A FRAMEWORK FOR SPATIO-TEMPORAL UNCERTAINTY-AWARE SCHEDULING AND CONTROL OF LINEAR PROJECTS

A FRAMEWORK FOR SPATIO-TEMPORAL UNCERTAINTY-AWARE SCHEDULING AND CONTROL OF LINEAR PROJECTS

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Abstract

Linear repetitive projects, which are resource-driven in nature, are characterized by a series of repetitive activities in which the resources share the same space either in sequential or parallel manner. The frequent movement of resources over limited shared space needs to be well-planned to avoid potential issues during the execution of linear projects. As such, schedules developed for these projects needs not only to take into account all the logical, project-dependent and precedence constraints of activities but also to incorporate the space and time constraints that co-exist for the movement of thei8r resources. Negligence in incorporating spatial and temporal constraints in developing and improving schedules of linear projects increases the risk of delays and workspace congestions that can substantially hinder the performance of the activity resources.

The study presented here proposes and develops an uncertainty-aware scheduling and control framework for linear projects to address the needs mentioned above. For this purpose, first, a new type of float was introduced as the Space-Time Float. The Space-Time Float is an envelope for all possible movement patterns that a linear activity or its associated resources can take considering the time and space constraints of that activity.

The next endeavor in the development of the uncertainty-aware linear scheduling and control framework was to augment the current linear scheduling methods by presenting an uncertainty-aware optimization method to optimize the duration of linear projects while minimizing their potential congestions. A constraint satisfaction approach was used for the two-tier optimization of duration and congestion, and a fuzzy inference system was incorporated to assess the inherent uncertainty in linear activities. A new type of buffer, Uncertainty-Aware Productivity Buffer is also introduced to account for the uncertainties inherent in project activities.

Spatial progress of activities needs not only to be considered in the planning phase but also to be closely monitored during construction. The framework presented in this study also applies to the monitoring and control of linear projects. While most of the current methods still do not accommodate real-time bi-directional control of linear projects, this framework is based on the Cyber-Physical Systems (CPS) architecture and bi-directional communication of data. To this end, a CPS-based application for Earned Value (EV) monitoring and control of road and highway projects is presented.

Different steps of the generated framework are validated through various literature and field-based case studies. The results demonstrate the effectiveness of the presented method in planning and control of unforeseen variations from the planned schedules of linear projects. As such, the present study contributes and adds to the current body of knowledge of linear projects by presenting an efficient scheduling and control framework that takes into account logical, spatio-temporal and project-based constraints of linear activities.

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Nomenclature

CEPRV	Cumulative Effect of Productivity Rate Variability (Yemin 2001)
CP	Constraint programming
CPM	Critical Path Method
CPS	Cyber Physical Systems
EL	End Location of Activities
ET	End Time of Activities
EVM	Earned Value Management
FF	Finish to Finish Precedence Relationship
FS	Finish to Start Precedence Relationship
GIS	Geographic Information Systems
GPS	Global Positioning System
HVLS	Horizontal & Vertical Logic Scheduling (Thabet (1992)
ICT	Information and Communications Technologies
LOB	Line of Balance
LSM	Linear Scheduling Method (Johnston 1981)
LSM_{VPR}	Linear Scheduling Model with Varying Production Rates (Duffy 2009)
Popt	Optimum Productivity Rate
RSM	Repetitive Scheduling Method(Harris and Ioannou (1998)
TLC	Time Location Chart
PERT	Program Evaluation and Review Technique
PVR	Productivity Variation Rate
PR	Precedence Ratio
PSM	Productivity Scheduling Method (Lucko 2008)
RFID	Radio Frequency Identification

RPi	Raspberry Pi
RTLS	Teal-Time Locating System
SF	Start to Finish Precedence Relationship
ST	Start Time of Activities
SL	Start Location of Activities
SS	Start to Start Precedence Relationship
STF	Space Time Float
UAB	Uncertainty-Aware Productivity Buffer
UWB	Ultra Wide Band
WLAN	Wireless Local Area Network

1. Chapter one: Introduction

1.1. Chapter Overview

Linear construction projects such as roads, highways, tunnels and bridges represent a class of construction projects typically characterized by a few sequential activities that are repeated for substantial times from beginning to the end of the project (Georgy 2008). The activities in this type of projects are extremely inter-related and therefore any delay can easily cause the overall project to fall behind schedule. This is because the resources of the repetitive activities usually need to share the same space either in sequential or parallel manner. As such, the repetitive and location-based nature of linear construction projects calls for special considerations in planning, controlling and optimizing their productive processes.

The schedules developed for these projects needs not only to take into account all the logical, project-dependent and precedence constraints of activities (Moselhi and Hassanein 2003, Hegazy 2005, Yang and Chi-Yi 2005, Polat et al. 2009, Song et al. 2009), but also should incorporate the space and time constraints that co-exist for the movement of resources of linear activities (Roofigari-Esfahan et al. 2015). The frequent movement of resources over limited shared space needs to be well-planned to avoid potential issues during the execution of linear projects. Furthermore, in order to ensure productive execution of planned schedules and to resolve potential issues in a timely manner, proper monitoring and control frameworks needs to be designed for these projects accommodating their special characteristics. (Quasi-) real-time availability of information regarding resource locations and project status as well as changes made to the plans throughout execution, combined with elemental space-time constraint considerations, leads to more flexible and efficient control approaches for linear projects.

The present study proposes a scheduling and control framework for linear construction projects. The proposed framework first adds to current Linear Scheduling Methods (LSM) through introduction of Space-Time Floats. The research is then taken to the next level to optimize the schedules generated with due consideration to Space-Time Floats. The goal of this step is to optimize the generated schedule to detect and minimize potential congestions in the planning phase, taking into account inherent uncertainties in linear activities. To this end, an uncertainty-aware constraint satisfaction approach is proposed; where a new type of buffer, Uncertainty-Aware Productivity Buffer is introduced and used. The study is not limited to the planning phase and is further expanded to the monitoring and control phase. A Cyber-Physical Systems (CPS) based framework for control of construction projects in general and an approach to real-time CPS based Earned Value (EV) monitoring and control of road and highway projects in particular, are then presented.

This chapter first goes over the current state of the art of scheduling and control of linear projects and accordingly introduces the main motivations behind the developments made in this research. The knowledge gap is then explored, and research objectives and deliverables that were set to address the found gaps are subsequently discussed. A brief introduction to the research methodology taken, followed by the overview of thesis structure are subsequently presented.

1.2. Background and Research Motivation

The literature on scheduling and planning of repetitive projects is rich. These projects are categorized into two groups based on the movement of resources: linear projects such as highway and pipeline projects and non-linear projects such as multi-story buildings. The current scheduling methods for linear repetitive projects schedule activities by planning for the spatial progress that the resources of activities need to accomplish over time, i.e. their productivity rate. This, in fact, serves as an important distinction between the resource-driven scheduling methods and duration-based scheduling methods such as Critical Path Method (CPM). A number of resource-driven scheduling methods including Linear Scheduling Method (LSM), Repetitive Scheduling Method (RSM), and Line of Balance (LOB) are presented in the literature to plan, schedule and control linear repetitive projects; e.g. (O'brien 1975, Johnston 1981, Stradal and Cacha 1982, Chrzanowski Jr and Johnston 1986, Handa and Barcia 1986, Harmelink and Rowings 1998, Harris and Ioannou 1998, Cosma 2003). All of these methods are essentially alike in that they schedule project tasks by plotting the progress of linear activities against time (called as productivity rate). In fact, the productivity of the activity resources drives the development and accuracy of linear schedules (Duffy et al. 2011).

Much research has been performed to predict the productivity rate of linear projects based on simulation, probability, or regression analysis; e.g. (Yamin 2001, Kuo 2004, O'connor and Huh 2005, Jiang and Wu 2007, Watkins et al. 2009, Duffy et al. 2011, Woldesenbet et al. 2012). Other methods consider variable productivity rates for linear activities; e.g.

(Lucko 2008, Duffy et al. 2011, Lucko et al. 2014). There are methods that attempted to visualize linear schedules in 4D CAD (Staub-French et al. 2008), Excel spreadsheet (Lluch 2009) or by using the slip charts from aerospace industry (Lucko et al. 2015).

In linear projects, the extent of activity inter-relevancies causes deviations from planned productivity rate of the resources to be translated to direct impacts on other activities' schedules as well as the overall project duration. As the linear activities share the same space in parallel or in sequence, deviation from planned productivities not only affects activity durations but also leads to potential congestions in space and time between consequent activities. Congestion in construction sites is proven to have negative impacts on efficiency and productivity of resources; directly hindering progress of construction projects (Aduagyei 2008, Watkins et al. 2009). Hence, early detection of such potential delays and space-time congestions in the planning phase is vital to the success of the linear projects in meeting their time and cost objectives.

