Off” and the IP address selected from the DHCP IP pool of the reader's network is entered to the “Current IP Address” box. The subnet mask is entered to the “Subnet Mask” box and the settings are saved using the “Set Properties” button .

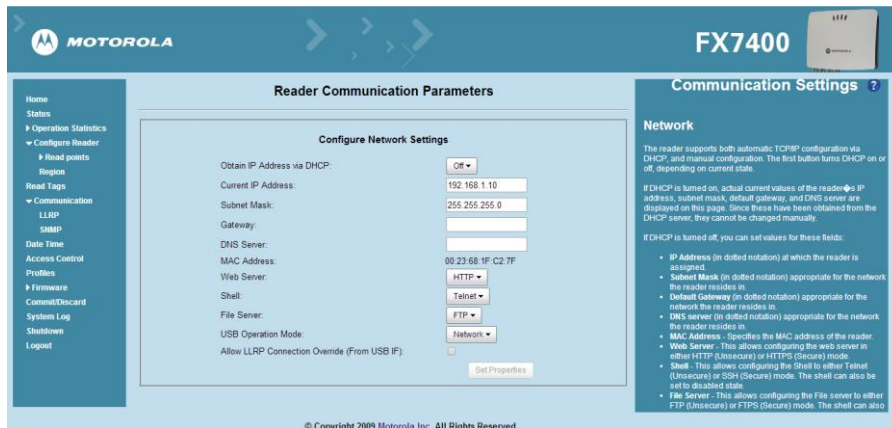


Figure 4.40 : Reader communication parameters page.

Reading tags over the Web browser

“Read Tags” option is selected from the menu on the left and “Reader Operation” page opens up (Figure 4.41). “EPC ID” column is the ID number of the tag, “TagSeen Count” column is the number of times the tag is detected by the reader, “RSSI” is the tag signal strength, “Antenna ID” is the number of the antenna by which the tag is detected, “FirstSeen” is the timestamp when the tag is first detected by the related antenna and “LastSeen” is the timestamp when the tag is last detected by the related antenna.

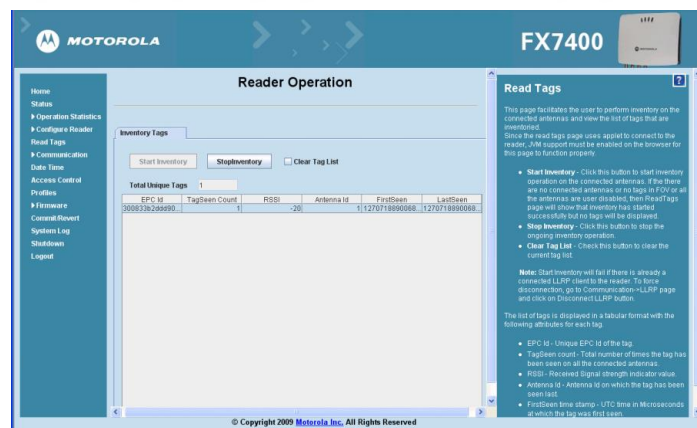


Figure 4.41 : Reader operation page for reading tags using the web browser.

The program was designed to store the data collected through the field experiments in a text file in CSV (Comma Separated Values) format. In this format, the first column is the EPC ID that is the ID number of the tag; while the second column is the number of the antenna by which the tag is detected, the third column is the date and time of the reading (Figure 4.42 and Figure 4.43).

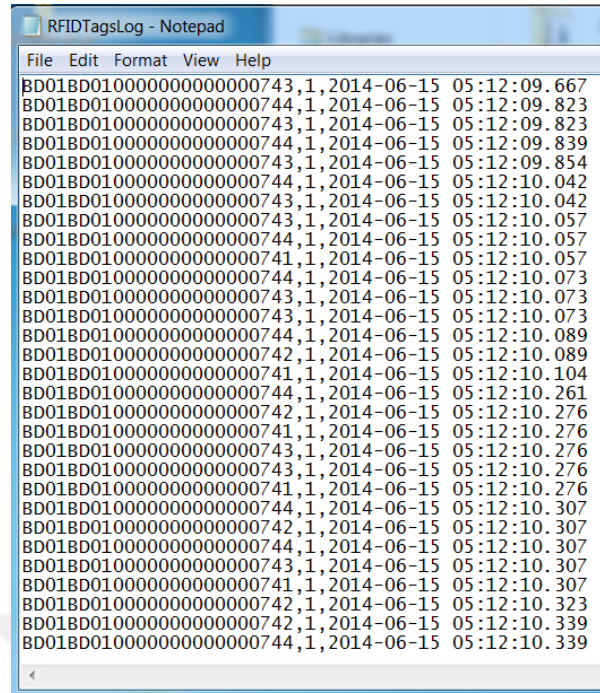


Figure 4.42 : Format of data storage for storing the data collected from RFID system.

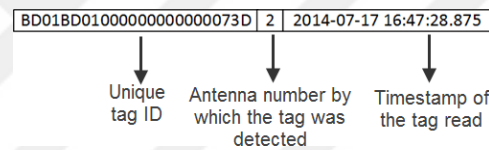


Figure 4.43 : Format of the data collected from RFID system.

RFID user interface for data processing

This section provides the details of the user interface developed to process the data collected with the RFID system. The data collection was performed as the empty AAC pallets are loaded on the elevator to be removed from the floor. Main function of this interface is to match the collected tag IDs with the IDs included in the tag ID database and identify the number and types of empty AAC pallets removed from the floor.

The user interface was developed in .NET framework 4.5 with C# programming language in Visual Studio 2013 Professional platform. Figure 4.44 shows the interface and its functions. After the RFID system performed tag readings, the user first selects the tag ID database file in CSV format ("Pallets Veritabanı Dosyasını Seçiniz" button), and then the RFID readings data in txt format ("Okuma Dosyası Seçiniz" button). "Hesapla" button displays the results as in Figure 4.45.

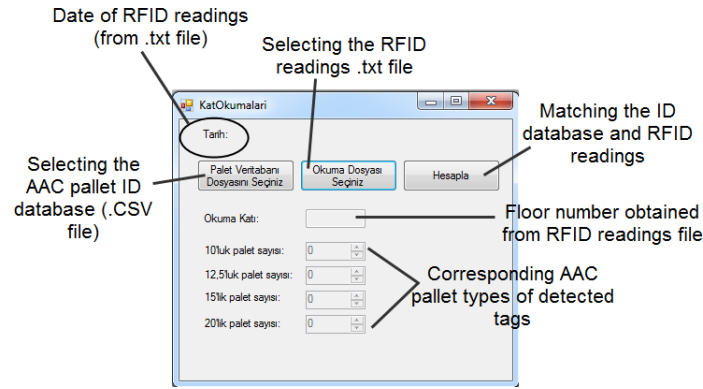


Figure 4.44 : User interface of the prototype application for processing RFID data.

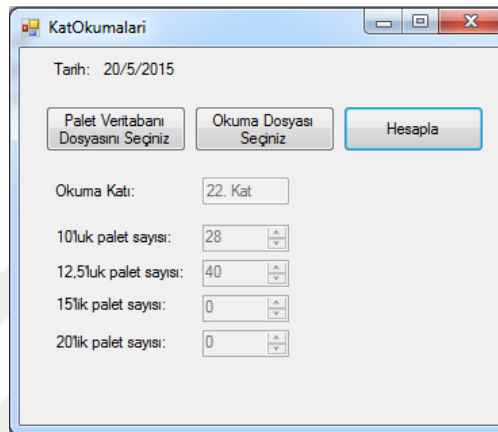


Figure 4.45 : User interface of the prototype application showing the results of reading tags.

The displayed results are also stored in two separate text files: (1) tag IDs that are detected but not included in the tag ID database (Figure 4.46-a), and (2) tags IDs included in the ID database but not detected (Figure 4.46-b). For example, Figure 4.41 shows that 68 tag IDs are detected in total at floor 22, on 20th of May. While 28 of these tags belong to 10 cm AAC pallets, remaining 40 belong to 12.5 cm AAC pallets. Figure 4.45-a shows the tag IDs that are detected during the readings but are not included in the tag ID database of floor 22. These tags might happen to be in the reading range of the reader by mistake or might belong to the AAC pallets that are later brought to the floor at which the readings were performed (Figure 4.46-a). Similarly, the tags that are included in the tag ID database but not detected during the readings show the tags that are attached on AAC pallets that have not yet been utilized (Figure 4.46-b).

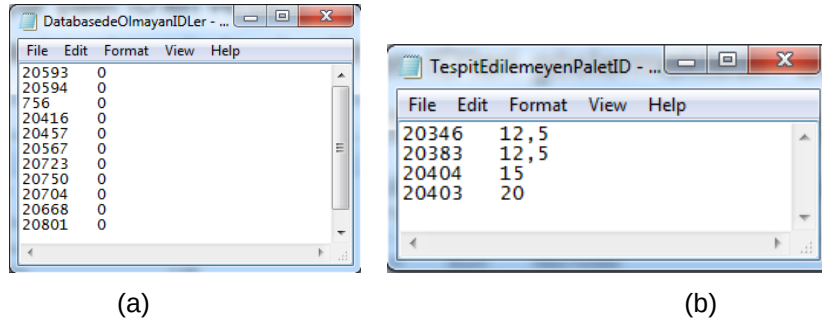


Figure 4.46 : Tag IDs (a) detected during the readings but not included in the database, and (b) included in the database but not detected during the readings.

Wireless accelerometer user interface

This section provides the details of the user interface developed to process the data collected with the accelerometer and it is used to understand the status of the hand drill and its working times. The user selects the text file that includes the accelerometer data and the results are displayed as in Figure 4.47. By evaluating the changes in the acceleration of the hand drill throughout the data collection period; the developed interface calculates how many times and for how long the hand drill was working, and lists when the hand drill started to work, for how long it was used, and when it stopped working.

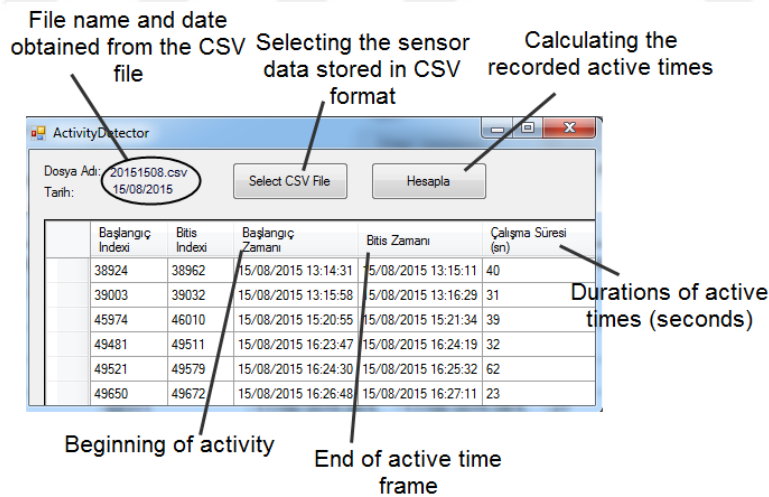


Figure 4.47 : User interface of the prototype application for processing wireless accelerometer data.

Tower crane sensors user interface

This section provides the details of the user interface developed to process the data collected with the tower crane sensors to track the tower crane movement and the

loads lifted by the crane. The screen and the functions of the user interface are shown in Figure 4.48.

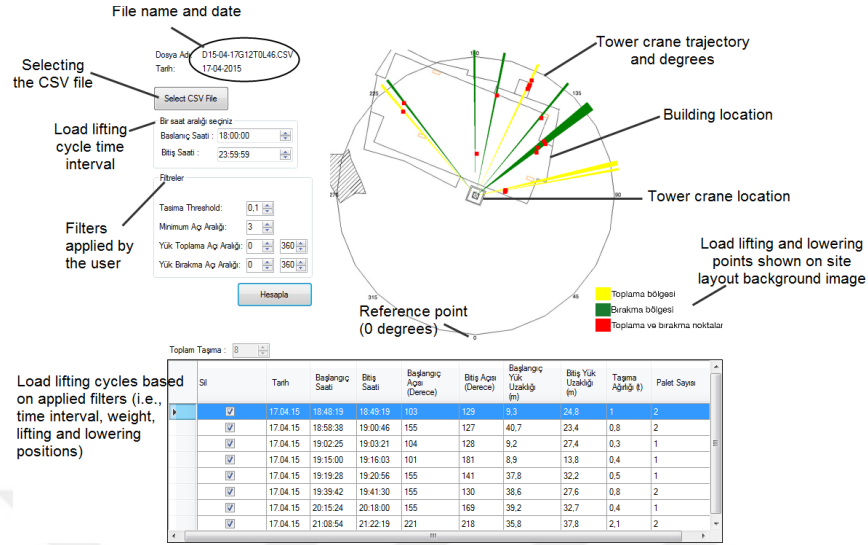


Figure 4.48 : User interface of the prototype application for processing tower crane sensor data.

This user interface enables visualizing the daily activities of a tower crane in terms of the load lifting activities that the tower crane performed in a day. The user interface is designed as a prototype that shows the daily activities of a tower crane, showing the load lifting and lowering locations and the weight of the corresponding load for each lift. The image used as the background is the site layout plan that shows where the building and other areas of interest (e.g., rebar cutting and bending area, wall block storage area), and the tower crane itself are located at site. Background image can be changed based on the needs and new locations can be added to the background. This user interfaces is aimed to be used by the site management for both the overall evaluation of the tower crane utilization and the progress and productivity of the related activities. Also, technical office personnel who are interested in obtaining data about the progress and productivity of activities that include the usage of tower crane can use this interface. Since the load lifting and lowering locations are visualized on the site layout for each movement of the tower crane, it enables the site managers to gain knowledge about how long the tower crane was used for what purpose and how much load is carried in a day, from where to where. Moreover, as the tower crane sensors collect data both at nighttime and daytime shifts, this interface provides data about the activities that have been performed in the night shift, even if the user (i.e. project manager) was not there for that period of time. For

the technical office personnel, on the other hand, this user interface provides the necessary progress and productivity information without the need for performing site observations and manually collecting data from site.

With little adjustments, the prototype user interface is designed as flexible as possible to be applicable for all building constructions that utilize tower crane as a means of transfer. Some filters are made available to the user from the screen to view the tower crane movements based on different needs (e.g., to distinguish different activities performed by the tower crane by filtering the load lifting and/or lowering locations).

The tower crane sensor data is stored in a CSV file for each day. If the default values are used for the time interval, the interface lists all the load lifting and lowering activities that are performed in a day, and the weight of the load that is carried in each lifting activity. If the user wants to look for the tower crane activities for a certain period of time, then the user selects a time period by entering a starting time and a finishing time for the selected CSV file. Based on the identified reasoning mechanisms explained in Chapter 3, Section 3.2.4.1 "Data extraction", the program looks for the load lifting activities within the intended time period and lists the load lifting activities on the screen.

The load threshold is set to 0.1 tons by default and the load weights smaller than 0.1 tons are assigned 0, while load weights greater than 0.1 tons are assigned 1 and stored in a string. As the "1" values within the string represent the times while a weight is being lifting, this enables determining the start and finish times of a weight lifting activity by checking the 0-1 transitions. The program performs two types of control: First, the total duration of the weight lifting times are checked and if the total number of consecutive "1" values is more than 30 (i.e., if the load is carried longer than 1 minute), then this time interval is accepted to belong to a load lifting activity. Second control is related to the movement constraints of the tower crane in compliance with the health and safety regulations and the usual practice at site. Both the slewing position of the crane and the position of the trolley are checked to remain static for the first 4 seconds of the weight lifting activity. It is accepted that the crane boom does not move more than 2 degrees clockwise or counter clockwise, and the trolley does not move more than 0.5 meters back and forth. After weight lifting activities are determined, the median of the load values are calculated for each lifting

activity and other related information (e.g., start and finishing angle, trolley distance, etc.) are extracted from the CSV file. Program utilizes this information for location calculations and shows the load lifting and lowering points on the site layout plan that is included in the user interface.

User can change the default values for performing filtering in the "Filtreleme" panel. The user can perform filtering based on these parameters:

- (1) minimum load weight,
- (2) minimum angular distance in between the load lifting and load lowering points,
- (3) locations of load lifting and load lowering (in terms of angles).

User can change the default load weight threshold value. This enables filtering the load lifting activities when the user wants to see only the results related to the lifting of loads heavier than a specified value (e.g., 0.5 tons). Second filtering aims to ignore the lifting activities that are performed within a very close distance (e.g., couple of meters away from one point to another). Default value is 3 degrees, meaning if the angular distance in between a load lifting point and load lowering point of a load lifting activity is less than 3 degrees, then it is ignored and not listed. Last filtering enables the user to filter the load lifting activities based on the areas from which the load is lifted and to which the load is lowered. Default value is set as 0-360 degrees to visualize all the load lifting movements, and all the lifting and lowering areas for the investigated day. Also, the user can enter new angle values to focus on a particular lifting or lowering area. For example, if the user wants to filter the load lifting activities only for the loads that are lifted from rebar cutting and bending area, he/she enters the angles of that area to the "Yük Bırakma Açısı Aralığı" field, and the related results are visualized accordingly.

Background image is the site layout plan showing (1) location of the building and the tower crane, (2) angle of the reference point (i.e., 0 degrees) and other points, (3) rebar production area (i.e., hatched area), and (4) location of the columns at which the rebar installation is tracked.

The program either lists all the load lifting activities for default values or lists the load lifting activities based on the specified time interval and applied filters. Each row in the list represents a lifting activity and includes these information:

- Load lifting start and finishing times,
- The angular position of the crane boom and the position of the trolley both at the beginning and at the end of the load lifting activity,
- Load weight in tons. It is accepted to be one AAC pallet if the weight of the load is lower than or equal to 0.7 tons, and otherwise it is two AAC pallets. Finally, if needed, user can filter the load lifting results from the list one by one.

The current version of the user interface enables determining:

- The date and time of AAC pallet transfers performed with tower crane, and the amount of material (e.g., AAC pallets, rebar, steel component) brought to a building floor.
- The exact time spent for material supply with tower crane, and therefore, determining the extra working hours accurately.
- Determining the amount of material (i.e., AAC pallets) transferred to floors and left in the stocks in the storage area.

The vision of this PhD thesis envisions that the tower crane sensor data is automatically transferred to a site computer and used for calculating the progress and productivity of the related activities and showing the results to the user. In this prototype, the tower crane sensor data is transferred to a site computer with a USB or SD memory stick by the user, and the user performs the steps (i.e., selecting the CSV file, applying time and other filters if needed) for processing the sensor data to list the tower crane load lifting movements.

4.1.3.2 User interface developed for monitoring masonry work

The user interfaces separately developed for collecting and processing data from the RFID system, the wireless accelerometer, the tower crane sensors and the total station were combined for data fusion and a user interface was developed for integrating data from these different data sources. The user interface consists of three tabs, each of which were assigned to the selected activities for the prototype implementation:

- (1) masonry work progress monitoring tab,
- (2) rebar installation progress monitoring tab,
- (3) steel component transfer progress monitoring tab.

Progress monitoring of each selected activity is performed for each building floor and every building floor is evaluated separately. First the progress monitoring of masonry work and the related tab of the user interface is explained and the other tabs of the user interface related to the monitoring of the rebar installation and steel work are explained in the following sections.

Masonry work monitoring tab

Individual user interfaces that were developed for the RFID system, wireless accelerometer and the tower crane sensors were integrated in this tab; along with a panel for the user to provide inputs related to the masonry quantity takeoff and the planned start and end dates of the masonry work for that particular floor (Figure 4.49).

- For the masonry work, the user enters the planned start and end dates using the calendar and enters the quantity takeoff value . Then the user selects the tower crane sensor data, RFID readings and accelerometer data files from the each related panels on the interface and presses the "hesapla" button.
- Tower crane panel lists each of the load lifting activities and the total number of load lifting activities.
 - Load lifting activities are listed according to the time interval selected and other filters applied by the user, if any. For example, the user can set the load lifting area angles to represent the wall block material storage area (i.e., 60 and 70 degrees) to list only the loads lifted from that particular area by manually entering angles for once, and the results are listed accordingly.

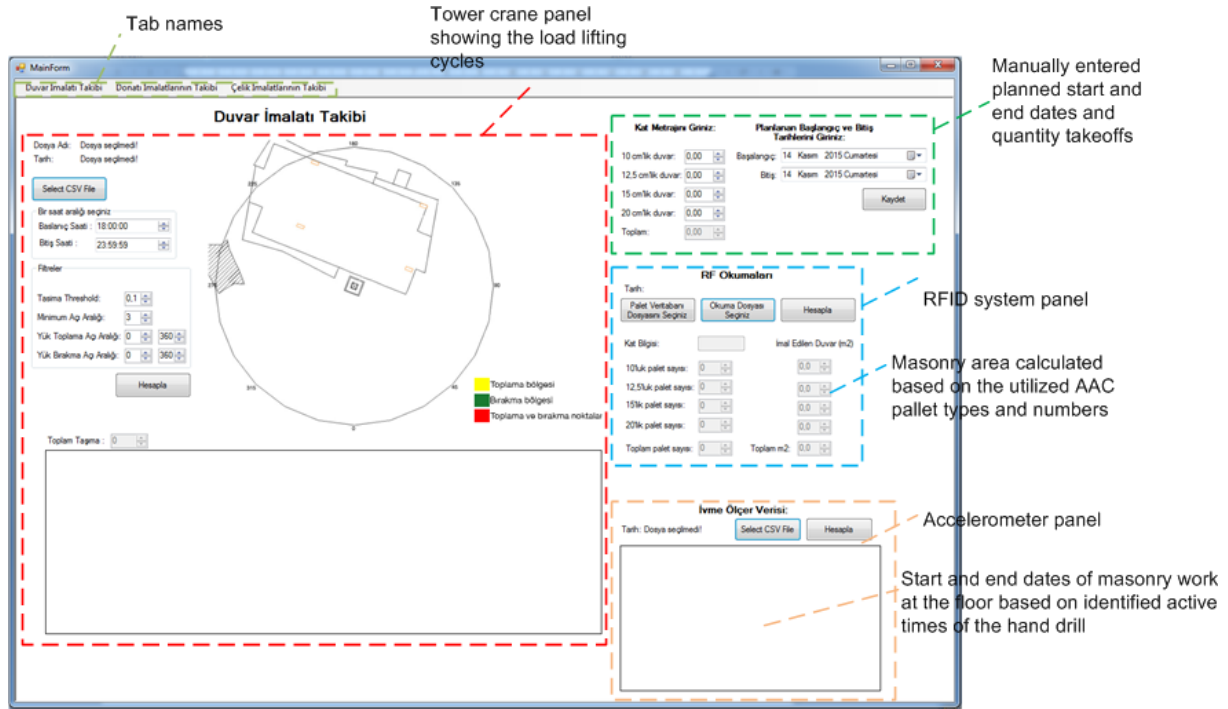


Figure 4.49 : User interface of the prototype application for monitoring the masonry work progress using the developed data fusion approach.

- The user interface processes the accelerometer and RFID data and shows the processed data for the accelerometer and RFID files that the user has selected. This provides the user to see the related equipment (i.e., hand drill) and material (i.e., wall blocks) usage at a glance, which might be of interest of the site management.
 - Accelerometer data panel lists the start and finishing dates of the masonry work for the particular floor and shows how many times the hand drill was used on each day.
 - Finally, the RFID panel shows the date of the RFID reading, the number and types of pallets utilized at the floor and the amount of masonry that can be built with each utilized number and type of pallet, based on the manufacturer specifications explained in Section 4.1 "Masonry Work Case Study: Current Process" in this chapter.
- Utilizing the sensor data files and the manually entered information, the user interface calculates the results, and material utilization, progress and productivity results displayed in a separate window, as shown in Figure 4.50 and explained in the following paragraphs. The program evaluates the

collected data in terms of (1) material utilization and progress evaluation, and (2) comparison with planned schedule.

Material utilization and progress evaluation:

(1) The amount of material delivered to the floor, and (2) the amount of material utilized at the floor are compared and the progress of the masonry work (i.e., % of completion) is calculated. The utilized material is used to calculate the completed masonry work and then it is compared with the masonry quantity takeoff to identify the extra amount of material needed to complete the remaining work.

- The number of AAC pallets (the amount of material) delivered to the floor is obtained from the tower crane sensor data.
- Emptied AAC pallets removed from the floor with the elevator and returned to the manufacturer. RFID system installed on the elevator detects the tag IDs on AAC pallets, and the number and types of utilized pallets are determined. The utilized pallet information is used to calculate the total amount of masonry work performed (in terms of area) at the floor.
- By calculating how much of the delivered material is utilized at the floor, the percentage of completion (i.e., progress) is calculated.
- The utilized amount of material (area) is compared with the masonry quantity takeoff (area) to and the remaining amount of masonry work (in terms of area) is calculated.
- Depending on the remaining amount of work, material needed to complete the work (in terms of number and types of AAC pallets) is calculated.
- The required amount of material calculated in the previous step is compared with the material that remained at the floor, to calculate the extra material that is needed to be delivered to the floor.

Comparison with the planned schedule:

- The actual start and end dates for the masonry work are obtained from the accelerometer data: the first day that the accelerometer is used at the floor is the first day of masonry work, and the last day that the accelerometer is used at the floor is the final day of the masonry work at that floor. These dates are compared with the planned start and end dates entered manually by the user and a notification is shown on the screen.

- Possible actual vs. planned conditions, the related notification messages and the symbolic representation are listed in Table 4.3. A detailed illustration for the symbolic representation is given in Figure 4.50.
- Results are displayed as in Figure 4.51.
- The current version of the prototype user interface shows the material utilization details and the future needs in addition to the calculated progress and productivity information.
 - This version of the user interface meets the needs of both the site management and the technical office personnel. As the site management is interested in seeing the utilized amount of material, the remaining material at the floor, and the extra material that will be needed to complete the work at the floor; the technical office personnel is only interested in obtaining the progress and productivity results of the masonry work.

Table 4.3 : Performance of tower crane sensors in determining the correct amount of material delivered to the floor.

Conditions	Notification message	Symbolic representation
1	Planned and actual start and end dates are the same	
2	Actual end date is before planned start date	
3	Actual start date is after planned end date	
4	Actual start date is before planned start date and actual end date is after planned end date	
5	Actual start date is before planned start date and actual end date is the same with the planned end date	
6	Actual start date is the same with the planned start date and actual end date is after planned end date	
7	Actual start date is the same with the planned start date and actual end date is before planned end date	
8	Actual start date is after planned start date and actual end date is the same with the planned end date	
9	Actual start date is before planned start date and actual end date is before planned end date	
10	Actual start date is after planned start date and actual end date is after planned end date	

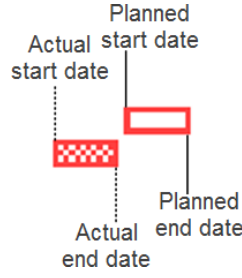


Figure 4.50 : Explanation of the symbolic representation for "actual start date is before planned start date" condition.

The screenshot shows a software window titled 'DuvarİmalatıRapor'. It contains several sections for data entry:

- Malzeme kullanım değerlendirilmesi**: Fields for 'Kata çöken palet sayısı' (114), 'Kata kalan palet sayısı ve türleri' (7), '30/4/2015 tarihi itibarıyla kata kullanılan palet sayısı' (104), and various palet types (10'luk, 12.5'luk, 15'lik, 20'lik) with their respective counts.
- İlerleme durum değerlendirilmesi**: Fields for 'Kullanılan Malzemeye göre katın tamamlanma yüzdesi (%)' (91), 'Kullanılan Malzemeye göre kalan iş miktarı (m2)' (94.5), and 'Kalan işi tamamlamak için gerekli palet türü ve adeti' (7).
- İş programı ile kıyaslama**: Date pickers for 'Planlanan başlangıç' (21.03.2015), 'Gerçeklenen başlangıç' (15.04.2015), 'Planlanan bitiş' (29.03.2015), and 'Gerçeklenen bitiş' (24.04.2015).

 At the bottom, a red box highlights a message: 'Gerçekleşen bitiş tarihi planlanan başlangıç tarihinden öncedir.' (Actual completion date is before the planned start date). Below this, it says 'Gerçekleşen performans: 10 gün/kat'.

Figure 4.51 : User interface of the prototype application for monitoring masonry work progress results.

4.1.4 Validation: Field tests and results for masonry work

The prototype system was tested at a building in a double shift construction site for monitoring the masonry work at floors 20 to 27. Data was collected from the tower crane sensors and the RFID system for three months while the masonry work was being performed. However, some technical problems given below occurred while collecting data with the accelerometer; therefore, accelerometer data was generated. The first problem was related to charging of the accelerometer. Despite being reminded every day, workers tended to forget recharging the accelerometer at the end of each working day. The second problem was related to attachment of the accelerometer to the hand drill. Since the accelerometer was not permanently fixed on the hand drill, in some cases it physically obstructed the use of the hand drill as

the adjustable belt of the encasing can get loose and often require to be refitted. Moreover, there were times when the encasing needed to be repaired as it got damaged at site. To overcome these technical issues, data collection with the accelerometer was performed for one week while the charging of the accelerometer and the attachment issues are handled. This data was examined and based on this data accelerometer data was generated for each floor throughout the field experiments. Also, the floor at which the hand drill was utilized was manually tracked during the field experiments. This method enabled demonstrating the utilization of accelerometer data for activity progress monitoring purpose by explaining the processes for data extraction and data transformation that are specific to accelerometer data format and how this data is fused with other sensor-based data.

In summary, the tracked equipment (i.e., tower crane, hand drill, elevator, material pallets) provided the following data about the masonry work:

- The generated accelerometer data enabled tracking the start and end dates of masonry work at a floor.
- The amount of material delivered to the floor was obtained from the tower crane sensors, in terms of number of AAC pallets.
- The amount of material utilized at the floor was obtained from the RFID system installed on the elevator, in terms of number and types of AAC pallets.

The following paragraphs explain how the progress of masonry work was tracked at one floor (i.e., floor 20) to demonstrate the monitoring process for all floors that were monitored during the field experiments and overall results are provided.

Results for masonry work at floor 20

Calculating the masonry work progress

Developed data fusion approach and the reasoning mechanisms were applied for tracking the masonry work progress. The main steps are given in the following paragraphs:

1. Extracting data items and data instances:

- Project related data (i.e., masonry quantity takeoff and planned start-end dates) was manually obtained from the schedule and quantity take-off documents and entered to the user interface.
- Pre-processing steps that were previously explained in Chapter 3, Section 3.2.4.1 "Data extraction" were applied on RFID, tower crane sensors and accelerometer data and the relevant data items and data instances were filtered:
 - Data related to load lifting activities were automatically extracted from tower crane sensors data by applying the determined rules to identify the load lifting activities related to masonry work (i.e., transfer of AAC pallets from storage area to the building floor)
 - RFID data was automatically filtered based on the ID of the antenna by which the tags were detected (i.e., inside or outside of the elevator cabin).
 - Data instances that represent the active (i.e., working) times of the hand drill were automatically extracted from the accelerometer data.