As a result, the issue of space-time conflicts and the need for integrating space into planning of construction projects was raised through a number of studies; e.g. (Zouein and Tommelein 2001, Akinci et al. 2002, Guo 2002, Dawood and Mallasi 2006, Winch and North 2006, Chua et al. 2010, Koo et al. 2013, Moon et al. 2013, Choi et al. 2014, Tomé et al. 2015). While these practices have recognized the importance of space as a construction resource and has incorporated it as an integral part of planning, less attention is paid to resolving the issue of space-time congestions for linear type of construction projects. Thabet and Beliveau (1997a, 1997b) addressed work zone planning for multi-story repetitive projects under constrained time and space. Cho et al. (2013) focused on managing space zoning while reducing the duration of linear projects. These studies, however, did not account for the potential congestions that are to occur as a result of changes in planned schedules of linear activities. Consequently, a spatio-temporal schedule that allows for adjustments for unforeseen circumstances with due consideration to the allowable variations in productivity of resources is an important asset for effective management of linear construction projects.

In addition, detecting construction delays entails prompt identification of delayed process and communication of discrepancies between actual and as-planned performances. Construction site of linear projects is a dynamic place involving a large number of resources that intensively interact with each other under varying site activities. Being able to locate resources accurately, and track the construction site progress and continuously transfer this information from the field to the office in a timely manner is critical to project control (Andoh 2012). Therefore, communication of construction progress between the construction sites and project parties is needed to identify progress discrepancies, better utilize resources in different locations and make timely corrective decisions (Golparvar-Fard et al. 2009a).

Automating the process of control data transmission from/to construction job sites has become a trend in construction research in the last decade. Emerging virtual models with wireless sensing and information technologies significantly improved different construction processes and operations in recent years. A number of studies presented advancements in this area through using various location-aware and communication technologies to collect data from construction job sites and transfer and incorporate this data into planning and control processes for different purposes; e.g.(Bowden et al. 2006, Erdogan et al. 2008, Irizarry and Gill 2009, Kim and Kumar 2012, Turkan et al. 2012a, Arslan et al. 2014, Su et al. 2014, Wang et al. 2014a, Wang et al. 2014b, Zhang and Bogus 2014, Khoury et al. 2015, Kim et al. 2015, Maalek et al. 2015). While the inter-related and repetitive nature of linear projects requests for higher considerations regarding their integrated control, the essence of using these technologies and processes for efficient monitoring and control is still an active area of study.

1.3. Problem Statement

After preliminary review of the literature, the following needs were identified and served as the main motivations behind this study:

Despite differences in the particular objectives of methods presented for scheduling and planning of linear projects, all of these methods are essentially alike as they consider only one productivity rate per each time interval (optimum productivity rate) for the associated activities. As such, the conventional linear scheduling methods overlook the space and time flexibilities and constraints of linear activities and subsequently other possible productivity rates that can be taken at each time interval. This accordingly reduces the flexibility of the generated schedules in responding to unforeseen deviations from the planned schedules. Therefore, any deviation from the planned productivity can result in delays and cost overruns.

Further, deviations from planned productivity rates not only impacts the time and cost of linear projects but also causes space and time congestions between resources of adjacent activities. In order to prevent these potential congestions from further reducing the productivity of activity resources, they need to be detected in the planning phase, before they actually occur. Current methods, however, do not account for such potential congestion that is likely to happen due to deviations from the planned productivity rate of the resources. As such, integrating space-time constraints and flexibilities in the movement of resources will improve the efficacy of the generated schedules in dealing with not-as-planned situations during construction.

In addition, successful, timely, and on-budget implementation of linear projects requires efficient management of sequentially used resources not only in the planning phase but also throughout the project execution. As a result, it is important not only to integrate the movement of resources continuously into their progress monitoring and control systems but also to reflect on any changes in the schedule of the activities on the job site and make necessary adjustments. Therefore, real-time bi-directional monitoring of the linear projects based on the actual progress during the project execution is another area to be studied further.

1.4. Research Objective

The primary objective of the proposed research is therefore to develop a scheduling and control framework for linear projects that accommodates the above-mentioned needs. For this purpose, several sub-objectives will be fulfilled:

- Add the spatio-temporal flexibilities and constraints of movement of resources to the current linear scheduling methods and accordingly plan for deviations from planned productivity rates before construction commences.
- Optimize the duration of linear schedules with due consideration to not only logical constraints but also their spatio-temporal flexibilities and constraints.
- Detect and minimize potential space and time congestions/conflicts in schedules of linear projects to avoid their resulting delays and disruptions in the execution of adjacent (spatial and temporal) activities.
- Manage uncertainty in scheduling and optimization of linear projects.
- Propose a framework for real-time bi-directional monitoring and control of construction projects in general and linear projects in particular.

1.5. Research Deliverables

The following deliverables were achieved through the course of this research study:

1. ***Introduction of Space-Time Float into Linear Scheduling Methods:*** Inspired from the Time-Geography concept, this new type of float adds to the current Linear Scheduling Methods by due consideration of spatio-temporal flexibilities and constraints of movement of linear activities resources.
2. ***Constraint Satisfaction Uncertainty-Aware Optimization Method for Linear Projects:*** This outcome includes a three-phase optimization method to minimize potential congestions in schedules of linear projects, in the planning stage. A new

type of buffer, Uncertainty-Aware Productivity Buffer is introduced and is estimated using Fuzzy Inference System.

3. ***Framework for using Cyber-Physical Systems (CPS) in Construction projects:*** A CPS-based construction-specific architecture was presented to provide a framework that can enable real-time bi-directional communication of data in a variety of applications.
4. ***CPS-based Earned Value (EV) management model for monitoring and control of linear projects:*** A CPS Approach for Progress monitoring and Control of Highway Projects is presented. The approach makes use of Raspberry Pi microprocessors for Earned Value Management of highway projects.

1.6. Research Methodology

The research began with a problem statement and the definition of the preliminary research objectives. These led to a comprehensive literature review, which covered a wide spectrum of related literature, including studies related to scheduling and control of linear projects, space management in construction, use of location awareness in enhancing construction processes, real-time project monitoring and control and Cyber-Physical Systems based project control in different fields of study. An overview of the research methodology and its different steps is presented in Figure 1.

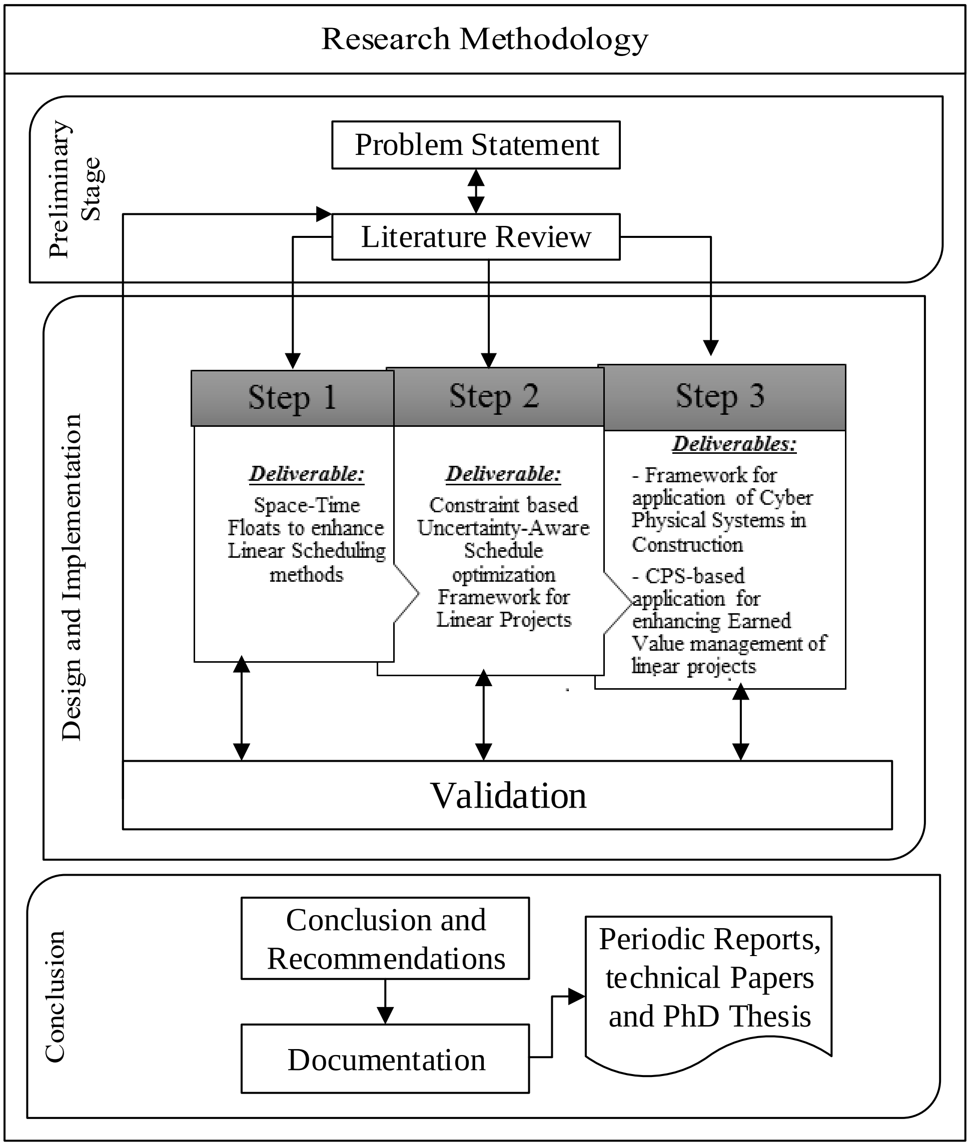

Figure 1: Research Methodology

As it is demonstrated in Figure 1, the developments of this research study were made in three steps to achieve research deliverables. These steps are as follows:

1.6.1. Step I: Space-Time Float

In order to address the crisp nature of the current linear scheduling methods that schedule linear activities with planning one productivity rate at each time interval, the notion of

Space-Time Floats is introduced. The concept of space-time float, introduced in this study, is a multi- dimensional float that presents an envelope for all possible movement patterns that an activity or its associated resources can take considering the time and space constraints of that activity. The notion of space-time float is inspired by the geographical tradition of time-geography developed for the study of human space-time behavior (Hägerstraand 1970). The essence of time-geography is the construction of a space-time prism that bounds the possibilities for time and space allocation of human activities and movements (Kraak 2003a).

Use of space-time float and adding it to the schedules of linear projects enables the linear schedules to adapt to variable production rates at each time interval (in essence exchanging time for space and vice versa). As such, the space-time float schedule is not limited to one planned productivity rate per time interval for each activity, but in turn uses the whole range of possible productivity rates that are available to each activity at each point in time and space. Such ranges of productivity relate to different project-dependent as well as management-dependent factors. Examples of these factors include effects of site condition on the productivity of the resources, and managerial decisions to use alternative type or size of resource to perform the same activity. The difference between the approach presented here and other methods with varying productivity rates lies in considering a range of productivity rates, particularly at each point in time. In other methods, the variate productivity rates are modeled in parallel, where one productivity rate is considered for each sub-interval of the activity. As such, the most important added benefit of generating linear schedules using space-time floats is providing a better understanding of the combined space and time floats that are available for each activity.

1.6.2. Step II: Generation of Constraint Satisfaction-Based Uncertainty-Aware Optimization Method for Linear Schedules

Due consideration to space and time flexibilities of linear activities achieved through Space-Time Floats not only helps in generation of more realistic and flexible schedules but also enables identification and forecasting of potential space-time conflicts/congestions. In other words, by considering the whole range of possible productivity rates in the scheduling phase, the space-time constraints and flexibilities of the activities' resources are better understood and can accordingly be used to identify and avoid potential congestions. These congestions are caused as a result of potential deviations from planned productivity rates of activities and accordingly are called potential congestions. The congestion in this research specifically means the workspace interference when two activities have both spatial and temporal overlaps. Deviations from planned productivity rates of linear activities may cause their respective resources to be placed in the same space over the same period of time, resulting in congestions in the job sites. As a result, pre-identification of places and times where congestions are probable to happen provides a potential to minimize work disruptions and delays caused by such congestions during construction.

To this end, the research was then taken to the next level to optimize the generated schedules and to minimize their potential congestions. For this purpose, an uncertainty-aware schedule optimization framework is proposed. The framework uses constraint satisfaction approach to finding the optimum duration of linear projects that also minimizes the potential congestions in their schedule. The proposed schedule optimization method has three essential phases. These phases include: 1) Constraint-Based Optimization of Linear Schedules; 2) Uncertainty-Aware Productivity Buffer Estimation using Fuzzy Inference System; and 3) Constraint-based Congestion Minimization of Linear Schedules.

In order to account for the uncertainties inherent in linear activities, a new type of buffer, Uncertainty-Aware Productivity Buffer, is introduced and used. This buffer is defined as allowable deviations from planned productivity rates of linear activities that need to be predicted and incorporated into the activity in the planning phase to prevent its unforeseen occurrence during construction. In other words, this buffer identifies the amount of uncertainty in productivity rates of linear activities that the schedule can manage without causing a negative impact. In contrary to the conventional duration buffers, the Uncertainty-Aware Productivity Buffer presents a buffer associated with productivity of linear activities. Consequently, the buffer is realized both in terms of time and space that is more suitable to the nature of linear schedules. This way, the uncertainty of the linear activities is accounted for in the planning stage, and its negative effects can be eliminated before occurring. The framework makes use of Fuzzy Inference Systems to estimate the size of the Uncertainty-Aware Productivity Buffer.

1.6.3. Step III: Generation of Real-Time Monitoring and Control Model for Linear Projects Using Cyber-Physical Systems Based Approach

Generated schedules need to be monitored in real-time to ensure timely implementation of project deliverables and efficient management of sequentially used resources of linear projects. This can be achieved through the integration of all project components including project schedules and documents, actual construction processes on site, as well as project management systems and technologies. Such integration offers significant potential for better collaboration, coordination, and communication in all construction projects including linear ones. Effective bi-directional interactions between cyber and physical components and processes of construction projects offered by Cyber-Physical Systems can help in achieving this objective.

Cyber-Physical Systems are physical and engineered systems, whose operations are monitored, coordinated, controlled and integrated by a computing and communication core (Karsai and Sztipanovits 2008, Rajkumar et al. 2010, Suh 2014). CPS uses computations and communication deeply embedded in and interacting with physical processes to add new capabilities to physical systems (Krogh et al. 2008). The integration between computational/control and the physical construction gained through Cyber-Physical Systems can significantly improve information handling in difference stages of construction projects; hence enhancing the control of the construction processes. With CPS, data from both the physical and cyber domains flow automatically in real-time. This occurs regardless of the physical constraints in the spatial distribution of project components.

In order to derive the most benefit from Cyber-Physical Systems in any domain, CPS architecture including layers, components and phases as well as their inter-relations must be understood; construction is not an exception. Therefore, a framework for Cyber-Physical Systems approach in Construction Applications is first presented and then used to enhance progress monitoring and control of highway and road projects. The proposed approach uses a microprocessor to enhance Earned Value management of road and highway construction. Raspberry pi, a simple microprocessor, equipped with different modules is utilized to retrieve the required progress information, perform calculation and analysis and to transfer them to the cyber space of the system. A web server is used to host the cyber space; to store the retrieved information and to transfer the results back to the construction site through the Raspberry Pi.

As such, the framework presented in this study is considered as both a planning and control tool. The framework accordingly enables detection of potential project delays, space-time congestions, work disruption and resource idling, cost overruns and accordingly suggesting corrective actions throughout project planning and execution. This helps in timely prediction and/or detection of these potential/actual problems and accordingly enables preventing or decreasing their effect on the project budget and time. The method also aids in taking corrective actions when needed to control the actual state of the project while also planning for upcoming activities.

1.7. Thesis Organization

This thesis is organized into seven chapters. Chapter One provides an overview of the research problem and describes the motivation, objectives, deliverables, and methodology of the research. Chapter Two provides background knowledge about scheduling and control of linear projects, space management in construction, use of location awareness in enhancing construction processes and Cyber-Physical Systems. Chapter Three briefly discusses the organization of the research study with due consideration to the sequential steps taken and the developments made in each step. The step by step developments made through the term of this study are then presented in chapters Four to Six. Chapter Four starts with an overview of the proposed framework for scheduling and control of linear projects followed by an introduction to the first step of this study, i.e. introduction of Space-Time Floats to the scheduling of linear projects. The uncertainty-aware constraint satisfaction approach developed for optimizing the schedules generated in step one is then presented in Chapter Five. Chapter Six presents the proposed framework for employing Cyber-Physical Systems in construction followed by application of the generated framework for real-time progress monitoring and control of road and highway projects. It should be noted that this research is validated step by step through a number of literature-based and/or field-based case studies. As such, the validation of each developed step is presented at its corresponding chapter. Chapter Seven summarizes the proposed research and presents research limitations and possibilities for future work.

2. Chapter Two: Literature Review

2.1. Chapter Overview

A comprehensive literature review has been conducted to establish a solid starting point to pursue each step of the proposed study. The literature review has been focused on investigating and analyzing relevant research studies in time and space management and control of construction projects in general and linear projects in particular. This chapter summarizes and organizes the reviewed literature in four main categories: (1) scheduling, optimization, and control of linear construction projects; (2) space management in construction projects; (3) use of location-aware technologies for enhancing construction processes; and (4) the emergence of Cyber-Physical Systems in different study domains including construction.