2. Data transformation:

- The dates when AAC pallets were delivered to the floor and the number of AAC pallets that were delivered were obtained from the tower crane sensors: For example, it was identified that in total, 114 AAC pallets were delivered to the 20th floor on April 10-11-12, 2015 (Table 4.4).
- Accelerometer data was used to determine the masonry work start and end dates: For example, masonry work at 20th floor started on April 15, and ended on April 24, 2015.
- Data collected by the RFID system was used to identify the amount of material utilized at the floor: 55 pieces of 10 cm, 36 pieces of 12.5 cm and 13 pieces of 15 cm empty AAC pallets were loaded on the elevator and removed from 20th floor on April 30, 2015.

Table 4.4 : Summary of material delivery and usage details at floor 20.

Floor number	Date of material transfer to floor	Total amount of material transferred to floor	Start date and end date of masonry work at floor	Number and types of material removed from the floor	Date of empty pallet removal from floor
20	April 10-11-12, 2015	114	April 15, 2015 April 24, 2015	55 x 10cm 36 x 12.5cm 13 x 15cm	April 30, 2015
				Total = 104	

Technology performances

In this section technology performances are evaluated for determining the actual amount of material (1) delivered to the floor and (2) removed from the floor. The actual amount of material (i.e., ground truth) was determined based on the site observations performed and the field notes. Table 4.5 reports the actual amount of material delivered to the 20th floor, and the performance of the tower crane sensors in determining this actual amount of material. The results of the tower crane sensor data, it was identified that 114 AAC pallets were brought to the 20th floor, while the actual amount of delivered AAC pallets was 111.

Table 4.5 : Performance of tower crane sensors in determining the correct amount of material delivered to the floor.

Number of AAC pallets delivered to the floor (according to tower crane sensors)	Actual number of AAC pallets delivered to floor (based on site observations and field notes)	Performance of tower crane sensors in determining the correct amount of material delivered to the floor		
		Precision	Recall	f-measure *
114 pallets	111 pallets	111/114= 97%	111/111= 100%	98%

$$* \text{ f-measure} = (2 * \text{Precision} * \text{Recall}) / (\text{Precision} + \text{Recall})$$

For evaluating the success of the tower crane sensors, two performance measures, namely precision and recall, that were utilized in determining the accuracy of data mining approaches were used (Coşkun and Baykal, 2011). In this study, precision and recall were defined as following:

- Precision: percentage of determined number of pallets that are correct (e.g., actual amount of AAC pallets delivered to floor/determined amount of AAC pallets delivered to floor (by tower crane sensors)).

- Recall: percentage of correct number of pallets that are determined (e.g., percentage of the actual amount of material delivered to floor being determined).

Precision and recall do not provide a sufficient performance measure alone and more accurate results are obtained when two measures are used together (Coşkun and Baykal, 2011). In this case, F-measure is used, which is the harmonic mean of precision and recall. Since the number of pallets delivered to 20th floor was determined as 114 and the actual amount of material brought to the floor was 111; precision of the tower crane sensors was 97%. Since all the 111 pieces of delivered pallets were determined, the recall was 100%. Accuracy of the tower crane sensors for determining the number of pallets delivered to the 20th floor (i.e., f-measure) was 98%.

Table 4.6 reports the actual amount of material left at the 20th floor at the end of the masonry work (i.e., ground truth based on observations on-site) and the performance of RFID and tower crane sensors in determining the correct amount of material left at the floor. 7 pieces of AAC pallets were left at the floor (i.e., 2 pieces of 10 cm, 1 piece of 12.5 cm and 4 pieces of 15 cm). Among 114 pallets that were delivered to the floor, based on the tower crane sensors; RFID system identified that 104 pallets were removed from the floor and 10 pieces of pallets were left at the floor. Accuracy of determining the actual amount of material left at the floor was (i.e., f-measure) 82% at this floor.

Table 4.6 : Performance of determining correct amount of material left at the floor.

Actual # of AAC pallets left at the floor (ground truth based on on-site observation)	(# of AAC pallets delivered to floor) - (# of AAC pallets removed from the floor) (tower crane sensors and RFID data)	Performance of determining the correct amount of material left at the floor (tower crane sensors and RFID data)		
		Precision	Recall	f-measure
7 pallets	10 pallets	7/10=70%	10/10=100%	82%

The factors which affect the success of tower crane sensors in determining the correct amount of material delivered to the floor are evaluated based on the site observations and interviews with technical personnel. The sensitivity of the sensors

that collect information about the angular position, load and distance of the tower crane and the trolley are effecting the measurements. Moreover, the impact of acceleration of the tower crane on the load being carried during the lifting and lowering movements (e.g., measured weight of the load varies due the speed of lifting and lowering actions); and the wind, friction, and weather factors affect the load and other collected parameters at the time of lifting and lowering.

3. Data fusion

Information about the "amount of material delivered to the floor" obtained from the tower crane sensors are integrated with information about the "amount of material utilized at the floor" obtained from the RFID readings, and the progress of masonry work is calculated (Table 4.7).

Table 4.7 : Masonry work progress at 20th floor.

# of AAC pallets delivered by tower crane (from tower crane sensors)	114 pallets
# of pallets utilized at the floor (from RFID system)	104 pallets
Estimated % of progress (utilized amount of material / delivered amount of material)	$104/114 = 91\%$
Percentage recorded in site progress documents (% of completion)	99%
Progress calculated from site observations (ground truth)	95%
Accuracy of the determined completed masonry work at the floor	$91/95 = 96\%$

By fusing the RFID and tower crane sensors data, the percentage of progress for the masonry work at 20th floor was estimated 91% by calculating the fraction of the utilized AAC pallets (i.e., 104 pallets) that were delivered (i.e., 114 pallets). According to the ground truth that is obtained from on-site observations, the actual progress is 95%. The 95% actual completion was determined by the data fusion approach described in this thesis as 91%; and this shows the performance of correctly determining the completed masonry work at the floor was 96% for this floor.

In practice, the progress for masonry work is based on the personal interpretation of the person in charge and is estimated in percentages. The progress estimation for this floor was recorded as 99% to the site progress documents with the current method. At Site 1, this estimation is made by the site personnel in charge every week for the weekly meetings. The estimation is based on the assumption that the masonry work is usually completed within one week; and even if the work is not complete, the same

value (i.e., 99%) is entered as progress, indicating that the work is almost complete, unless there is a significant delay. Although there does not seem to be a significant difference in between the value that is estimated with the current intuitive approach and the value calculated with the developed data fusion approach; the main advantage of the developed approach is enabling a realistic progress estimation without the need to make site observations and manually collecting data from site. Moreover, the meetings are performed at the beginning of every week and the site personnel do not collect any information about the progress in the middle of the week. However, this approach is capable of monitoring the daily and more up-to-date progress if the empty pallets are removed from the floor on a daily basis. During the implementation of the prototype, on the other hand, the removal of the empty pallets were performed at the end of the masonry work at each floor and therefore, only one progress estimation was made for each floor.

Evaluation based on schedule:

Based on accelerometer data, masonry work started on April 15 and ended on April 24 at the 20th floor. Data obtained from the schedule showed that the planned start and end dates were determined as March 21 and 29. Therefore, the actual start date is after the planned date and there is almost 1 month delay. This necessitates an update in the schedule. Also, the planned performance predicted for completion of masonry work at a floor was 8.1 days; while the actual performance was 10 days per floor.

Table 4.8 reports the results of the analysis and the performances of the developed data fusion approach in determining the masonry work progress at all floors that were monitored during the field experiments. Accuracy of the developed approach in correctly determining the masonry work progress was over 96% for seven floors out of eight, and accuracy of only one floor was 85%. These results show that the developed approach can successfully be used for monitoring the masonry work at double shift construction sites.

Table 4.8 : Performance of determining the masonry work progress based on tower crane sensors and RFID data.

Floor	20th	21st	22nd	23rd	24th	25th	26th	27th
# of AAC pallets delivered by tower crane (from tower crane sensors)	114 pallets	107 pallets	90 pallets	87 pallets	100 pallets	113 pallets	107 pallets	99 pallets
# of pallets utilized at the floor (from RFID system)	104 pallets	105 pallets	90 pallets	80 pallets	68 pallets	101 pallets	99 pallets	89 pallets
Estimated % of progress (utilized amount of material / delivered amount of material)	104/114 = 91%	105/107 = 98%	90/90 = 100%	80/87 = 92%	68/100 = 68%	101/113 = 89%	99/107 = 93%	89/99 = 90%
Percentage recorded in site progress documents (% of completion)	99%	99%	99%	99%	99%	99%	99%	99%
Progress calculated from site observations (ground truth)	95%	99%	95%	94%	80%	96%	95%	94%
Accuracy of the determined completed masonry work at the floor	91/95 = 96%	98/99 = 99%	90/95 = 95%	92/94 = 98%	68/80 = 85%	89/96 = 93%	93/95 = 98%	90/94 = 96%

4.2 Rebar Installation Case Study: Current process

Site observations were conducted at Site 1 to elaborate the current process for rebar installation that is involved in the structural works. At site, a set of activities related to structural works are performed in the same order at each floor of the building as explained in the following paragraphs:

- **Determining a stock area for materials:** An area that is close to the building being constructed, is selected to store the necessary materials (e.g., iron rods) and equipment (e.g., iron cutting and bending machines).
- **Column and wall alignment:** After the slab concrete has been poured, the surveying technicians perform the layout and alignment of columns and shear walls with total station and also check the corners of the slab and the core to make sure that the structure is aligned. The measurements conducted with the total station are stored in the on-board memory of the total station and transferred to the computer at the office.
- **Rebar preparation:** In the stock area, irons are cut and bent as indicated in the structural and rebar placing drawings, and prepared for installation.

Prepared rebars are transferred from the stock area to the building with tower crane.

- The way that the rebar is prepared depends on the installation location (i.e., building element) at which the rebar will be used. All parts of the rebar can be prepared at the production area (e.g., as in columns), or the rebar can be partially prepared at the production area and completed at the installation area on the building (e.g., as in shear walls).
- After the ironworker crew completes the work, the rebar inspection is conducted and the process continues with the formwork production after the inspection acceptance.
- **Formwork production:** A storage area is assigned for storing formwork parts and equipment near to the building being constructed, and a similar process is followed as in rebar production and transfer. Pieces of formwork are lifted from the formwork storage area and transferred to the installation place on the building with tower crane.
 - Formwork preparation depends on the type of the formwork (e.g., conventional, tunnel formwork) and the building element at which the formwork will be used (e.g., column, slab, shear wall). For example, for buildings with large floor area, the column formwork is first used at columns located at one half of the slab and stripped on the following day and same formwork is used at the columns located on the other half of the slab. Tower crane is used to remove the pieces of formwork and carry them to their new installation locations (i.e., to other columns). For slabs, same formwork material is used at every two to three floors by manually removing the formwork from the lower floor and transferring formwork to the upper floor with tower crane.
- **Columns and shear walls concrete pouring:** Concrete pouring of columns and shear walls is conducted upon the completion of rebar and formwork installation. This might be completed in two sections for large buildings. As in the formwork installation, concrete pouring is first performed at columns located on the one half of the slab and on the other half of the slab on the following day.

- **Slab construction:** The day after the column and shear wall concrete is poured, installation of slab formwork is performed on the following days and concrete pouring is performed for the slab.

4.2.1 Proposed approach for tracking rebar installation progress

In this thesis, it is proposed that by using the existing tower crane sensors and total station data, rebar installation progress and daily productivity can be automatically determined. By fusing crane and total station data, the daily productivity of the rebar crew, and progress of rebar installation (e.g., percentage of completion) can be determined. Table 4.9 reports the data to be collected from each construction equipment to be tracked and the project related data source (i.e., quantity takeoff documents and schedule).

Table 4.9 : Tracking approach developed for monitoring the progress of the rebar installation work.

Data collected from	Tracking method	Collected data	Data used and results obtained	Integration of results
Tower crane	- Angular position, trolley position and load sensors (on tower crane)	(A) Load weight (ton)	(A) + (B) + (C) = Total amount of rebar brought to the floor (tons)	(A) + (B) + (C) = Daily productivity of rebar installation
		(B) Angular position of the crane boom (degree) (C) Position of the trolley and the depth of the hook (m)		$[(A)+(B)+(C)]/(F) =$ Percentage of completion (%)
Total station	- Total station (measurements performed for alignment and layout of building elements)	(D) Elevation of the slab (m)	(D) + (E) = Floor at which the concrete pouring is completed	(D) + (E) = The floor at which the rebar installation has started
		(E) Date of data collection		(D) + (E) = The floor at which the rebar installation has started
Project related data sources	- Manual data extraction from related documents	(F) Rebar quantity takeoff (tons)	(F) = Total amount of rebar work (tons) (I) = Planned start and end dates for rebar installation	(G) vs. (E) = planned vs. actual date comparison

Total station is used for the alignment of columns, shear walls, and corners of slab and core structure, and collected data is transferred to the site computer. This information (e.g., collection of alignment data at a floor) indicates that the structural

works are completed at the floor below, and the rebar production and installation is started at the current floor. The data that is collected from the total station is used to identify the floor at which the rebar installation has started and when (Table 4.9). Tower crane sensors are used for determining the daily amount of rebar brought to the floor for installation. While the rebar is being transferred from the rebar cutting and bending area to the floor, following data is tracked from the tower crane sensors to observe the progress of the rebar installation at the floor: (1) weight of the load carried by the tower crane (in tons), and (2) load lifting activities of the tower crane started at the rebar cutting and bending area and ended at the floor (Table 4.9).

Figure 4.52 illustrates the parameters related to the rebar installation need to be tracked for each load lifting activity of the tower crane: (1) angular position and the coordinates of the crane boom and hook when the load is lifted, (2) weight of the load measured throughout the lifting activity, and (3) angular position and the coordinates of the crane boom and hook when the load is lowered. Based on the reference point that is determined at the time of installation of the anti-collision system on tower cranes, the angular position sensor of the tower crane collects the real-time position of the crane boom. The real-time position of the crane trolley is collected by the position sensor in terms of the distance from the tower crane cabin, and finally the load sensor measures and stores the load that the tower crane is carrying. A depth sensor can also be added in the anti-collision system configuration to collect the coordinates of the crane hook. Fusing these information items enables automatic identification of the load that is lifted and the type of activity being performed.

Data obtained from the total station and the tower crane sensors are fused in a complementary fashion utilizing the developed reasoning mechanisms and data fusion approach explained in detail in Chapter 3.

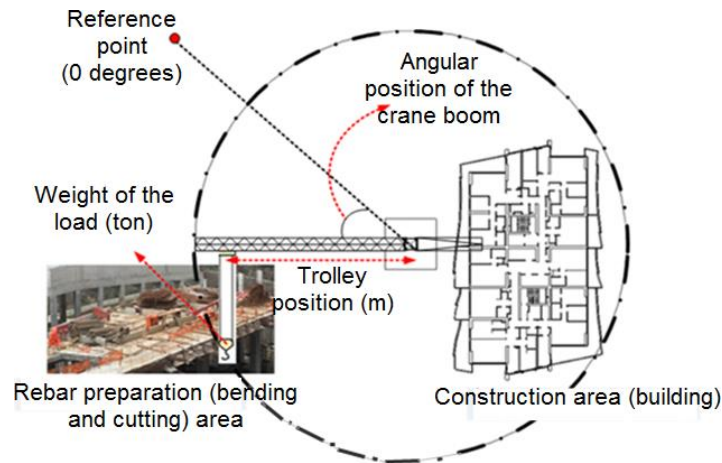


Figure 4.52 : Parameters tracked by the tower crane sensors during rebar installation.

4.2.2 Prototype system design

The prototype system was designed based on the functional requirements identified and the selected sensor-based technologies described in Chapter 2. The prototype consisted of the tower crane sensors and total station device for monitoring the rebar installation. As explained in the previous sections that described the monitoring of masonry work, tower crane sensors for tracking the movement of tower crane (i.e., angular position sensor, trolley position sensor and load sensor) were already installed as part of the anti-collision system and were used as is. Data collected from the tower crane sensors are stored in an SD card inside the data logger that is located in the central unit, and the SD card is used for data transfer to local computer(s).

Total station, on the other hand, was included in the data collection process without any modification to the regular use of the total station. Data collected with the total station was first stored on-board and then transferred to the site office computer. Elevation of building slabs measured with the total station and the date of data collection was obtained from the device itself. Following sections describe how the prototype was implemented and how the field tests were performed with the prototype.

4.2.3 Prototype implementation

Rebar installation at a floor is tracked with data collected with the tower crane sensors and the total station. Following sections describe the work flow for monitoring the rebar installation, the related studies and the developed approach. Figure 4.52 shows the flow diagram for the monitoring process of rebar installation.

- *Tracking process:* After it is identified that the rebar installation has started at the current floor, daily movements of the tower crane are tracked to identify the load lifting activities in between the rebar production area and the building.
- *Data sources:* Total station measurements are used to identify the dates that the concrete pouring of the lower floor has been completed and the rebar installation has started at the current floor. Starting from this date, data collected with the tower crane sensors are used to calculate the time spent for the rebar installation activities and the total weight of rebar transferred from the rebar production area to the building for each day.
- *Data collection and storage:* Tower crane sensors perform data collection in real-time and wireless data transfer is available. However, during the prototype implementation, collected data was stored on an SD card placed inside the tower crane central unit and the total station's internal memory and then manually transferred to a local computer at site office.

Preliminary work:

- Since the readily available data collection methods are utilized, no preliminary work is necessary.

Steps for tracking the rebar installation:

- **Total station measurements:** Total station measurements are recorded on-board during the layout and alignment of columns and shear walls, and corners of slabs and the core structure. The stored data is then transferred to the site computer and used to identify the date and floor at which the concrete pouring has been completed and the rebar installation has started (Figure 4.53-a).
- **Lifting the rebar from the production area:** Tower crane movements are tracked and related load lifting activities are identified. The location of the rebar production area on the site layout plan is known (e.g., 240-280 degrees), and therefore, the lifting locations of the load lifting activities are filtered accordingly. The median of the weight of the load is calculated to determine the weight of the load being carried in each lifting activity (Figure 4.53-b).

- **Lowering the rebar to installation area:** For the identified load lifting activities, the lowering locations are determined. By tracking the depth of the crane hook, the floor at which the rebar is lowered is identified (Figure 4.53-c). As there were no depth sensor included in the prototype, this was performed manually during the field tests.

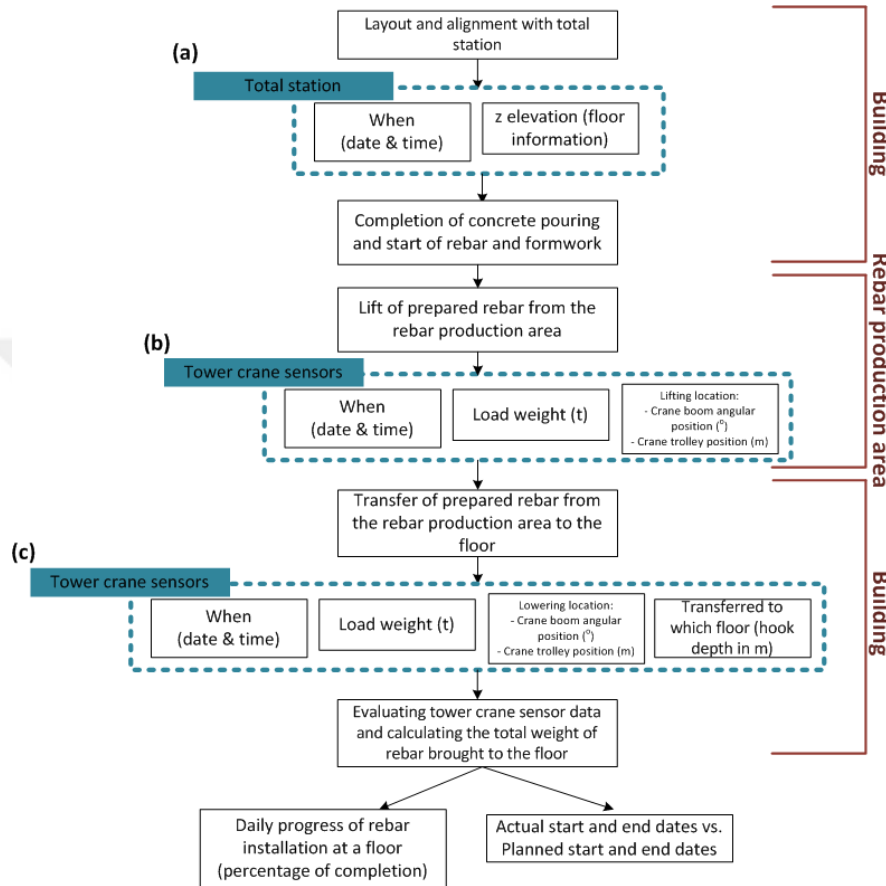


Figure 4.53 : Tracking of rebar installation work flow diagram.

- **Analyzing the tower crane data and evaluating the progress and performance of the activity:** Load lifting activities in between the rebar cutting and bending area and the building are examined in terms of (1) the total weight of the rebar brought to the building on each day, and (2) actual start and end dates. This enables calculating the daily progress of the rebar installation (i.e., percentage of completion) and comparing the planned and actual dates for the rebar installation.
 - First evaluation is to understand the total time the tower crane spent on the rebar installation. More efficient utilization of tower crane among different trades could be possible if non-value adding activities

that will be identified by the investigation of the tower crane usage could be removed.

- Second evaluation calculates the amount of rebar transferred from the rebar cutting and bending area to the floor. Daily progress of rebar installation is calculated by comparing the amount of rebar brought to the floor with the total amount of rebar needed at the floor based on the rebar drawings (i.e., rebar quantity takeoff). Total progress of rebar installation work is calculated at the end of the rebar installation work.
- Final evaluation is the comparison of the actual start and end dates of the rebar installation activity with the planned start and end dates obtained from the schedule. Based on being behind or ahead of the schedule, schedule updates are performed.

4.2.3.1 User interface developed for monitoring rebar installation

Tower crane sensors user interface as explained in Chapter 4, Section 4.1.3.2 were utilized for processing the tower crane data for monitoring the rebar installation and steel component transfer to installation area activities.

When the tower crane is used for transferring rebar from the rebar cutting and bending area to the building, interface enables determining the time and date of:

- Activities related to the rebar installation, the floor at which the rebar installation is performed,
- Rebar installation performed at a floor.

As explained in detail in Chapter 4, Section 4.1.3.1, the user interfaces separately developed for collecting and processing data from the RFID system, the wireless accelerometer, tower crane sensors and the total station were combined for data fusion and a user interface was developed for integrating data from these different data sources. First tab of the general user interface performs the data fusion for monitoring the masonry work, and the second and third tabs perform the data fusion for monitoring the rebar installation and steel component transfer to installation area, respectively. As explained before, the progress monitoring for each selected activity is performed for each building floor and every building floor is evaluated separately. Figure 4.54 shows the user interface of the prototype application for monitoring the rebar installation using the developed data fusion approach. This user interface is

similar to the one designed for monitoring the masonry work, however, this interface includes a panel for total station data. Two panels are located on the user interface, one is for the tower crane sensors data and the other is for receiving the total station data. Also, the user can manually enter the planned start and end dates from the screen.

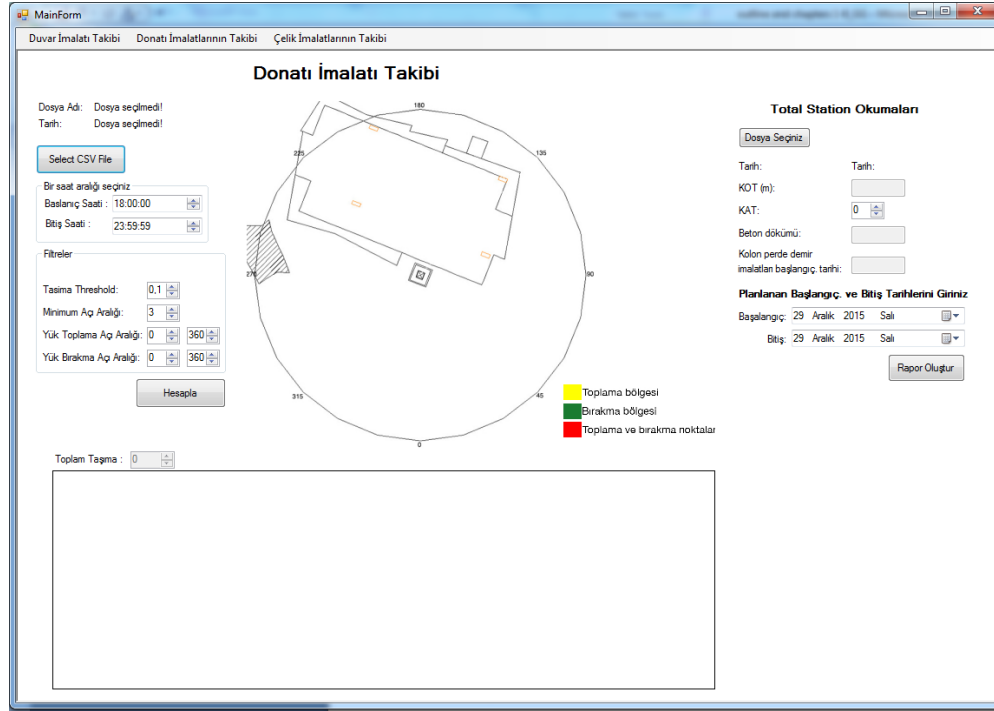


Figure 4.54 : User interface of the prototype application for monitoring the rebar installation work using the developed data fusion approach.

- The user manually enters the floor's rebar quantity takeoff from the related project document, and the planned start and end dates for rebar installation work is obtained from the schedule and manually entered to the interface.
- The user selects the total station file. Z elevation and date of layout and alignment are extracted from the total station records and total station panel automatically fills up with the following information:
 - z elevation (i.e., floor) is used to identify the floor at which the structural works are complete at the lower floor and rebar installation has started at the current floor, and when.
- User selects the tower crane sensor data file in CSV format. Total station load lifting activities are automatically extracted from the daily tower crane data.
 - User manually applies filtering if necessary, for example, the angular position of the rebar cutting and bending area (i.e., 240-280 degrees)

is entered to filter the lifting activities starting from the rebar production area. User can also filter the load lowering positions to automatically identify the loads lifted from the rebar production area and brought to the floor.

- Among the listed load lifting activity results, user can apply further filtering if necessary (e.g., removing lifts under a certain weight from the list).

Progress evaluation:

The total amount of rebar lifted from the rebar cutting and bending area and transferred to the floor for the identified time frame is calculated from the tower crane sensor data. Daily progress of rebar installation is calculated by comparing with the rebar quantity takeoff. Finally, total percentage of completion is calculated by adding up daily progress values (Figure 4.55).

Schedule comparison includes the same steps with the masonry work schedule evaluation as explained in Chapter 4, Section "4.1.3.2 User interface developed for monitoring masonry work".

The screenshot shows a software window titled "DonatıİmalatıRapor". Inside, there is a section titled "İlerleme durum değerlendirmesi" with a sub-header "İlerleme durumu değerlendirmeleri:". Below this, two lines of text provide progress updates: "15.04.2015 tarihinde 25. katın beton dökümü tamamlanmıştır." and "16.04.2015 tarihinde 26. katta başlanan donatı imalatlarının %100'ü 20.04.2015 tarihinde tamamlanmıştır." Below the text is a section titled "İş programı ile kıyaslama" containing four date pickers: "Planlanan başlangıç:" (16.10.2014), "Planlanan bitiş:" (17.10.2014), "Gerçeklenen başlangıç:" (16.04.2015), and "Gerçeklenen bitiş:" (20.04.2015). At the bottom, there is a red bar chart with two bars of different heights, and text indicating that the actual start date is later than the planned end date and that the performance is 5 days per floor.

Figure 4.55 : User interface of the prototype application for monitoring masonry work progress results.

4.2.4 Validation: Field tests and results for masonry work

Rebar installation is monitored at floors 27 to 32 floor building in Site 1 for nearly three months by tracking the data collected with the total station and tower crane sensors. As the rebar transfer from the rebar cutting and bending area to the building

was performed both during the daytime and nighttime, the tower crane data was continuously collected at both shifts. The process is explained in detail for the 27th floor, and the overall results for all floors are examined in detail in the following paragraphs.

- Z elevation (floor number) and date are extracted from the total station data for the 27th floor (i.e., 182.00 m and April, 9). Date of the measurements performed with the total station is used to understand the end date of the structural works at the lower floor and start date of the rebar installation work at the current floor. For example, total station measurement date is April, 9 and this indicates that the concrete pouring at the lower floor is completed on April 8, and rebar installation started on 11th of April.
- From this date on, the load lifting activities starting from the rebar cutting and bending area and ending at the building are identified. The rebar installation at 27th floor was performed on April 11-22, 2015. The planned start and end dates for 27th floor was entered as October 23-28, 2014 by the user. This comparison shows that the actual start date is after the planned end date and the rebar installation work is late for about 6 months. The schedule needs to be updated accordingly.
- Planned performance of the rebar installation work in the schedule was 6 days/floor, while the actual performance is identified as 11 days/floor and lower productivity rates are observed (Figure 4.56).

Donatı İmalatı Raporu

İlerleme durumu değerlendirilmesi

İlerleme durumu değerlendirmeleri:

- 08.04.2015 tarihinde 26. katın beton dökümü tamamlanmıştır.
- 11.04.2015 tarihinde başlanan donatı imalatları 22.04.2015 tarihinde tamamlanmıştır.
- İlerleme yüzdesi: %97

İş programı ile kıyaslama

Planlanan başlangıç:	23.10.2014	Planlanan bitiş:	28.10.2014
Gerçeklenen başlangıç:	11.04.2015	Gerçeklenen bitiş:	22.04.2015

Gerçekleşen başlangıç tarihi planlanan bitiş tarihinden sonradır.

Gerçekleşen performans: 11gün/kat

Figure 4.56 : User interface of the prototype application for monitoring rebar installation progress results.

Table 4.10 : Rebar installation progress at floors 27-32 and actual performances.