2.2. Scheduling and Control of Linear Projects

Duration-based scheduling methods such as the Gant Charts, Critical Path Method (CPM) and Program Evaluation and Review Technique (PERT) are proven to be powerful scheduling and progress control tools and have been used for years by academics and industry professionals alike. However, these techniques exhibit major drawbacks when applied to schedule repetitive construction projects (Hegazy and Wassef 2001, Agrama 2014). Projects involving repetitive activities may be grouped into two categories: point-based/non-linear projects and distance-based/linear projects (Moselhi and Hassanein 2003, Duffy 2009). Examples of non-linear projects include multi-unit housing complexes and high-rise building construction, whereas examples of linear projects include pipelines, airport runways, bridges and highways construction projects. In fact, duration-based network methods are not ideal for scheduling repetitive projects for several reasons (Ioannou and Yang 2016), some of the most important ones include:

- Duration-based network methods do not take into account resource work continuity (Jun 2010b, Ioannou and Yang 2016). Repetitive construction projects involve a considerable amount of identical or similar tasks repeatedly performed in various locations of the project. As a result, negligence in consideration of work continuity of resources causes schedule deviations that can lead to significant schedule performance deficiencies (Baqerin et al. 2015).
- When network schedule is used to schedule repetitive activities, the resulting schedules have either a small number of activities (if the durations of the activities are large) or an excessive number of activities (if the durations of the activities are subdivided artificially by physical place or location); which in either case the schedule would not be best presenting the project (Duffy 2009).
- Repetitive activities often have different productivity rates and as a result scheduling repetitive projects is sensitive to productivity estimates for each activity. Since there is no indication of productivity rates in duration-based schedule networks, the difference in productivity rates of activities cannot be taken into account by the scheduler during the development of a network schedule, nor can it be detected in conventional network analysis (Tokdemir 2003).

As such, a significant number of graphical resource-driven techniques have been proposed as alternatives for scheduling repetitive construction projects since 1960s that are discussed here.

2.2.1. Resource Driven Scheduling Methods

The need to develop scheduling tools tailored to repetitive projects was realized decades ago (Lumsden 1968). The awareness that traditional duration-based network scheduling techniques are not well suited for planning and scheduling repetitive projects resulted in the emergence of resource-driven scheduling methods (Handa and Barcia 1986). Ever since the resource-driven scheduling was introduced to the construction industry, it has influenced many researchers to improve the means of scheduling repetitive construction projects. Resource-driven scheduling methods (also referred to as Time-location based scheduling methods) are mainly presented to overcome the inefficiency of duration-based methods in presenting required details when scheduling repetitive projects. These methods use two-dimensional production diagrams in which activities are represented by production lines. Such production lines relate work progress on one axis with time on the other. As such, they better depict repetitive nature of activities and accordingly have the potential to enhance the scheduling of repetitive projects (Rahbar and Rowings 1992).

The origins of resource-driven scheduling are not clear, and there might have been multiple origins (Rahbar and Rowings 1992). Several methods have then been proposed to schedule this class of projects; e.g. (Arditi and Albulak 1986, Handa and Barcia 1986, Rahbar and Rowings 1992, Eldin and Senouci 1994, Harris and Ioannou 1998, Hassanein 2003, Ioannou and Srisuwanrat 2007b, Polat et al. 2009, Tang et al. 2014b). Some of the first traces of these adaptations include: vertical production method (O'brien 1975), time-space scheduling method (Stradal and Cacha 1982), linear scheduling method (Johnston 1981, Chrzanowski Jr and Johnston 1986), repetitive activity scheduling process (Rahbar and Rowings 1992), and horizontal and vertical logic scheduling (Thabet and Beliveau 1994). Resource-driven methods have also been applied to real life projects. Some of the applications of these methods in real projects include repetitive housing units (Lumsden 1968), high-rise building projects (O’Brien 1975), tunnel excavation projects (Dressler 1980), highway construction projects (Johnston 1981), railway bridges (Stradal and Cacha 1982), rapid transit projects (Barrie and Paulson 1984), road upgrade projects (Chrzanowski and Johnston 1986), renovation projects (Whiteman and Irwig 1988), pipeline projects (Duffy 2009) and multistory buildings (Thabet and Beliveau 1994).

Using resource-driven scheduling methods provides a number of advantages in scheduling repetitive projects. Duration-based network scheduling methods are a more powerful tool for most situations, especially projects with discrete activities. However, in repetitive portions of projects, graphical representation offered by resource-driven methods more quickly conveys the nature of the work and helps in identifying and solving potential problems. These methods provide valuable insight at the early stages of planning repetitive projects as they are based on production rates that in turn depend on available resources. The visual presentation of these scheduling methods is also helpful in project control (Hassanein 2003, Duffy 2009). In addition, the preparation of resource-driven schedules is generally easier than the preparation of a duration-based network schedule considering required calculations, especially as repetition increases.

Vorster et al. (1992) suggested that resource-driven scheduling methods be categorized based on their ability to accommodate activities with constant and non-constant quantities of work. The term "linear scheduling method" (LSM) was suggested to be used for methods that could accommodate activities with varying quantities of work while the term "line of balance" (LOB) was suggested to refer to methods that could model activities with constant quantities of work. As such, the Line of Balance (LOB) method of scheduling applies to point-based/non-linear projects, whereas the Linear Scheduling Method (LSM) applies to distance-based/linear projects.

The Line of Balance (LOB) technique was developed by the U.S. Navy in the early fifties (Harmelink 1995), and has been successfully employed to plan, schedule and control repetitive projects (Arditi and Albulak 1986). In the early development of graphical techniques, many researchers have adopted the concept of Line-Of-Balance (LOB) and focused on balancing crew productivity and maintaining continuity of workflow (Hassanein 2003). Other models to advance the capabilities of LOB have also been developed (Suh 1993; Suhail and Neale 1994; Harris 1996). However, LOB could not accommodate linear activities with non-uniform quantities of work in its units, and this has limited its application in the construction industry, where activities frequently have non-uniform work quantities.

The Linear Scheduling Method (LSM) was first introduced by Johnston (1981). As stated, it is more suitable for linear projects such as highways, bridges, and pipelines. In this type of projects, typically the same crew repeats each of linear activities from one end of the project to the other. Often the only distinguishing feature of these linear-type activities is their rate of progress (i.e. productivity rate). The graphical presentation of LSM is very similar to line-of-balance diagram (See Figure 2). The main difference is that an LOB diagram usually presents a discrete cumulative progress (e.g., floors) while LSM diagram presents continuous cumulative progress (e.g., miles). Moreover, activities in an LOB diagram are presented by horizontal lines from the start to the finish of the activities while activities in an LSM diagram are presented by production lines with the slope of activity unit productivity rates.

The power of the linear scheduling method is mainly gained through the multitude of graphical capabilities inherent to this method. In fact, one of the main characteristics of LSM is the ability to visually communicate both the location and the progress of work. Linear Scheduling monitors the progress of multiple continuous activities graphically by illustrating the time, location of work, and rates of production (Herbsman 1999). In addition, LSM is a reliable planning method that ensures that all activity resource requirements are considered during planning to assist in the efficient execution of the project. As such, the most significant advantage of LSM is the simplicity with which it can convey a detailed work schedule.