Floor number	Date	Total weight of rebar transferred in a day (kg) (from tower crane sensors) (A)	Rebar quantity takeoff (kg) (Q)	Estimated progress (%) (A/Q)	Ground truth
27	11.04.2015	4100	88984	5%	8%
	12.04.2015	8400		14%	24%
	13.04.2015	7636		23%	36%
	14.04.2015	16700		41%	36%
	15.04.2015	464		42%	39%
	16.04.2015	8300		51%	45%
	17.04.2015	3200		55%	45%
	18.04.2015	10600		67%	45%
	19.04.2015	7900		76%	45%
	20.04.2015	14900		92%	67%
	21.04.2015	2900		96%	85%
	22.04.2015	3000		99%	99%
28	17.04.2015	3200	88984	4%	7%
	18.04.2015	10600		16%	25%
	19.04.2015	7900		24%	39%
	20.04.2015	14900		41%	39%
	21.04.2015	2900		44%	39%
	22.04.2015	3000		48%	39%
	23.04.2015	9700		59%	46%
	24.04.2015	6000		65%	46%
	25.04.2015	4100		70%	46%
	26.04.2015	8556		80%	64%
	27.04.2015	7200		88%	84%
	28.04.2015	7100		96%	99%
29	24.04.2015	6000	88984	7%	6%
	25.04.2015	4100		11%	21%
	26.04.2015	3844		16%	30%
	27.04.2015	7200		24%	30%
	28.04.2015	7100		32%	30%
	29.04.2015	11500		45%	37%
	30.04.2015	5400		51%	45%
	01.05.2015	5000		56%	45%
	02.05.2015	7668		65%	64%
	03.05.2015	14400		81%	81%
30	04.05.2015	6600	88984	89%	100%
	01.05.2015	5000		6%	19%
	02.05.2015	6532		13%	37%
	03.05.2015	14400		29%	37%
	04.05.2015	6600		37%	37%
	05.05.2015	14800		53%	46%
	06.05.2015	5500		59%	46%
	07.05.2015	12213		73%	58%
	08.05.2015	10000		84%	75%
31	09.05.2015	11300	85869	97%	98%
	06.05.2015	5500		6%	16%
	07.05.2015	5487		13%	25%
	08.05.2015	10000		24%	25%
	09.05.2015	11300		38%	25%
	10.05.2015	11500		51%	35%
	11.05.2015	1000		52%	46%
	12.05.2015	10700		65%	46%
	13.05.2015	1400		66%	46%
	14.05.2015	23800		94%	72%
32	15.05.2015	3672	86571	98%	99%
	12.05.2015	10700		12%	15%
	13.05.2015	1400		14%	32%
	14.05.2015	23800		41%	32%
	15.05.2015	1728		43%	37%
	16.05.2015	3800		48%	37%
	17.05.2015	4800		53%	47%
	18.05.2015	9800		65%	47%
	19.05.2015	1400		66%	60%
	20.05.2015	21900		92%	83%
32	21.05.2015	1500		93%	99%

Table 4.10 reports the daily and total progress monitoring results for floors 27 to 32 and the actual performances of each floor (i.e., day/floor). For each day, the total weight of the rebar transferred from the rebar cutting and bending area to the floor is obtained from the tower crane sensors.

Daily progress estimation is calculated by comparing the rebar quantity takeoff with the amount of rebar transferred to the floor on each day. Although the rebar installation is 100% complete for each floor before the rebar installation starts at the upper floor; a ground truth for each day's progress is necessary for comparison with the daily progress estimations of the developed approach. Therefore, the daily estimations of the developed approach are compared with the daily progress that is calculated from the number of personnel working in rebar installation on a particular day. First, the total man-hour that is required for the whole rebar installation work to be completed is calculated for the tracked floors. Then, the amount of rebar installation work that one worker can perform within one working hour is calculated for each floor (i.e., ton/man-hour). Finally, the number of personnel that is recorded to be working on each day at the rebar installation is multiplied with this value, and the result is compared with the rebar quantity takeoff to calculate the amount of work completed on that day (i.e., daily progress). This was the ground truth for measuring the performance of the developed approach in determining the actual progress of rebar installation work.

Rebar installation work progress can be predicted with an average of 95% accuracy. Only at one floor (i.e., 29th floor) the developed approach estimated the progress as 89%, although the work was actually 100% complete. This might be due to the technical and environmental factors that affect the success of tower crane sensors (e.g., sensor sensitivity, impact of lifting and lowering movements on the measured load, impact of wind, friction, and weather factors on load). Excluding that one faulty estimation, the average variance of the remaining five floors is 0.09% and the average standard deviation is 3.0%. If the 89% estimation is included, then the average variance is 0.25% and the average standard deviation is 5.0% for the six floors. Results demonstrate that the developed approach can successfully be used to monitor the progress of rebar installation.

4.3 Steel Component Transfer to Installation Area Case Study

Site 1 includes the construction of reinforced concrete buildings, however, these buildings have some parts that include steel components. The following paragraphs provide the steps performed for steel component transfer to installation area:

- Steel components are ordered and produced according to the drawings.
- Upon completion of their production, steel components are delivered to site and received by the personnel in charge. Steel components are stored in a laydown area close to the building to be stocked for a short time before being installed.
- Tower crane is used to lift the steel components from the laydown area to the installation location on the building. Installation of steel components are usually performed within the same day.
- These steel components are either one piece or consists of several pieces and the installation is completed by welding the steel pieces to each other or bolting the steel pieces to the concrete surface of the building based on the design requirements.

The developed approach estimates the steel component installation progress based on the amount of steel transferred to the installation area and the next section provides the details of the proposed approach.

4.3.1 Proposed approach for monitoring the steel component transfer to installation area

Data collected from the tower crane is used for monitoring the progress of steel component installation from the weight of the steel components transferred to the installation area. The proposed approach is to compare the weight of the steel components transferred to the installation area (e.g., 0.3 ton) retrieved from tower crane to the total amount of steel to be installed (e.g., 1.5 ton) from the budgeted quantity, and calculate a percentage of completion (e.g., 20%) based on the weight of the completed installation.

Since the installation of the steel components are usually performed within the same day as they are lifted with the tower crane from the laydown area, the proposed

approach is a practical way of monitoring the progress of steel work. Although the scope of this study is limited to reinforced concrete buildings, this tracking approach is very suitable for steel construction and it is envisioned that this approach can be applied at steel construction sites efficiently. Activities in steel construction are more organized as opposed to reinforced concrete construction and similar activities are performed repeatedly, and therefore conditions are more favorable for usage of machinery and equipment at steel construction sites. Using only the weight of the steel component that is transferred to the installation area is necessary to determine the progress of the steel component installation, unless the building is a steel construction and/or a location-based progress tracking is necessary. In such case, all components or only the critical ones can be tagged and an RFID system can be included in the tracking process (e.g., by attaching a reader on the tower crane hook) for identification purposes.

Table 5.2 lists the data to be collected from the tower crane and summarizes the tracking approach developed for monitoring the steel component transfer to installation area. While the steel components are transferred from the laydown area to the installation location at the floor, following data is tracked from the tower crane sensors to observe the progress of the steel component installation based on the weight of the transferred steel: (1) weight of the load carried by the tower crane (in tons), and (2) load lifting activities of the tower crane started at the steel laydown area and ended at the installation location at the floor (Table 4.11).

Table 4.11 : Tracking approach developed for monitoring the progress of the steel component transfer to installation area.

Data collected from	Tracking method	Collected data	Data used and results obtained	Integration of results
Tower crane	- Angular position, trolley position and load sensors (on tower crane)	(A) Load weight (ton) (B) Angular position of the crane boom (degree) (C) Position of the trolley and the depth of the hook (m)	(A) + (B) + (C) = Identification of the steel component lifted by crane (A) = Weight of the lifted steel component	(A) / (D) = % of completion for steel component installation
Project related data sources	- Manual data extraction from related documents	(D) Steel quantity takeoff (tons)	(D) = Total amount of steel (tons)	

4.3.2 Prototype system design

Steel components are used as non-load bearing separation panels and roof joint components at the building. There were no steel component assemblies that have been scheduled and performed during the field experiments at the experiment building, however, the steel component delivery and assembly processes were observed at other buildings at Site 1. Therefore, the approach to monitor the steel installation progress was demonstrated using the data set that was fictitiously generated to illustrate the steel component transfer to installation area.

- *Tracking process:* Tower crane movements are tracked to identify the load lifting activities performed in between the steel laydown area and the building.
- *Data sources:* Tower crane sensors are used to collect data and calculate the total weight of steel component transferred from the laydown area to the installation location on building. The weight of the transferred steel component is compared with the total steel quantity takeoff to calculate the progress in terms of percentage of completion.
- *Data collection and storage:* As explained earlier, tower crane sensors collect data in real-time and can transfer the data wirelessly. However, during the prototype implementation, collected data was stored on an SD memory stick and then manually transferred to a local computer at the site office.

Preliminary work:

- Since the readily available data collection methods are utilized, no preliminary work, such as tagging, is necessary. However, the quantity takeoff of steel work should be obtained from the drawings.

Steps for monitoring the progress of steel component installation are provided in the following paragraphs and illustrated in Figure 4.57.

- **Delivery of steel components to site:** Steel components are delivered to site with trailers and stacked at a laydown area near to the building at which the installation of the components will be performed (Figure 4.57-a).

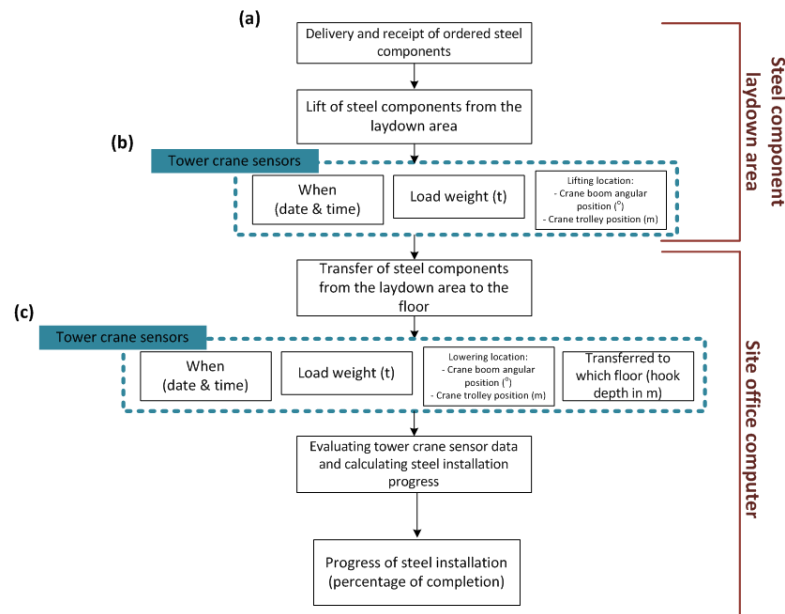


Figure 4.57 : Tracking of steel component transfer to installation area work flow diagram.

- Lifting the steel components from the laydown area:** Steel components that have been stacked in the laydown area are securely tied with thick ropes to the tower crane's hook and lifted with the tower crane (Figure 4.57-b). As in the tracking processes of other activities, load lifting activities of tower cranes are identified and filtered based on the angular position (i.e., 60-70 degrees) of the lifting location (i.e., steel laydown area). The median of the weight of the load is calculated to determine the weight of the load being carried in each lifting activity (Figure 4.57-b).
- Lowering the steel components at the installation area:** For the identified load lifting activities, the lowering locations are determined. By tracking the depth of the crane hook, the floor at which the steel component is lowered is identified (Figure 4.57-c).
- Analyzing the tower crane data and evaluating the progress and performance of the activity:** Each load lifting activities related to the transfer of steel components from the laydown area to the installation location were examined in terms of the weight of the load carried.
 - The weights of the steel components carried by the tower crane (e.g., 2.5 ton and 3 ton) are compared with the steel quantity takeoff (e.g., 10 ton), and the steel installation progress is calculated in terms of percentage of completion (e.g., 55% for this example).

4.3.2.1 User interface for monitoring steel component transfer to installation area

Third tab of the user interface is designed for monitoring the steel component transfer to installation area. When the tower crane is used for transferring steel components from the laydown area to the installation location on the building, the interface enables determining (1) the time and date of steel component transfer to the installation area, and (2) the amount of steel component transfer to installation area to calculate the steel component installation progress by comparing the weight of the transferred components to the overall steel quantity takeoff.

This interface includes a panel for visualizing and processing the tower crane data and a separate area for the user to manually enter the total steel quantity takeoff (Figure 4.58).

- The user manually selects the tower crane data in CSV format and as in the tracking process of other activities, the load lifting activities are identified.
- Based on the time interval manually selected by the user and the filtering on the lifting location angles to sort the load lifting activities that start from the steel component laydown area; the loads that are lifted from the steel component laydown area are listed.
- The user also manually enters the steel quantity takeoff.

Progress evaluation:

As explained earlier, only the weight of the steel component that is transferred to the installation area is necessary to determine the progress of the steel component installation. By comparing the weight of the steel component transferred to the installation area to the overall load of the steel components in the project; a percentage of completion is calculated. The user is notified with a message written on the results screen "Steel component is carried to the installation location on (date of installation), (percentage) % of the steel work is completed".

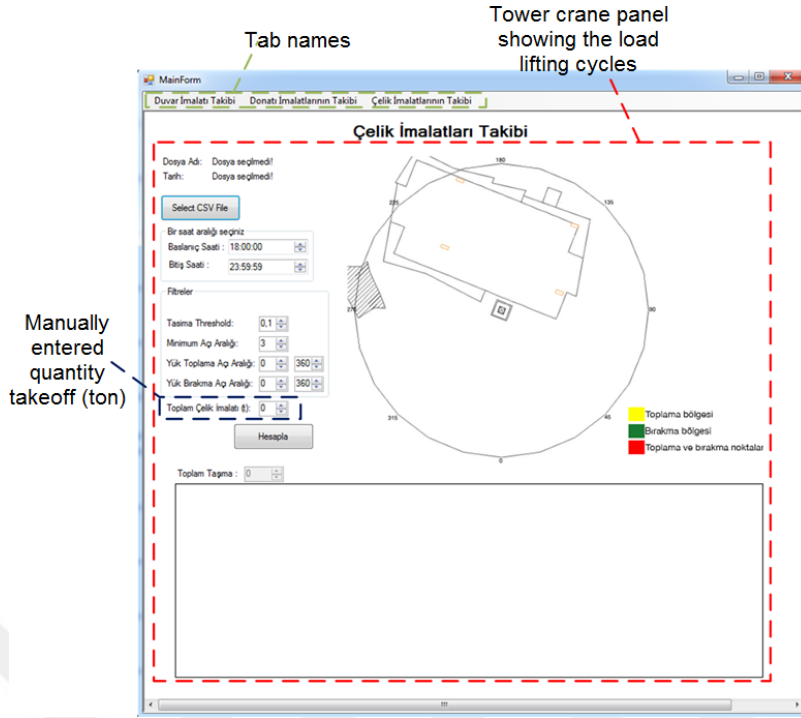


Figure 4.58 : User interface of the prototype application for monitoring the steel component transfer to installation area using the developed data fusion approach

4.4 Conclusions

A physical prototype that meets the functional requirements identified in the previous chapters was developed and implemented at a construction site by using the data fusion approach given in Chapter 3. The field experiments demonstrated that the prototype system was successful in determining the progress of the masonry work and rebar installation work by using the developed reasoning mechanisms. The results validated the functional requirements identified for the selected technologies and the developed data fusion approach.

Field tests for the masonry work illustrated the feasibility of the proposed automated approach that integrated RFID, tower crane sensors and wireless accelerometer data for tracking masonry work progress in a building. The prototype system implemented during the tests involved all the features of the envisioned conceptual system except the accelerometer. Fictitious data was generated for the accelerometer in the field tests as data collection could not be performed using the wireless accelerometer at site due to technical difficulties.

The performance of tower crane sensors in correctly identifying the amount of material delivered to eight floors that were monitored during the field experiments

had 99% precision, %100 recall and the f-measure was 99%. Based on the tower crane sensor and RFID data that were integrated (i.e., material delivered - material utilized), the performance of correctly identifying the amount of material left at the floor in seven floors out of eight had 84% average precision, 99% average recall and 90% average f-measure. Only in one floor out of eight, the prototype system was unable to identify the number of remaining pallets at the floor as it calculated all the delivered material was utilized and all pallets were removed from the floor, although two pallets actually remained at the floor.

The results showed that, by fusing the data from tower crane sensors (i.e., the amount of material delivered to the floor) and from the RFID (i.e., the amount of material utilized at the floor), masonry work progress can be predicted with an average of 96% accuracy. It has been demonstrated that the developed approach can successfully be used to monitor the progress of masonry work.