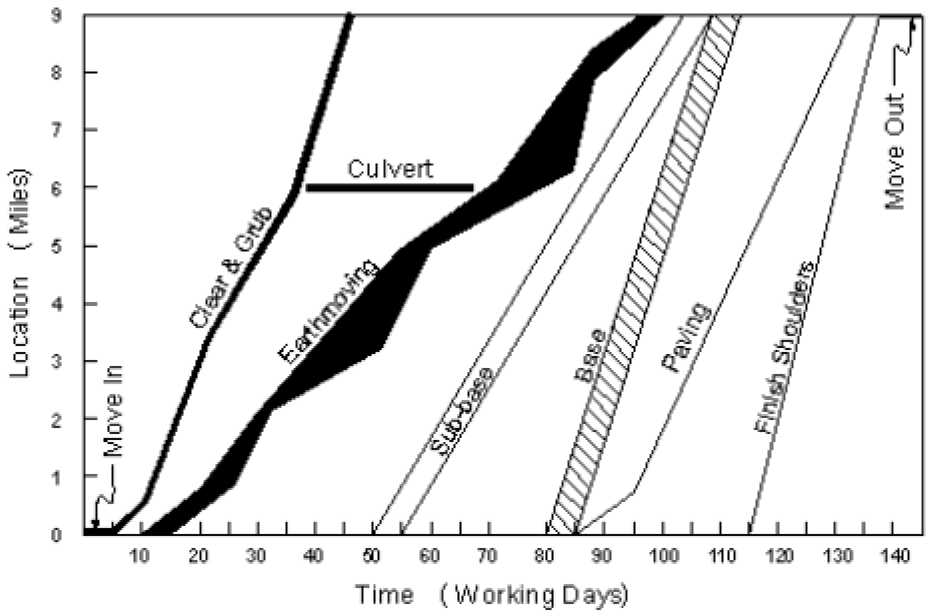

Figure 2: Example of Linear Schedule for a Highway Project (Johnston 1981)

Applications of LSM in the construction industry have been proposed by Johnston (1981), Chrzanowski and Johnston (1986) and Rowings and Rahbar (1992). The need to develop models integrating both repetitive and non-repetitive activities in the scheduling procedure was also identified by O'Brien (1975) and Laramee (1983). On the other hand, adding flexibility by enabling multiple predecessors and successors for each activity was proposed by Birrell (1980) and Cole (1991). Several methods integrating linear and network scheduling techniques have been proposed to address the need to make linear schedules more versatile in modeling combinatory types of projects (Birrell 1980; Russell and McGowan 1993; Russell and Wong 1993; Suhail and Neale 1994).

Harmelink (1995) developed a model of linear scheduling method in conjunction with an AutoCAD-based program. His work focused on: 1) computerization of linear scheduling method and 2) illustrating procedures to identify the controlling activity path in the schedule. Harmelink concluded that LSM has the following advantages over duration-based scheduling methods such as CPM: The Linear Scheduling Method can realistically determine the controlling activity path and accurately model the production rate characteristics of linear activities; As-built production rate information can be easily utilized to track the progress of linear activities and control the project, provides managers with realistic information for making decisions; provides a visual method of planning linear projects and accordingly facilitates the communication of the project plan to other parties involved in the project.

Other significant resource-driven methods were also introduced which combined benefits of previous methods. Harris and Ioannou (1998) introduced repetitive scheduling method (RSM) and the concept of controlling sequence. RSM is a graphical method that combines graphical and analytical approaches to scheduling repetitive projects. It can be applied to a repetitive project consisting of all types of activities including typical, non-typical, repetitive, and non-repetitive activities. Yang (2002) developed a sophisticated application, named "Repetitive Project Planner," that integrated the concept of RSM to activity graphics formats (lines, bars, and blocks). In his method, Yang employed graphical and analytical approaches to model the following realistic characteristics of repetitive project scheduling: variable work quantities; composition of crew sizes, tools, and equipment; changing in work direction (east-to-west, top-to-bottom, etc.); different precedence relationships (finish-to-start, start-to-start, etc.); specified buffer in time (lead-time) and space (lead-space); and allowed interruption if desired.

Thabet (1992) proposed a method called "Horizontal and Vertical Logic Scheduling method" (HVLS), which combines graphical, knowledge-based, and analytical methods in order to schedule multistory buildings. The HVLS application is considered the very first computerized extension of LOB that provides a full benefit of construction information system. It is user-friendly and database-driven and utilizes information extracted from a 3D CAD model.

2.2.2. Productivity of Repetitive Activities

The term “productivity” is generally used to present a relationship between the outputs of a production process and the corresponding inputs; usually, but not necessarily, expressed in person per hours (p-hrs). In the construction industry, the term productivity and its definition can vary based on its application to different areas of construction, ranging from industry-wide economic perceptions to individual measurement perspectives (Thomas et al., 1990, Dozzy and Abourizk, 1993). In the literature, many other terms are also used to describe productivity in the construction industry, such as the production rate, unit rate, performance factor, cost factor and efficiency (Hossain and Ruwanpura 2010). High productivity is also defined as the intensive and/or efficient use of scarce resources in order to increase project profit (Arditi 1985).

As stated earlier, the productivity of the activity resources drives the development and accuracy of linear schedules (Duffy et al. 2011). Much research has been performed to predict the productivity rate of linear activities using simulation, probability, or regression analysis; e.g. (Yamin 2001, Kuo 2004, O'connor and Huh 2005, Jiang and Wu 2007, Watkins et al. 2009, Duffy et al. 2011, Woldesenbet et al. 2012). Other methods considered variable productivity rates for linear activities; e.g. (Lucko 2008, Duffy et al. 2011, Lucko et al. 2014). Linear scheduling has also been extended to model variability in activity durations and the determination of optimal crew mobilization times under uncertainty (Ioannou and Srisuwanrat 2006, Srisuwanrat and Ioannou 2007).

Duffy (2009) developed a framework for scheduling linear projects which accounts for sequential variation in productivity rates of linear activities. The aim of the method is to illustrate and predict when and where changes in productivity rates occur in time and space and to enhance the visual capabilities of linear scheduling method. He accordingly presented a method called Linear Scheduling Model with Varying Production Rates (LSM_{VPR}). Despite traditional linear scheduling method that depicts the entire time and location when and where the construction is proposed (referred to as Time-Location Chart (TLC) in his thesis), Duffy’s method looks at smaller pieces of the TLC called working windows (See Figure 3). A Working Window (WW) is defined as a time-space rectangle with a homogenous set of variables that affect the construction productivity rate. The research was focused on a narrow band of productivity variables which affects pipeline construction production rates. He concluded that using variate productivity rates and awareness of times and locations where rates change, would help schedulers of the linear projects in better analyzing the impact of the selection of various routes or start dates on the schedule.

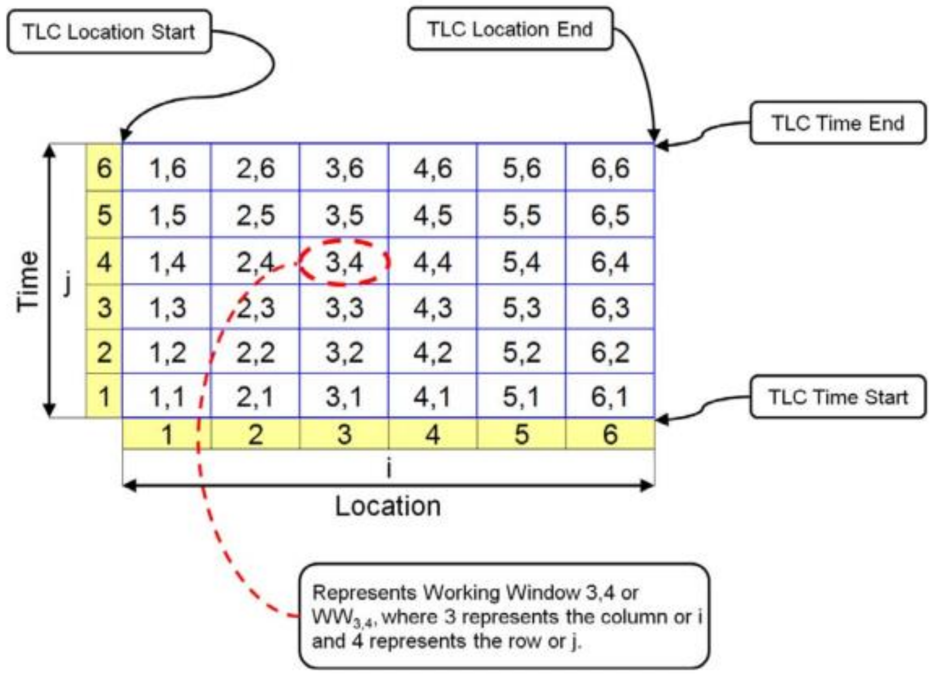

Figure 3: Naming Conventions for Working Windows (Duffy 2009)

Yamin (2001) developed an approach to analyzing the cumulative effect of productivity rate variability (CEPRV) on linear activities of highway projects. The research focused on advancing the risk analysis capabilities of linear scheduling methods and accordingly forecasting the probability of project delays. Yamin also developed methods for determining secondary controlling activity paths (SCAPs). These SCAPs occur due to activities that are near critical and have high productivity rate variability (PRV) and as such the probability that such activities may become critical is high. Yemin suggests further research in evaluating PRV by statistically analyzing construction factors such as the type of work being done, soil conditions, weather, equipment type, the experience of labors, and general layout. This would enable managers and schedulers to better forecast the impacts of the variability of the different components. Lucko (2008) also generated a formulated approach called productivity scheduling method (PSM) using singularity functions to depict changes in productivity rates of linear activities. The PSM keeps activities and their buffers mathematically intact throughout the analysis regardless of how many segments of different productivity rates they contain. As such, Lucko's method is considered as one of the first methods that presented a formulated mathematical presentation of Linear scheduling and its different components.