A rule-based reasoning is developed based on the data fusion approach for monitoring the rebar installation and field tests were performed for validating the developed approach. During the field tests, monitoring of rebar installation at floors 27 to 32 was performed. The progress and performance of the rebar installation activity was estimated based on the data obtained from the tower crane sensors and total station data. The developed approach estimated the rebar installation progress daily, by comparing (1) the total weight of rebar brought to the floor, with (2) the rebar quantity takeoff of the floor. Every load lifting activities on each working day were identified from the tower crane sensor data and total weight of rebar transfer for each day was calculated. This is then compared with the quantity takeoff to estimate the daily progress.

The developed approach was able to estimate the rebar installation progress with 95% accuracy at six floors (i.e., average of six floors). Only at one floor (i.e., 29th floor) the developed approach estimated the progress as 89%, although the work was actually 100% complete. Excluding that estimation, the average variance of the remaining five floors is 0.09% and the average standard deviation is 3.0%. If the 89% estimation is included, then the the average variance is 0.25% and the average standard deviation is 5.0% for the six floors. Results demonstrate that the developed approach can successfully be used to monitor the progress of rebar installation.

Fictitious data was generated to represent the movements of a tower crane transferring a steel component from the laydown area at site to the installation location on the building. This data was used to demonstrate how such data is used to monitor the progress of steel component installation and the necessary reasoning mechanisms were described. The approach developed for monitoring the progress of steel component installation compares the weight of the steel component that is transferred to the installation area, with the total weight of the steel project and calculates a percentage of completion.

Results of the field tests revealed that there are some environmental and technological factors affecting the success of tower crane sensors, and these can be listed as: the sensitivity of the sensors that collect information about the angular position, load and distance of the tower crane and the trolley; impact of acceleration of the tower crane on the load being carried during the lifting and lowering movements (e.g., measured weight of the load varies due to the speed of lifting and lowering actions); impact of wind, friction, and weather factors on the load and other collected parameters at the time of lifting and lowering.

The following paragraphs list the advantages of the proposed approach:

- Closely monitoring the site by knowing the amount of material (1) delivered to the site, (2) transferred to the floor, and (3) left at the storage,
- Accurately monitoring the progress of the activities,
- In the case of masonry work, calculating the amount of wasted material realistically by comparing the actual amount of material utilized at the floor and the amount of material planned to be used at the floor based on the quantity take-off,
- Enabling mechanisms to notify the contractor when more wasted material is detected than acceptable values specified in the contracts (e.g., 2%).

When such a monitoring system is not available, such information can only be determined at the end of the activity. As the material is continuously supplied to the site, it is very difficult to keep a realistic track of the amount of material transferred to floors and left in site stocks, and to know how much more material is needed and how much material is wasted. Especially, at sites as big as Site 1, at which the field experiments were conducted, capturing the progress of the activity and the amount of material left at the stock necessitates collecting and fusing data from multiple parties

and data sources, which are fragmented in nature. Moreover, there is a lack of communication among parties and personnel in charge. For example, the dispatch note of the delivered material is sent to the technical office, material transfer to floors is managed by foremen, material allocation is performed by the site engineer. This aggravates the process for manual data collection and merging.

For being able to track the material left at the stocks and at the floors without such a tracking system proposed in this study, more than one person is presumably needed to be assigned with this job and he/she must have the necessary skills to take notes and make site observations properly. Considering such activities are simultaneously being performed at multiple floors within the same time period, monitoring can become quite complex. Also, due to bad writing skills and irregular entries, it is highly likely to have left with incorrect and missing data. Taking into account the extra labor cost that such a manual system will bring, it is invaluable to have collected the site information related to the progress of ongoing activities without the need for the technical office personnel to go out to the site.



5. DISCUSSIONS

This section discusses the findings of the study, evaluates the implementation cost of the developed approach, and provides the details of the main steps that are needed to be applied for implementing and using the developed approach.

Findings of the study

Traditional methods for progress monitoring are problematic as they are based on manual data collection from visual site investigations and paper-based notes. Progress estimations are made based on their personal experience and the findings show that progress tracking cannot be performed effectively especially at large-scale sites where different subcontractor crews and trades work simultaneously.

Monitoring the project is even more problematic in double-shift construction projects. However, literature review reveals that no attention was given to monitor both the daytime and nighttime work, and instead, the existing studies focused on monitoring of the daytime work only. Moreover, equipment tracking were performed for large construction equipment mostly for monitoring the earthmoving and excavation activities and the potential of equipment tracking for progress monitoring in building construction has been overlooked. The aim of this study is to fill this gap by tracking equipment used in building construction to monitor progress of activities in both daytime and nighttime work.

An equipment-tracking based activity monitoring approach was proposed in this study and the following equipment and activities were selected to develop this approach: (1) Tower crane, elevator, hand drill and wall block material pallets are tracked for monitoring the progress of masonry work, (2) tower crane and total station are tracked for monitoring the progress of rebar installation, and finally, (3) tower crane is tracked to monitor the progress of the steel component installation by tracking the steel component transfer to installation area.

The main objective was to develop an approach that will perform both during the daytime and nighttime. Therefore, the following high-level requirements for the

technologies to be used at a double shift construction site were identified: (1) working under different lighting conditions, (2) internal power source and/or need for minimal or no wiring, (3) cost-efficiency, (4) having minimal worker input and interference with existing work flows, (5) ability to track multiple activities, (6) physical durability, and (7) non-line-of-sight and long reading distance.

Based on the high-level requirements sensor-based technologies were selected and technology-specific requirements were identified for each technology selected. A passive RFID system was selected for tracking the elevator and the materials (i.e., brick) that were carried by the elevator. The selected RFID system was able to meet the requirements related to the reading range and installation configuration based on to the geometry of the elevator and distances from the tagged items. Initial tests also demonstrated the need for an additional power supply and a better method to fix the tags to objects, as well as the need to filter redundant tag readings.

A wireless accelerometer was designed to be installed on a hand drill to track the idle and working times of the hand drill. The components were located in an encasing to keep them together while attached on the hand drill and to enable working on its own batteries, as indicated by the identified requirements.

Functional requirements were also determined for the sensors that track the position of the tower crane and the loads (e.g., wall block material pallets for masonry work, pieces of rebar and steel components) carried by the crane. Tests demonstrated that the angular position sensor on the crane boom and the position sensor on the trolley, both of which are sensors of the anti-collision system on the tower crane, provided the tower crane position on the site layout plan in 2D (i.e., x and y coordinates) at a given time. This positioning information was combined with the load sensor data and the 2D location of points at which the tower crane started and ended a specific lifting activity were identified. Since the identified requirement was to collect the coordinates in 3D, the depth of the hook (i.e. building floor which the material was carried to) was recorded manually during the tests. However, in the future, this data can be automatically collected by mounting a depth sensor or a separate GPS unit on the crane hook.

Finally, for the total station device that will be used to track the beginning of rebar production activity at a particular floor of a building, no additional means of sensor-

based tracking was deemed necessary. The functional requirements were determined as to have on-board data storage capability and ability to store data in different formats. The initial tests demonstrated that these requirements are met by a regular total station device that are in use in most of the construction sites.

Based on the identified functional requirements and selected technologies, the reasoning mechanisms for data fusion were developed. The findings of the data fusion literature review show that a generalized approach for data fusion for construction industry applications have not yet been developed and every study developed customized approaches to solve the data fusion problem at hand. On the other hand, Pradhan and Akinci (2012) developed a taxonomy of reasoning mechanisms to fuse a pair of spatial and temporal data sources to support construction productivity monitoring in road excavation projects using either space (i.e., spatial) or time (i.e., temporal) information. The data fusion approach developed in this study is built on this existing taxonomy of reasoning mechanisms to fuse the data collected from construction equipment for monitoring the progress of activities in double shift construction sites. However, since the data sources defined and the reasoning steps described in the previous study were not sufficient for the purpose of this study; a new non-spatiotemporal data source (i.e., physical property) was proposed for construction activity monitoring, and the existing taxonomy of reasoning mechanisms was extended.

Physical property data source was defined as the new data sources that measure and/or collect the physical properties (e.g., weight, volume, color, texture, physical shape, material) of entities (e.g., material, human, equipment), regardless of the time and space of the data collection. Three types of reasoning mechanisms, namely (1) data extraction, (2) data transformation, and (3) data merging, were already described in the existing reasoning mechanisms for spatial and temporal data sources. A new step was added to the existing taxonomy, named data interpretation, for interpretation of the non-spatiotemporal data sources used in construction activity tracking applications. Two types of data interpretation were defined and implemented in this study: (1) transformation of physical properties (e.g., weight) into objects (e.g., brick, rebar), and (2) transformation of physical properties (e.g., velocity) into states of objects (e.g., moving or static). Also, a new data merging step, named rule-based

reasoning, that is applicable to all types of data sources was added to the existing taxonomy.

Based on the developed data fusion reasoning mechanisms, a physical prototype that meets the identified functional requirements was developed and implemented in field experiments at a double shift residential project. Field tests for the masonry work illustrated the feasibility of the proposed automated approach that integrated RFID, tower crane sensors and wireless accelerometer data for tracking masonry work progress in a building. The prototype system implemented during the tests involved all the features of the envisioned conceptual system except the accelerometer. Fictitious data was generated for the accelerometer in the field tests as data collection could not be performed using the wireless accelerometer at site due to technical difficulties. The results showed that, by fusing the data from tower crane sensors (i.e., the amount of material delivered to the floor) and from the RFID (i.e., the amount of material utilized at the floor), masonry work progress can be predicted with an average of 96% accuracy. It has been demonstrated that the developed approach can successfully be used to monitor the progress of masonry work.

The field tests were performed for monitoring the rebar installation at the test building at floors 27 to 32 using the data obtained from the tower crane sensors and total station. The developed approach estimated the rebar installation progress on a daily basis, by comparing (1) the total weight of rebar brought to the floor, with (2) the rebar quantity takeoff of the floor. It was possible to estimate the rebar installation progress with 95% accuracy at six floors (i.e., average of six floors) and the results demonstrated that the developed approach can successfully be used to monitor the progress of rebar installation.

Fictitious data was generated to represent the movements of a tower crane transferring a steel component from the laydown area at site to the installation location on the building. This data was used to demonstrate how such data is used to monitor the progress of steel component installation and the necessary reasoning mechanisms were described. The approach developed for monitoring the progress of steel component installation compares the weight of the steel component that is transferred to the installation area, with the total weight of the steel project and calculates a percentage of completion.

The field experiments demonstrated that the prototype system was successful in determining the progress of the masonry work and rebar installation work by using the developed reasoning mechanisms. The results validated the functional requirements identified for the selected technologies and the developed data fusion approach. The field tests also revealed that there are some environmental and technological factors affecting the success of tower crane sensors, and these can be listed as: the sensitivity of the sensors that collect information about the angular position, load and distance of the tower crane and the trolley; impact of acceleration of the tower crane on the load being carried during the lifting and lowering movements (e.g., measured weight of the load varies due to the speed of lifting and lowering actions); impact of wind, friction, and weather factors on the load and other collected parameters at the time of lifting and lowering.

Implementation and utilization of the developed approach

For the practitioners who are willing to implement and/or use the developed approach at a job site, the flowcharts given in Figure 5.1 and 5.2 were prepared to provide the main steps. These steps are not necessarily sequential, however, should be considered before implementing or using the developed approach at site. The first step of implementation is deciding on which activity to be tracked using the developed approach (Figure 5.1). Based on this decision, the availability of the necessary construction equipment used in the development of the prototype system in this study (e.g., tower crane, elevator, hand drill, total station) is checked.

The available construction equipment for the intended activity to be tracked should be checked whether any means of readily available data collection and storage are available on the equipment. The practitioners are encouraged to use the available means of data collection and storage on construction equipment as much as possible to enable more economic configuration. These might be the load and angle sensors on tower cranes, the internal data collection and storage capabilities of a total station, or an OBI enabled equipment. If there are data collection systems available on equipment but no data storage is being performed, then the practitioners should look for ways to store the collected data (e.g., data logger, USB sticks, SD cards, wireless data transfer).

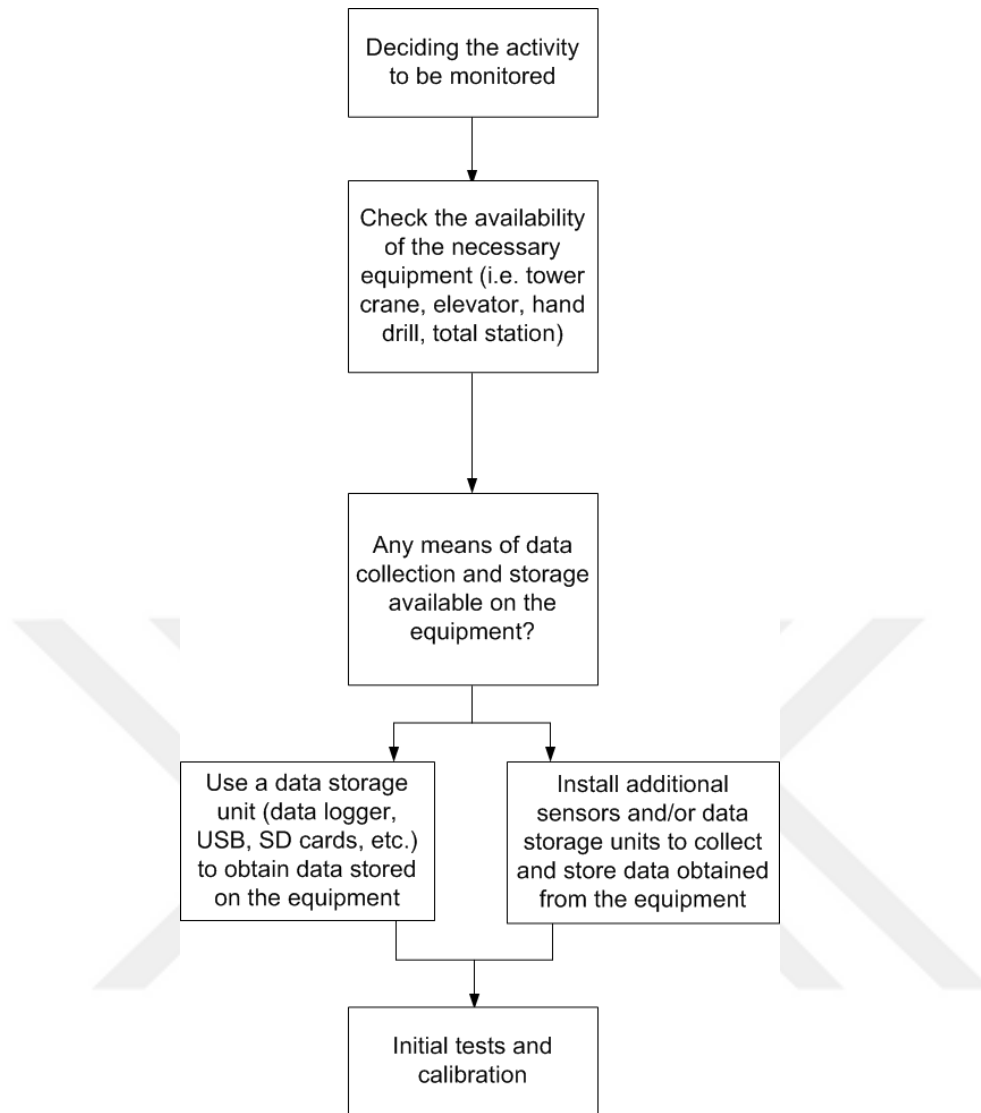


Figure 5.1 : Main steps for implementing the developed approach at a job site.