2.2.3. Optimization of Resource-Driven Scheduling

Ever since their introduction, variations of resource-driven scheduling methods were presented by scholars to expand their applicability and efficiency. Several methods have been proposed to optimize the resource-driven scheduling methods with different objectives. The optimization methods presented in the literature can be categorized into three groups (Hassanein 2003): Operations Research-based methods including linear and dynamic programming; Artificial Intelligence-based methods including Artificial Neural Networks and Genetic Algorithms; and Simulation Models. These optimization methods have been used to address different objectives. A number of methods were proposed focusing on maximizing resource continuity of repetitive projects and optimizing the duration and/or cost of these projects, etc.

The methods presented in literature for optimizing the schedules of linear projects can be divided into three main categories:

1) Methods that optimize the schedule to maintain work continuity in terms of minimized resource fluctuations; e.g. (Mattila and Abraham 1998, Shu-Shun and Chang-Jung 2007,

Georgy 2008, Tang et al. 2014a, Tang et al. 2014b) or minimized resource idle times (Vanhoucke 2006, Gonzalez et al. 2013, Ioannou and Yang 2016);

2) Methods that optimize project schedule considering minimization of project cost as objective; e.g. (Handa and Barcia 1986, Senouci and Eldin 1996, Hegazy and Wassef 2001, Moselhi and Hassanein 2003, Ipsilandis 2007, Ezeldin and Soliman 2009, Menesi et al. 2013);

3) Methods which tend to minimize the duration of the linear projects (Russell and Caselton 1988, Hassanein and Moselhi 2005, Fan and Lin 2007, Bakry et al. 2013, Cho et al. 2013, Bakry et al. 2014).

- **Resource Continuity**

One of the main focuses in scheduling linear projects is to maximize resource utilization by keeping resources to work continuously without interruption. This is because construction crews of linear activities are often required to repeat the same work while moving between locations. Due to this frequent resource movement, scheduling methods for repetitive construction projects need to maximize their resource continuity. Resource continuity constraints normally enforce delay in activities to improve continuous resource utilization.

One of the main interests in scheduling linear projects is the ability to keep resources working continuously without idle time. Accordingly, activities should be scheduled in such a way that idle time of resources is eliminated or minimized. Nevertheless, delaying repetitive activities could adversely prolong project duration. Thus, the trade-off between increasing project duration and decreasing idle time must be considered in order to obtain a practical and efficient schedule. The trade-off can be analyzed by performing sensitivity analysis between enforcing and relaxing resource continuity constraints. In order to obtain the most efficient schedule, it is suggested that the analysis of the trade-off be incorporated with the fundamental characteristics of repetitive activities (Liu 1999, Ioannou and Srisuwanrat 2007a).

A number of methods have been presented that optimize resource usage and resource leveling for these projects using different terminologies; e.g. (Eldin and Senouci 1994, El-Rayes and Moselhi 2001, Moselhi and Hassanein 2003, Jun 2010a, Lucko 2010a, Bakry et al. 2013). These methods focus on different objectives including (1) resource leveling e.g. (Ahuja 1976, Mattila and Abraham 1998, Son and Skibniewski 1999, Hiyassat 2000, Son and Mattila 2004); (2) resource allocation e.g. (Ahuja 1976, Chan et al. 1996, Mingozzi et al. 1998, Leu and Yang 1999, Zhang et al. 2006b, Chen and Shahandashti 2009); and (3) the impact of utilizing multiple shifts and overtime hours on construction productivity, duration, and cost e.g. (Hegazy 1999, Hegazy and Ersahin 2001, Moussourakis and Haksever 2004, El-Rayes and Kandil 2005, Zhang et al. 2006a); and (4) probabilistic scheduling e.g. (Ahuja and Nandakumar 1985, Gong and Hugsted 1993, Guo et al. 2001, Lee and Arditi 2006).

- **Probabilistic Scheduling**

A number of optimization methods are presented that take into account probability associated with linear activities with different purposes. El-Sayegh (1998) developed a probabilistic model which accounts for variability and uncertainty associated with linear activities and accordingly produces a linear schedule based on Monte Carlo simulation. The model was included in a software package named “Linear Construction Planning Model” (LCPM). LCPM allows input of work breakdown structures, resource constraints, crew dynamics, and labor and material costs. The software is capable of outputting linear schedules (both deterministic and probabilistic) sorted by different attributes including work areas, crew movement charts, and the active and idle times of crew members.

Srisuwanrat (2009) generated a new algorithm named Sequence Step Algorithm (SQS-AL) to minimize the duration of repetitive projects considering probabilistic activity durations and continuous resource utilization. The research focuses on technical and resource constraints in order to achieve a schedule that eliminates or minimizes idle time in resource utilization. Consequently, the algorithm employs idle time elimination to optimize and balance project time and cost, taking into account uncertainty in work amount and resource productivity. In order to minimize idle time, the Sequence Step Algorithm postpones the arrival date of resources. It is claimed that results from minimizing idle time usually provide cost reduction and productivity improvement. To this end, the concept of work breaks is presented to relax resource continuity constraints in repetitive activities, which in turn may shorten project duration. Work breaks are defined as deliberate interruptions that are not considered idle time since they are carefully pre-determined as a part of the project schedule. Under uncertainty, work breaks relax the resource continuity constraints, while still minimizing crew idle time.

Baqerin (Baqerin et al. 2015) presented probabilistic modeling to evaluate and forecast the schedule performance for each activity in repetitive projects. To achieve this objective, a novel probabilistic model named the Weibull evaluation and forecasting model (WEFM) was developed that uses Weibull analysis and an Earned Value (EV) based schedule forecasting method. Their proposed model uses historical data, baseline schedule plan, and actual progress reports as inputs. Based on the input data, the model creates reliability and prediction graphs through a sound mathematical model.

Other authors have proposed methods that take into consideration project cost flow and its components and optimize project cost e.g., (Hegazy and Wassef 2001, Hyari and El-Rayes 2006, Ipsilandis 2007, Hegazy and Kamarah 2008). Lucko (2010b) has also modeled the cash flow of linear projects using singularity functions. Other methods also took into account the learning curve effect when scheduling resources of linear activities (Tokdemir 2003, Zhang et al. 2014, Ergun and Pradhananga 2015).

2.3. Space Management in Construction Projects

Space is a dynamic and strictly limited resource in construction sites. Construction workspaces constantly change to accomplish different activities throughout the pre-construction and construction phases of a construction project. Site planning has been known to be one of the key factors of efficient management of construction projects (Zouein and Tommelein 2001). Management of project site layout and identification of space conflicts is an important issue raised in many construction job sites. Acknowledging activity workspace requirements and integrating this requirement into the scheduling process provides a number of benefits such as improved safety, fewer space conflicts among workers working on adjacent areas, reduced crew idling, increased efficiency and productivity, and fewer project delays (Thabet and Beliveau 1994, Su and Cai 2013). The main purpose of integration of spatial information into schedules is to prevent available and/or potential congestions. Such congestions are identified as interferences in space and time between resources of subsequent activities. When congestion occurs in construction sites, it not only decreases resource productivity, but also impacts safety, and may lengthen project duration.

Previous research has recognized the importance of space as a construction resource and has subsequently incorporated it as an integral part of planning construction projects (Winch and North 2006, Hildum and Smith 2007). Site planning in construction has been studied in two different domains: (1) the site layout problem which focuses on the location of temporary facilities of various kinds; e.g. (Karan and Ardeshir 2008, Zhou et al. 2009, Andayesh and Sadeghpour 2014, Pradhananga and Teizer 2014, Hammad et al. 2015) and (2) the space scheduling problem, which focuses on planning task execution spaces; e.g. (Thabet and Beliveau 1997a, Thabet and Beliveau 1997b, Dawood and Mallasi 2006, Koo et al. 2013, Choi et al. 2014, Siddiqui 2014).

A number of previous studies focused on space zoning in construction sites. These studies focus primarily on development of solutions for the efficient performance of space zoning, such as securing and efficiently distributing workspaces. Winch and North (2006) developed a decision-making support tool via the identification and arrangement of work spaces for efficient construction. Guo (2002) presented a solution to the problem of productivity loss that occur due to the constraints and path interference in construction workspaces. Akinci et al. (2002) compared the types of time-space conflicts due to space constraints and proposed a solution that determines the precedence of activities. Zouein and Tommelein (2001) analyzed the trade-off between time and space through the adjustment of the activity duration.

Bansal (2011) tackled this problem using location-aware technologies and geographical information system (GIS) . He used the topology of construction sites along with their spatial constraints. The project schedule is to be changed whenever conflicts are detected. Recently, the use of location-aware technologies was expanded by Turkan (Turkan et al. 2012b) to track project earned value throughout project execution. Other methods have also studied the use of location-aware technologies to track schedules and progress of construction projects while also considering space, resource, and time constraints; e.g. (Jongeling and Olofsson 2007, Dzeng et al. 2014, Shah 2014, Riaz et al. 2015).