Also, the ability of the selected construction equipment to track multiple activities must be considered. If so, this will also assist in creating an economic configuration. In addition to the readily available means of data collection, additional sensors are deployed to the selected construction equipment following the implementation details described in this study. The initial tests and calibration of sensors must be performed before starting to collect data on activities. This also includes the adaptation of the user interface to the conditions of that particular construction site using the filters or by making minor adjustments to the code.

As the installation of the developed equipment tracking based approach for collecting data on intended construction activities, this is followed by the training the site office

personnel on how to use the interface and how to collect data manually from the internal data storage units of the equipment (Figure 5.2). By checking if wireless network connection is available at the site for that particular activity, the type of data retrieval is decided. If wireless connection is available, either methods can be used and manual data collection will be optional and can be used redundantly. Otherwise, the data stored on-board (e.g., data logger, USB, SD card) needs to be collected manually.

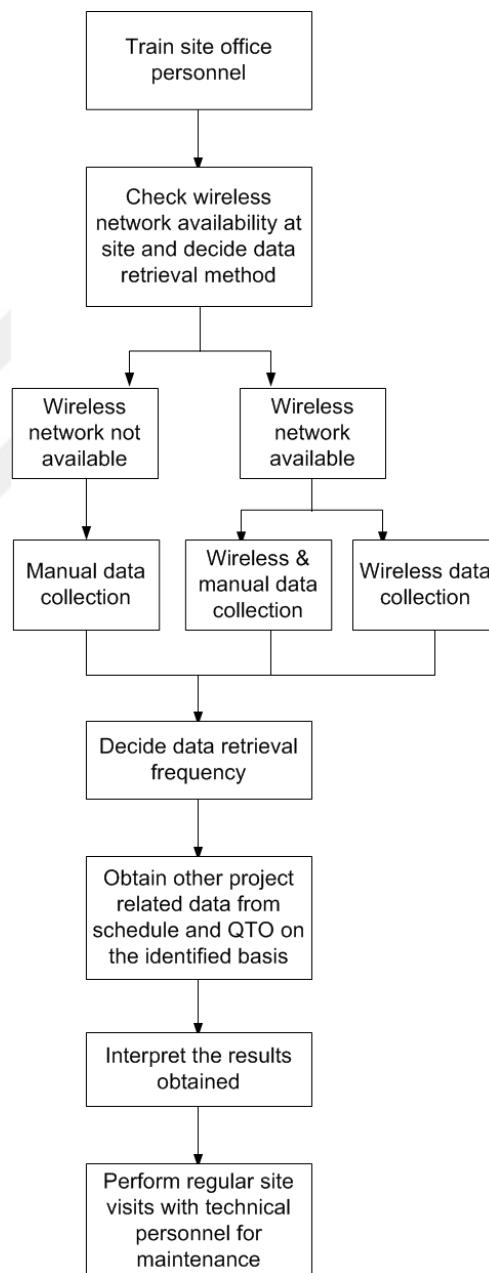


Figure 5.2 : Main steps for using the developed approach at a job site.

The practitioners must decide the data retrieval frequency (e.g., daily, weekly, etc.) to schedule a program for the trained personnel to use the data collected wirelessly or to visit the site to manually collect the data. In addition to the field data obtained from the equipment, other project related data (i.e., quantity take off, planned start and end dates) needed for the developed prototype to calculate the progress and schedule delays must be obtained from the related project documents. Every time the prototype provides results, the personnel in charge interprets the results and shares the findings and the insights with the management. Another step for the utilization of the prototype implemented at a site is the maintenance. The site office personnel in charge, must perform maintenance visits with a technical personnel (e.g., an electrician, a technician) on a regular basis, to ensure that the data collection is being performed smoothly. The frequency of such visits could be decided based on the weather and site conditions and other project dynamics.

Cost of the developed approach

To give some insights about the cost of implementing such a system to a building at a construction site, the cost of the components of the system was calculated. Including (1) a set of anti-collision system installed on a tower crane (i.e., \$ 14,500), (2) an RFID system configuration on an elevator (i.e., a Motorola FX7400 RFID reader, two MTI 242040 antennas, one Eurostar 12V 40Ah power supply, one Zyxel wireless bridge, one 10.1" notebook) (i.e., \$ 1,900), and (3) a wireless accelerometer kit on a hand drill (i.e., 3-axis accelerometer, Arduino Yun board, and custom design encasing) (i.e., \$290), the cost of implementing developed prototype at a site is around \$16,690. RFID tag costs (i.e., \$ 0.27 per tag) are negligible as the material pallets are assumed to be tagged at the fabrication stage. The monthly expenses for the electricity needed for the sensors deployed on the construction equipment are negligible, as well. No extra personnel is needed for using the developed equipment-based approach as one of the technical personnel available at the planning department of the site office could be trained to use the prototype interface. Similarly, no extra personnel is needed for the maintenance of the sensor-based equipment as an electrician or a technician currently working at the site can help the technical personnel from the site office for several repair works or to fix problems caused by, for example, power loss.

Considering the fact that if not such an automated progress monitoring method is utilized, at least one separate qualified personnel who is capable of correctly tracking the progress of particular activities is needed. Because in the current practice, no personnel is assigned only to track the progress of activities, and therefore, the progress cannot be monitored realistically and can only be determined at the end of the activity. The monthly cost of that qualified personnel to the construction project will be around \$ 1,700 (including salary, insurance, accommodation expenses and occupational safety expenses). On the other hand, there will always be the risk of human error in data collection, and health and safety issues. Considering such activities are simultaneously being performed at multiple floors within the same time period, monitoring can become quite complex. As the developed approach eliminates the need for an additional personnel to track the progress of activities at site, and since the cost of the prototype system can be lowered for mass applications, using the developed approach is more advantageous. The advantages of the proposed approach is listed as follows:

- Closely monitoring the site by knowing the amount of material (1) delivered to the site, (2) transferred to the floor, and (3) left at the storage,
- Accurately monitoring the progress of the activities,
- In the case of masonry work, calculating the amount of wasted material realistically by comparing the actual amount of material utilized at the floor and the amount of material planned to be used at the floor based on the quantity take-off,
- Enabling mechanisms to notify the contractor when more wasted material is detected than acceptable values specified in the contracts (e.g., 2%).

Utilizing the collected data for performing predictions

Another advantage of using the progress results obtained from the equipment data and calculated with the developed data fusion approach is the possibility to perform future projections for the monitored activities. This will enable performing realistic productivity analysis for the monitored activities. Consequently, schedules can be updated based on the results of the projections and timely solutions can be developed for productivity-related problems. Several methods (e.g., regression, artificial neural networks, genetic algorithms) have been used by researchers in the literature for estimating the productivity of labor (Portas and AbouRizk, 1997; Sonmez and

Rowings, 1998; AbouRizk et al., 2001; Dikmen and Sonmez, 2011), productivity loss caused by change orders (Cheng et al., 2015), and productivity of equipment and machinery (Karshenas and Feng, 1992; Chao and Skibniewski, 1994; Leung et al., 2001; Tam et al., 2004; Ok and Sinha 2006; Schabowicz and Hola, 2007; 2008; Hola and Schabowicz 2010).

Artificial neural networks are one of the most commonly used method in the literature to understand the relationship in between several factors, such as weather, crew size, type and capacity of equipment used, and the productivity. Artificial neural networks are based on the principle of how the human brain processes visual data and learns to recognize objects, and is configured for a specific application through a learning process (Dikmen and Sonmez, 2011). It has been stated in the literature that the most significant aspects of applying artificial neural networks in a practical application within an industrial setting are (1) defining the input factors and (2) collecting sufficient relevant data for training (AbouRizk et al., 2011). To built an artificial neural network, some of the collected data is used for training while some is used for testing. The data collection method proposed in this study provides an efficient way of collecting the necessary amount of data to be used for training and testing the artificial neural network model. However, the amount of data collected during the field tests is not sufficient to build a neural network to perform future predictions for understanding the productivity of monitored activities as it was observed in the previous studies that the databases usually included at least a hundred records. Since the weekly productivity is calculated for the masonry work for instance, this corresponds to collecting at least a hundred week productivity data to be used for training and testing. Another important point is that the factors affecting the productivity of the monitored activity should be collected (e.g., weather conditions, site conditions, availability of mateials) at the time of data collection. Therefore, investigating the feasibility of such prediction methods that can be used to effectively estimate the future productivity of activities based on the progress results calculated using the developed approach will be performed as a future work.

6. CONCLUSIONS

The main objective of this PhD research is to identify the requirements for monitoring the progress of activities in double shift building projects using construction equipment and to develop an automated sensor-based approach that tracks equipment for this purpose. To achieve this objective, high-level requirements were determined for data collection technologies to be used at double shift construction projects and appropriate sensor-based technologies were selected. Initial tests were performed to identify the technology-specific requirements for the selected sensor-based technologies. The reasoning mechanisms were developed for fusing the data collected from construction equipment and a prototype system was built. A physical prototype was implemented as a proof of concept, and field tests were performed for validating the developed approach in terms of determining the progress of (1) masonry work and (2) rebar installation at a double shift building construction project. On the other hand, progress monitoring of steel component installation was demonstrated over a fictitious data set that was generated to illustrate a steel component transfer to installation area activity.

The contributions and validations of the study, discussion of the method and the findings, expected practical implications and future studies are described in the following sections.

6.1 Summary of Contributions and Validations

Current project monitoring methods in construction sites are problematic and unreliable as they rely heavily on manual and paper-based data collected from field through visual investigation. Monitoring the project can be even more problematic in double-shift construction projects due to lack of supervision and nighttime working conditions. There is a need for automated tracking of construction progress for double shift projects and the developed approach need to function well both nighttime and daytime conditions. This research has been targeted to develop an

approach that will enable continuous monitoring of both day and night shifts in a reinforced concrete building construction project, ensuring that the construction resources (material, labor and equipment) are used effectively throughout the shifts and hence, the intended productivity levels are achieved. Previous studies on automated progress monitoring at construction sites focused only on monitoring of daytime work. Additionally, the potential of construction equipment that are utilized at different stages of a construction activity in providing information about the progress of that on-going activity has been overlooked.

The first contribution is the identification of equipment tracking requirements, and this includes identification of the activities to be monitored, identification of the equipment to be tracked and the related parameters to be collected from the equipment, and determining the high-level requirements for data collection technologies to be used at double shift construction sites.

Once the high-level requirements were identified, technologies that meet these high-level requirements were selected. Second contribution is determining the technology-specific requirements for each technology selected by conducting initial tests with the selected technologies in a double shift construction site.

Based on the identified technology-specific requirements, the reasoning mechanisms were defined for integrating the data collected from the sensor-based technologies. To achieve the equipment tracking-based activity monitoring vision of this PhD research study, data obtained from several construction equipment via sensor-based technologies are needed to be fused with project related information, such as quantity takeoffs, schedules and site reports. These different data sources provide data at different time intervals and are fragmented in nature. The third contribution is developing the reasoning mechanisms and a data fusion approach to fuse this fragmented data in a complementary and supporting fashion for monitoring the progress of construction activities.

To validate the identified requirements and reasoning mechanisms developed for monitoring the progress of activities in double shift building projects with sensor-based tracking approach; a prototype was developed. The prototype was implemented at a double shift building construction site and field tests were performed.

The following paragraphs describe each contribution in detail.

Contribution 1: Identifying the equipment tracking requirements for progress monitoring at double shift construction sites

The studies that track equipment at construction site exist in the literature; however, studies for tracking equipment that is used in building construction are limited. A few studies focused on monitoring the movements of a couple of equipment, such as cranes and elevators, for identifying the activities performed and for tracking productivity (Gong and Caldas, 2009; Costin et al., 2012; Yang et al., 2012). There are currently no studies that tracked construction equipment that is used in building construction both during the daytime and nighttime and collected data on productivity and progress of activities.

In this study, the first contribution is identification of equipment tracking requirements for progress monitoring at double shift reinforcement concrete building projects. This includes identification of (1) the activities to be monitored, (2) the equipment to be tracked, (3) the parameters (of the related equipment) to be tracked, and (4) the high-level requirements for data collection technologies to be used at double shift construction sites. The following activities and the related equipment were identified: (1) For tracking the progress of the masonry work: elevator, tower crane, hand drill, and wall block material pallets were selected to be tracked. (2) For tracking the progress of rebar installation: tower crane and total station were selected. (3) For monitoring the progress of the steel component installation, tower crane was selected. Finally, a set of high-level requirements were determined for data collection technologies to be used at double shift construction sites and appropriate technologies were selected based on the determined high-level requirements. This ensures that data collection is continuously performed both through the day and night shifts; enabling to capture different types of achievements in different shifts (e.g., material handling in the night shift, and installation and production in the day shift).

Activities, equipment and related parameters were determined and technology-independent requirements were identified for tracking construction equipment with the purpose of progress monitoring of activities at reinforcement concrete building projects. This contributes to the current knowledge by providing a basis for future studies that will develop new approaches and design new systems for progress

monitoring by tracking equipment. Validation of the equipment tracking requirements for the selected technologies were performed with field tests that were conducted in a double shift construction site. The details of the field tests were given in Chapter 4 for the masonry work and the rebar installation.

Contribution 2: Identifying the technology-specific requirements for the selected sensor-based technologies

As stated in the previous section, no previous studies tracked construction equipment that is used in building construction for progress monitoring during the daytime and nighttime. Thus, requirements for sensor-based technologies were not identified for this purpose. In this study, once the appropriate technologies that meet the determined high-level requirements were selected, initial tests at site were performed with the selected technologies, and the technology-specific requirements were determined for: (1) A passive RFID system that was implemented on an elevator for tracking the elevator and the materials (i.e., brick) that were carried by the elevator, (2) a wireless accelerometer installed on a hand drill, (3) position and load sensors of a tower crane's anti-collision system, and (4) a regular total station.

Initial tests showed that all technologies were able to meet the identified functional requirements. Also, during the initial tests, new requirements were identified for the RFID system, such as the need for additional power supply and a better method to fix the tags to objects, as well as the need to filter redundant tag readings. Additionally, it was observed that the existing anti-collision system only provides 2D information and the crane's position in the z coordinate cannot be collected. Therefore, the building floor which the tower crane carried loads to, was manually recorded during the field tests to meet the primary functional requirement for the tower crane (i.e., determining the position of the tower crane when a load is lifted and lowered).

The technology-specific requirements identified in this study will provide a basis for future equipment tracking studies that will utilize the selected technologies. Using the identified functional requirements for the selected technologies, other researchers can develop new systems at double shift construction sites using the selected technologies and the related technology-specific requirements. The determined technology-specific requirements were validated for the selected technologies with field tests that were conducted in a double shift construction site. The details of the

field tests were given in Chapter 4 for the masonry work and the rebar installation, respectively.

Contribution 3: The reasoning mechanisms for developing a data fusion approach for monitoring the progress of construction activities by tracking construction equipment

Previous data fusion studies in the construction management domain developed their own data fusion methods for the specific needs of the problem that they are dealing with and most of those studies focused on fusing data that is collected at overlapping time frames from different data sources. In this study, a data fusion approach was developed for integrating fragmented data obtained from multiple data sources at different time frames in a complementary and supporting fashion for monitoring the progress of activities in double shift construction sites.

A rule-based reasoning approach, which is commonly used in other data fusion studies in the literature, was utilized. In this approach, principally rules and thresholds are determined for processing the raw data. The reasoning mechanisms necessary for processing data obtained from each sensor were developed by extending the taxonomy of reasoning mechanisms that was developed by Pradhan and Akinci (2012) mainly to fuse a pair of spatial and temporal data sources to support construction productivity monitoring in road excavation projects. However, the type of data sources defined and the reasoning mechanisms described in the previous study was not sufficient for the automated activity monitoring purpose of this study that is based on equipment tracking. Therefore, a new non-spatiotemporal data source category (i.e., physical property data source), was proposed in this study for construction activity monitoring. The existing taxonomy of reasoning mechanisms was extended accordingly by adding two types of data interpretation: (1) transformation of physical properties (e.g., weight) into objects (e.g., brick, rebar), and (2) transformation of physical properties (e.g., velocity) into states of objects (e.g., moving or static). Finally, a new data merging step, named rule-based reasoning, that is applicable to all types of data sources, was added to the existing taxonomy.

The reasoning mechanisms that were developed provide ways to automatically monitor the progress of activities in double shift construction sites by tracking the

construction equipment. The reasoning mechanisms provide foundation towards the equipment tracking vision of this study that envisions tracking the activity related information from the location and usage details of the related equipment in all phases of a construction project. The progress of activities obtained using the developed data fusion approach can be used for projecting the productivities of the activities that will be performed in the project. This will enable performing realistic productivity analysis and updating the schedules accordingly. Moreover, productivity data can be used for planning the future projects. Although over the period of the field tests material handling was usually performed at night shifts, while the production and installation activities were usually performed at day shifts; same activities might be needed to performed at both day and night shifts in case of a tight schedule. Therefore, in such case, the developed approach will enable comparing the difference in the productivity of same activity being applied in both day and night shifts.

The user interfaces were developed and used for the prototype implementation. Technical office personnel and site management were envisioned as the users of the developed user interfaces. Technical office personnel will be able to integrate the field data collected via sensor-based technologies with the quantity takeoffs and planned start and end dates of activities to obtain realistic progress and productivity information. While the site management will be able to visualize the utilization of material and equipment in more detail. The developed approach enables obtaining data from site without the need for personnel to physically visit the field to collect data and even when less supervisory personnel is available at night shifts. The developed prototype is designed to be applicable to all building constructions that utilize the selected equipment without the need for writing completely new code. User interfaces provide filters that sort the activities based on time, location and context (i.e., weight of the load carried by the crane), which can be adjusted to the needs of other construction sites. Finally, the findings of this study are not unique to the project at which the field experiments were conducted as the requirements were identified and reasoning mechanisms were developed to meet the general needs to perform progress monitoring at double shift building sites by tracking construction equipment with sensor-based technologies.

How the developed reasoning mechanisms were implemented on the data collected by the selected technologies for activity progress monitoring purpose was explained

in Chapter 3 in detail. Validation of the reasoning mechanisms identified for progress monitoring of the selected activities was performed with field tests conducted with a proof-of-concept prototype that was implemented in a double shift construction site, and the details of the field tests were explained in Chapter 4.

Field test results

In the field tests, actual progress data were collected for three months via the developed prototype using the tower crane sensors, RFID system on the elevator, wireless accelerometer on a hand drill and total station device for masonry work and rebar installation at a building. Since no steel installation was scheduled within the time period of the field experiments, the approach to monitor the steel installation was demonstrated by fusing the generated data that represent a steel component transfer to installation area and steel quantity takeoff. Details of the validation studies were given in Chapter 4.

In the field experiments the results showed that, masonry work progress can be predicted with an average of 96% accuracy by fusing the data about the amount of material delivered to the floor obtained from tower crane sensors and the amount of material utilized at the floor obtained from the RFID data. For progress monitoring of the rebar installation, the developed approach was able to estimate the percentages of completion at six floors with 95% accuracy. These findings demonstrate that the developed approach can be effectively used in determining the progress of masonry work, rebar installation and steel component installation at double shift construction sites.

6.2 Expected Practical Implications

This study identifies the requirements for monitoring the progress of activities in double shift building projects using construction equipment and develops an automated sensor-based approach that tracks equipment for this purpose. In the current practice, progress of activities are intuitively estimated based on the field investigation. Data collected for documenting productivity is inaccurate and less reliable in the night shifts as less number of supervisory personnel is available in the night shifts. Therefore, the practitioners can use the automated activity progress and productivity monitoring approach developed in this study to consistently collect data

from both shifts to (1) avoid conflicts that occur between the employer and the contractor on the amount of completed work in progress payment calculations, and (2) detect fluctuations or decreases in productivity and develop timely solutions for these productivity problems. This will enable time and cost savings as more accurate and efficient data collection from field will be available without the need for manual data collection and entrance.

Due to continuous material supply to construction sites and lack of communication among parties and personnel throughout the day and night shifts, it can be very difficult to keep a realistic track of the amount of material transferred to floors and stored at laydown areas or storage yards at site, and to know how much more material is needed and how much material is wasted. The developed activity monitoring approach will enable practitioners to determine the amount of material delivered to the site, transferred to the floor, and stored at laydown areas or storage yards at site. This will enable effective material management by better control of material inventory throughout both shifts. Therefore, less time will be spent for determining the future material needs and updating schedules, which lead to less schedule delays and labor costs.

The focus of this study was progress monitoring via equipment tracking. Main reason was that the equipment at construction sites are less in number, and therefore provide a less complicated and more economic means of resource tracking. Field experiments showed that the equipments provide reliable sources of information for progress monitoring of activities. In addition to the sensor-based technologies mounted on construction equipment, developed prototype utilized data collection methods readily available on construction equipment. Therefore, practitioners can utilize the developed approach at their sites only by small investments and by applying the reasoning mechanisms described in this study to collect data from field for progress monitoring of activities. Finally, the parameters identified and collected from the construction equipment in this study are expected to provide a starting point for practitioners to develop systems for different activities and equipment based on different data collection technologies. This will enable timely and effective project control and monitoring by eliminating the need for manual data collection that can be incorrect and unreliable.

6.3 Recommended Future Work

The scope of this study was determined as double shift reinforced residential building sites and findings of this study demonstrated that the activity monitoring approach developed in this study can be used at reinforced concrete construction sites. Based on the findings and the results obtained during the implementation of the prototype, it has been identified that this approach is suitable for prefabrication or steel construction. The reason is that the activities in these construction sites are more organized as opposed to reinforced concrete construction and similar activities are performed repeatedly. Therefore, more favorable conditions are available for usage of machinery and equipment at both prefabrication and steel construction sites. By tracking the location of the equipment, time and other usage details of the equipment, the progress of activities can be automatically monitored at prefabrication and steel construction sites. The applicability of the developed progress monitoring approach for steel component transfer to installation area was successfully demonstrated using a fictional data set. Thus, the future research direction is to perform field tests in a steel construction site.

The scope of this study was limited to equipment tracking with sensor-based technologies. Therefore, the extended version of the taxonomy of reasoning mechanisms were demonstrated for sensor-based data sources that are spatial, temporal and non-spatiotemporal. A future research direction can be focused into investigating the applicability of the developed reasoning mechanisms for other means of data collection (e.g., vision-based) and developing additional reasoning mechanisms where needed.

Utilizing sensor-based technologies provided advantages over vision-based technologies in terms of better performance at nighttime, shorter processing times and accurate results. However, applicability of other types of data collection technologies for tracking the activities and equipment that were identified to be tracked in this study can be investigated in the future studies. Moreover, manual data collection steps performed in the field data collection can be automated for providing less human intervention and a more improved data collection process. For example, hand-held RFID readers can be used to identify the tag IDs on wall block material pallets at the storage area, or an RFID reader can be mounted on the tower crane

hook for more automated means of data collection and identification at the time of transferring items from one point to another.

Another future research direction can be focused on which methods (e.g., machine learning and artificial neural networks) can be used to effectively estimate the future productivity of activities based on the progress results calculated using the developed approach. The projected results can be reflected in the schedules and a realistic productivity analysis can be conducted for the monitored activities. This will enable taking timely actions against activities with lower productivities and preventing potential delays in the schedule.

Finally, manual steps included in the implementation of the current prototype can be automated. For example the project related information, such as the quantity takeoff, planned start and end dates of activities, material information, were entered manually to the data fusion user interface. Future research direction is to automate these steps by integrating Building Information Models for extracting such information automatically. The requirements will be identified for defining the necessary LOD levels needed for this type of usage of BIMs and steps will be determined for practitioners on how to define necessary project related data within building elements.

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APPENDIX

Table A.1 summarizes the characteristics of Arduino Yún's two processors (Url-6). Different than the other Arduino boards, Arduino Yún can communicate with the Linux distribution onboard and this enables a networked computer and running Linux commands (e.g., cURL), and developing python scripts. As ATmega32u4 processor of Arduino Yún has built-in USB communication; it creates a virtual COM port and appears to a connected computer as a mouse or a keyboard.

Table A.1 : Arduino Yún processor characteristics (Url-6).

AVR Arduino Microcontroller		Linux Microprocessor	
Microcontroller	ATmega32u4	Processor	Atheros AR9331
Operating voltage	5V	Architecture	MIPS @400MHz
Input voltage	5V	Operating voltage	3.3V
Digital I/O pins	20	Ethernet	IEEE 802.3 10/100Mbit/s
PWM channels	7	WiFi	IEEE 802.11b/g/n
Analog input pins	12	USB Type-A	2.0 Host
DC current per I/O pin	40 mA	Card reader	Micro-SD
DC current 3.3V pin	50 mA	RAM	64 MB DDR2
Flash memory	32 KB (of which 4KB used by boot loader)	Flash memory	16 MB
SRAM	2.5 KB	SRAM	2.5 KB
EEPROM	1 KB	EEPROM	1 KB
Clock speed	16 MHz	PoE compatible	802.3af card

Two microprocessors on Arduino Yún (i.e., ATmega 32u4 and Lilino AR9331) communicate over the Bridge library, as illustrated in Figure A.1. The Bridge library enables Arduino sketches to run shell scripts, communicate with network interfaces, receive information from the AR9331 processor, and interfacing with the USB host and SD card (read/write) (Url-6).

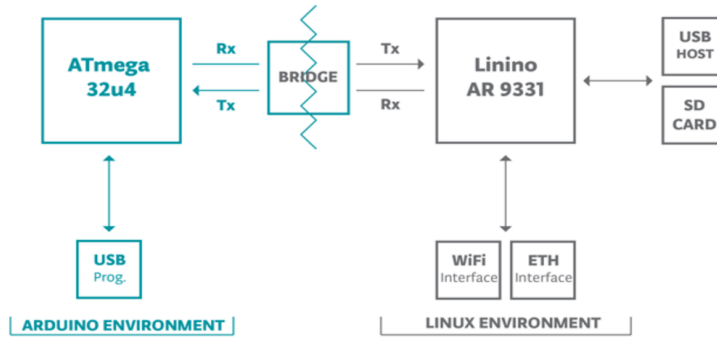


Figure A.1 : Arduino Yún microprocessors and bridge (Url-6).

It is suggested to power the Arduino Yún board over the USB connection with 5VDC as there is no on-board voltage regulator. The board can also be powered over PoE (Power over Ethernet) if additional PoE module is added. Arduino Yún power pins are as follows (Url-6):

- VIN: This is the input voltage to the Arduino board. If the board is powered through this pin, a regulated 5V must be provided.
- 5V: This is the power supply that either comes from VIN or is supplied by the USB, and is used to power the microcontrollers and other components on the board.
- 3V3: The 3.3 volt supply generated and regulated by the on-board regulator. Maximum current draw from this pin is 50 mA.
- GND: These are the ground pins.
- IOREF: The voltage at which the I/O pins of the Arduino Yún are operating, which is 5V.

Atmega32u4 microcontroller has 32KB memory, 4KB of which is used for the boot loader, and 2.5KB SRAM and 1 KB of EEPROM that can be read and written with the EEPROM library. AR9331 memory is not embedded inside the processor and therefore the RAM and storage memory communicate externally. While the board has 64 MB DDR2 RAM and 16MB flash memory; a micro-SD card can be used as an external space for data storage. A 32 GB micro-SD card is mounted on the Arduino Yún board to save the data collected during the prototype implementation.

All I/O pins on the Arduino Yún are controlled by the Atmega32u4 and I/O pins of the AR9331 processor cannot be accessed. Each of the 20 digital pins operate at 5V

and provide or receive 40mA, and can be used as input or output. Some of these pins can be used for specialized functions, as well (Url-6) (Figure A.2):

- **Serial 0 (RX) and 1 (TX):** Used to receive (RX) and transmit (TX) TTL serial data using the ATmega32U4 hardware serial capability and enables the communication in between the two processors.
- **TWI: 2 (SDA) and 3 (SCL):** Enables TWI communication using the Wire library.
- **External Interrupts 3 (interrupt 0), 2 (interrupt 1), 0 (interrupt 2), 1 (interrupt 3) and 7 (interrupt 4):** These pins can be configured to trigger an interrupt on a low value, a rising or falling edge, or a change in value, however, pins 0 and 1 are not suggested to be used as interrupts as they are the also the hardware serial port used to communicate with the Linux processor.
- **PWM 3, 5, 6, 9, 10, 11 and 13:** This pin provides 8-bit PWM (Pulse-Width Modulation) output.
- **SPI:** These pins support SPI communication using the SPI library but necessitates an external module and can be used as a bridge that enables communications in between the two processors.
- **LED 13:** This digital pin has a built-in LED and when the pin is HIGH value, the LED is on and otherwise the LED is off (Figure 2.13).
- **Analog Inputs A0 - A5, A6 - A11 (on digital pins 4, 6, 8, 9, 10, and 12):** Labeled A0 through A11, Arduino Yún has 12 analog inputs. These can be used as digital I/O as well.
- **AREF:** This is the reference voltage for the analog inputs.

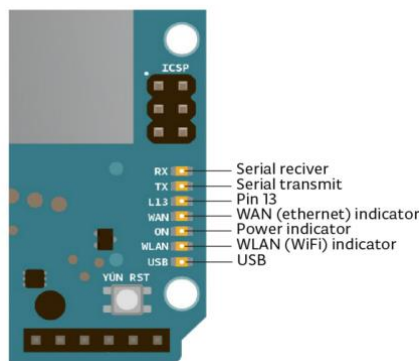


Figure A.2 : Arduino Yún status indicators (Url-6).

There are three reset buttons (1) Yún RST, (2) 32U4 RST, and (3) WLAN RST located on Arduino Yún that serve different functions (Figure 2.11) (Url-6):

- **Yún RST:** This is used for resetting the AR9331 and result in the reboot of the Linux system and losing all the data stored in RAM and terminating all the running programs.
- **32U4 RST:** This is used to reset the Atmega32u4 microcontroller.
- **WLAN RST:** This reset button has two functions, first is to restore the WiFi settings to factory configuration and the second is to restore the Linux image. The factory configuration put the Yún in access point mode (AP) and assigns the default IP address (i.e., 192.168.240.1) to it; enabling connecting with a computer to the WiFi network that appear with the SSID name "Arduino Yun-XXXXXXXXXXXX" (i.e., MAC address to the Yún). Once the computer connects to the board, the web panel of the Yún can be opened by typing in 192.168.240.1 or "http://arduino.local" address. If the WiFi configuration is restored, it necessitates rebooting the Linux environment. To restore the WiFi configuration the WLAN RST button must be pressed and hold for 5 seconds. A blue LED will start to blink and will keep blinking when the button is released after 5 seconds indicating that the WiFi restore procedure has been recorded. To restore the Linux image to the default factory image by using the second function of the WLAN RST button, the button must be pressed for 30 seconds.

CURRICULUM VITAE

Name Surname: Gürşans GÜVEN İŞİN

Place and Date of Birth: İstanbul, 27.11.1985

E-Mail: gursans.guven@itu.edu.tr

EDUCATION:

B.Sc.: 2007, Yıldız Technical University, Civil Engineering Department, Civil Engineering

M.Sc.: 2010, Istanbul Technical University, Civil Engineering Department, Construction Management

PUBLICATIONS, PRESENTATIONS AND PATENTS ON THE THESIS:

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