Accordingly, the issue of space-time conflicts in the construction schedules was raised through a number of studies. Guo (2002) analyzed spatial conflict and temporal conflict separately, introducing two independent interference indicators called the interference space percentage and the interference duration percentage. Other studies used graphical methods to explain potential interferences among trades in the congested areas of the job site (Chua et al. 2010, Koo et al. 2013). Many construction practitioners and researchers developed four-dimensional (4D) models by linking the three-dimensional (3D) components of buildings with the network activities of a project schedule (Mallasi 2006, Moon et al. 2014, Wang et al. 2014c).

As stated earlier, due consideration to space and time constraints and requirements is an important factor in scheduling linear construction projects. Thabet (1992) was the first who included space constraints into the scheduling of linear projects in addition to precedence, resource availability, and resource continuity constraints. Thabet suggested that activities in multi-story buildings are performed within a limited space in which material storage also needs to be taken into account. Ignoring the requirements of work and storage areas may incur a conflict among different trades, decrease productivity, impact safety, and lengthen project duration (Thabet 1992; Thabet and Beliveau 1994). Effectively incorporating the space and continuity constraints into technical constraints, Thabet grouped technical constraints into two categories: horizontal and vertical constraints. The vertical and continuity constraints impose on activities in different units, while the horizontal and space constraints impose on activities in the same unit. During the course of scheduling, these constraints must be satisfied. Riley and Savindo (1995) proposed a space model by defining a collection of descriptive space types and typical space use patterns in multistory building construction. In a recent attempt Shah (2014) also reported the information needed for identification of time–space conflict in earthwork operations of road and railway construction projects.

2.4. Use of Location Awareness in Enhancing Construction Processes

Construction projects often demand a quicker and more accurate approach to information transmission. Accurate and timely understanding of on-site information about work tasks and construction resources facilitates management decisions toward improving construction productivity (Kim et al. 2013). The locations of materials, labor, and equipment, along with the current status of progress, are difficult to be understood at construction sites. This accordingly calls for the development of tools equipped with suitable sensing and communication capabilities to acquire and exchange construction information efficiently.

Location awareness is an emerging application used in the construction industry as a support for scalable decision-making, timely tracking of the project status, surveying, proactive safety hazard prediction and monitoring, and operation and maintenance of constructed facilities (Teizer et al. 2008, Grau et al. 2009, Teizer and Vela 2009, Razavi and Haas 2010, Bansal 2011, Yang et al. 2011, Zhang et al. 2011). Recently, tracking construction workers and materials has received considerable attention. The ability to track material or worker locations in real-time and then utilize this data to deliver decision support information leads not only to the development of "Intelligent Job Sites", but also has the potential to improve monitoring and control of construction projects significantly (Teizer et al. 2013).

Data-capture technologies and devices (e.g., radio frequency identification, laser scanners, sensors, wireless local area network, etc.) started to be used by scholars in the past few decades to increase the speed and accuracy of capturing information from construction job sites. Such on-demand and inexpensive data acquisition from job sites provides access to on-site project information and can significantly improve decision-making during construction execution. The information is retrieved in different forms from construction sites, including but not limited to location-based information, specifications, schedule information, etc. Fast access to the information from construction sites offered by these technologies enables prompt identification, processing, and communication of discrepancies between actual and expected performances. Such an access consequently helps project managers to decide proactively on corrective actions and minimize the cost and delays due to performance discrepancies (Bae et al. 2013).

2.4.1. Location Aware Technologies Used in Construction

In order to facilitate the process of performance data collection from job sites and analyzing the collected data, researchers have focused on presenting methods that can semi-automatically or automatically assess ongoing operations both at project and operation level (Yang et al. 2015). To this end, the first stream of efforts were made to apply sensing technology to construction sites for automated data acquisition. Three-dimensional (3D) sensing technologies, such as total stations, Global Positioning System (GPS), Ultra Wide Band (UWB), laser scanning, and digital photogrammetry, are being studied. Real-time locating systems (RTLSs) are one of the effective ways used to identify and track the locational data of construction objects in both indoor and outdoor environments. As a result, a number of researchers and industry professional have started to use real-time locating system (RTLS) technologies in the construction sector in the past two decades. RTLS is an application used to locate the current geographic position of a person, materials, or equipment. As such, using RTLS facilitates data tracking and management in construction job sites , and is considered as one of the innovations that have changed traditional practices in the construction industry over the last two decades

(Li et al. 2016). The data collected not only can be used for real-time purposes but also for further analysis after a set of data is collected.

Some types of RTLS consist of location sensors (i.e. receivers) and tags/transponders. The tag communicates with the receivers through a signal. Different algorithms such as the received signal strength indicator (RSSI) and the time of arrival (TOA) are then used to calculate the location of the tag/transponder. Other types, such as vision-based positioning systems, do not require tags/ transponders. In a recent study, Li et al. (2016) reviewed use of RTLS in the construction industry and identified ten main RTLS technologies. These technologies are composed of one outdoor positioning system (GPS) and nine indoor positioning systems (IPS) comprising of infrared (IR), ultrasound, radio frequency identification (RFID), wireless local area network (WLAN), Bluetooth, ultra-wideband (UWB), magnetic signals, vision analysis, and audible sound.

Recent advances in sensing technologies have enabled the deployment of a range of simple to complex sets of sensors for identifying and locating targets. These sensing technologies have been used widely for detecting, locating and tracking dynamic construction objects in real time to improve productivity and enhance construction safety. In general, sensing technologies used in construction can be divided into three main categories (Irizarry et al. 2013, Yuan 2014), namely sensor-based technologies, vision-based and Hybrid technologies.

2.4.1.1. Sensor-Based Technologies

One of the most widely used data acquisition strategies is attaching various types of transponders to identify, locate and track materials and equipment on construction sites.

The basic principle is: (1) The necessary information (such as object id, status, vendor name, shipping date, etc.) is written into the chips of the attached tags/ transponders. (2) The receivers can capture the electromagnetic signals which carry the data from the tags/ transponders via local wireless network at radio or microwave frequency, such as Radio Frequency Identification (RFID) and Ultra-Wideband (UWB). As the data carried by the signals to the receivers already contains rich information of the target objects, it is a very straightforward manner to recognize objects. (3) Different locating algorithms are applied to compute the locations of tags/ transponders based on detected information from multiple receivers or readers in the wireless network.

Currently, many research efforts have been made in automated detecting, locating and tracking construction site objects using tag-based sensing technologies. For example, tag-based Radio Frequency Identification (RFID) (Andoh et al. 2012, Kumar and Sommerville 2012) and Ultra-Wideband (UWB) (Zhang and Hammad 2011, Teizer et al. 2013) have been used for recognizing and tracking heavy equipment, labors, and construction materials. Akinci et al. (2006), Kim et al. (2011), Sorensen et al. (2009), and Wang (2008) applied RFID technologies to capture timely and accurate quality data and construction resource information to enhance material management in terms of performance and productivity.

RFID readers can also be equipped with Global Positioning System (GPS) capabilities to determine the locations of RFID readers and, consequently, the locations of RFID tags in a real-world coordinate system (Caron et al. 2007, Torrent and Caldas 2009). Andoh (2012) presented a framework which integrates RFID and GPS as a dynamic tracking system on the construction site to give a better understanding of objects' interactions to all stakeholders. A number of methods have also proposed the use of transponder-based technologies in indoor environments; e.g. (Li et al. 2011, Costin et al. 2014, Costin and Teizer 2014, Li et al. 2014, Ibrahim and Moselhi 2015, Xu et al. 2015).

However, the electromagnetic signals are easily disturbed by various obstacles available in congested construction environment. As such, the low accuracy in localization and unstable performance in accurate detection hinder their application in a construction site (Khoury and Kamat 2007). Besides, it is not economical to attach a tag (such as a RFID tag, a GPS logger, etc.) to each site object and keep maintaining the information stored in each tag (Teizer et al. 2007).

LIDAR is very similar to Radio-wave Detection and Ranging (RADAR) except that it emits laser or infrared respectively instead of radio and microwave. Basically, a laser or infrared signal is sent out of a transmitter, and the emitted pulses are scattered back to the receiver. According to the speed of light, the time of flight or the phase shift between the emitted signal and returned signal, the distance between the sensor and the scanned surfaces can be calculated. It outputs a very dense point cloud vision of the scanned environment with high accuracy, Therefore, as long as the target objects can be segmented from the environment, the performance of location and tracking is quite satisfactory.

Zhang and Bogus (2014) proposed the use of remote sensing technology using digital aerial photography and high-resolution airborne LiDAR for collecting condition information on infrastructure assets. As it requires substantial post-processing to segment objects manually from the dense point clouds in current practices, such as three-dimensional as-built reconstructions (Argüelles-Fraga et al. 2013; Bosché 2012; Gilsinn et al. 2005; Tang and Alaswad 2012; Yue et al. 2006), it is still a big challenge in automating the process of object segmentation and even more difficult to implement such technologies for object detection, location and tracking at real-time or near real-time.

2.4.1.2. Vision-Based Sensing Technologies

As a traditional vision-based sensing technology, digital cameras and camcorders emerged on construction sites recently. This sensing technology is easily accepted by people owing to its "what you see is what you get" impression in a form of 2D or 3D images. Various image processing algorithms has been developed by computer vision field aiming at automated detection and tracking of specific objects from 2D images or video frames. Besides, in order to tell the 3D location of the detected objects, photogrammetry/videogrammetry investigated the relationship between 2D image space and 3D object space, and designed specific algorithms for different scenarios to restore the 3D information from the 2D images or video frames.

Therefore, the next stream of studies investigated existing algorithms to detect, locate and track construction objects using vision-based sensing technologies. For instance, Zou and Kim (2007) used image color space to detect hydraulic excavators. Teizer and Vela (2009) used video cameras to track personnel on construction sites. Rezazadeh Azar and McCabe (2011) used Haar-histogram of Oriented Gradients (HOG) to extract the features of dump trucks and used Haar–HOG cascade method to detect dump trucks. Teizer (2008) applied a three-dimensional (3D) range imaging camera as part of active sensing technologies to collect range data. The collected range data was used to generate real-time feedback about the location of objects in the field of view of the sensor, and thus to allow fast and accurate range measurements. Zhu and Donia (2013) also used RGB-D cameras in modeling building indoor environments. Another example is the webcam systems offered by EarthCam Inc., which has been used for construction site monitoring and progress recording. Using this webcam systems, 2D image processing algorithms can be used for object recognition (Rezazadeh Azar and Mccabe 2011, Uslu et al. 2011). However, there are still two big challenges in use of vision-based technologies: (1) automated object detection process, because of the low accuracy of objects detection, especially for objects with kinematic movement (such as an excavator) and (2) real-time locating and tracking processes, owing to low performance of 3D spatial coordinate's reversed calculation from 2D images (Gore et al. 2011, Uslu et al. 2011).

2.4.1.3. Hybrid Technologies

The hybrid image-point cloud sensing technologies have minimized the challenges associated with both image-vision based sensors (such as camera/camcorder) and point-cloud vision based sensors (such as LIDAR/IRDAR). However, there is still one big challenge unsolved which is caused by the complexity and variety of construction objects, lacking a generic modeling approach to analyze varying objects, and a follow-up "seamless" workflow to automated detecting, locating and tracking dynamic objects in real-time or near real-time. As a result, emerging hybrid range sensing technologies, such as color depth cameras, have a great potential in achieving real-time object recognition and tracking in an efficient manner. Color-depth cameras capture both color (gray or

RGB) images and point clouds at high frame rates. As color-depth cameras can detect depth information in point cloud format, dynamic tracking will be simplified without any intermediate transformation between image space and object space (Teizer et al. 2007). For object recognition, image processing algorithms and three-dimensional point cloud algorithms can be combined and supplement each other. Liefeng et al. (2011) also proposed a set of depth kernel descriptors (such as size, shape, edges, etc.) to improve the accuracy of object recognition using RGB-depth cameras.

2.4.1.4. Mobile Computing and Smartphones

Mobile phone sensing is another emerging area of interest for researchers of different industries including construction. Sensor-enabled mobile phones or smartphones are becoming the center of the next revolution in many areas including green applications, global environmental monitoring, sensor-augmented gaming, virtual reality and smart transportation systems (Khan et al. 2013). Unprecedented opportunities has been opened during last decade to improve the existing processes of on-site construction management through the advent of smartphones and mobile computing technology (Kim et al. 2013). The previous studies demonstrated that mobile computing technologies have great potential to improve various construction activities significantly, including material tracking, safety management, defect management, and progress monitoring. The potential improvement is largely attributed to the enhanced mobility of computing devices, which allows users at any location to access and share important construction project information in an efficient manner. Chen and Kamara (2008) performed research on how mobile computing technology, consisting of mobile devices, wireless networks, and mobile applications, can be used in construction site environments to retrieve and transfer on-site information.

The recent strengthened features of smartphones including: GPS navigation, high-resolution color touch screen, digital camera, sensors, and high-speed data transfer enable a new generation of on-site management processes, such as location-based customized work orders, real-time information exchange, and augmented reality (AR)-based site visualization. GPS navigation provides the localizing capability that allows a user to have customized information based on a unique location. A large touch screen with a high-resolution color display allows a user to search intuitively for needed information on the mobile computing device. A digital camera is an effective monitoring tool that can record numerous site conditions for progress monitoring and quality management. Smartphones are also equipped with gyroscope and accelerometer to understand device orientation promptly. As such, these added features provide an ideal environment for the AR-based display of construction information. Finally, high-speed data transfer capability, using either a WLAN (802.11b/g Wi-Fi) or a Wideband Code Division Multiple Access (WCDMA, 3G)/Long Term Evolution (LTE, 4G) data networks, enables the fast access to information on the server located in a remote place.

On the other hand, the full potential of sensing technologies can be achieved only when the information collected on the job site is effectively distributed and shared among project participants in timely manner. The real-time project information can enable a range of project participants, including project managers, site engineers, and construction workers, to make informed decisions. In particular, the flow of information to the level of construction workers can generate a new breed of knowledge workers. As a result, a number of researchers focused on providing solutions for use of mobile technologies to enable collaborative management. Pena-Mora and Dwivedi (2002) presented a collaborative management platform that enables project participants in different locations to share project information using mobile computing devices.

Bowden et al. (2006) made effort to engage industry professionals and illustrate to them how the use of mobile information technology can improve construction processes. The industry response showed enthusiasm, along with indications of some typical barriers to overcome. Chen and Kamara (2011) introduced a framework for the implementation of mobile computing on construction sites, comprising of an application model and a technical model. The application model identified key factors, such as mobile computing, construction personnel, construction information, and construction sites, and explored the interactions of these factors, whereas the technological model generalized mobile computing technologies to provide a structure for designing mobile computing systems. Son et al. (2012) investigated the factors that influence the successful application of mobile computing devices in the construction industry. They found that user satisfaction plays as an important indicator of implementation success and that satisfaction is more likely to be affected by usefulness rather than user-friendliness of the tools. Dong et al. (2009) presented a method for construction defect management that made use of telematic digital workbench, a horizontal tabletop user interface integrating mobile computing and wireless communication. Subsequently, the defect information collected by on-site mobile devices is synchronized with their 3D model in the server to provide reduced information loss between site and office collaboration.

Reinhardt et al. (2005) described a navigational model for mobile computing users to effectively create and manage different views of information contained in various processes. The model established direct links between appropriate information representations and entities of a process model, resulting in the elimination of retrieval and matching operations during run time. Behzadan et al. (2008) argued that a mobile worker's spatial context must be continuously tracked in both outdoor and indoor environments for a location tracking system to effectively support construction projects. They described the use of Wireless Local Area Network (WLAN) for indoor tracking and GPS for outdoor spatial context tracking for an integrated tracking technique targeting ubiquitous location sensing. Lipman (2004) discussed the use of the Virtual Reality Modeling Language (VRML) on handheld mobile computers. He showed several examples of 3D structural steelwork models visualized on a handheld mobile computer and identified some of the limitations imposed by the visualization technology.

2.4.2. Applications of Location Aware Technologies in Construction

A host of researchers used a hybrid of the stated technologies and had come up with different approaches for construction site monitoring; e.g. (Grau 2011, Cheng et al. 2012, Chen et al. 2014) as well as monitoring of existing buildings; e.g. (Volk et al. 2014). Kim et al. (2010) integrated RFID and ZigBee to manage materials on construction sites by acquiring real-time information. Closed circuit television (CCTV) has also been used to monitor construction sites remotely (Leung et al. 2008). Another line of work focused on using data collected from sites to be informed of actual (semi-) real-time progress on site. Some methods made efforts to automatically generate 3D as-built point cloud models of the ongoing construction and then compare the documented as-built model to the underlying 4D BIM e.g. (Brilakis et al. 2011, Golparvar-Fard et al. 2011). Bosché et al. (2015) presented a case of using as-built 3D laser scanned data for tracking MEP components with circular cross-sections including pipes, and some conduits and ducts in order to compare as-built data with planned works.

The advent of 3D BIM directed many of the newer approaches towards active use the (3D) information contained in BIM models. This has led to development of supervised object detection and recognition algorithms that more effectively process the point cloud data (El-Omari and Moselhi 2008, Golparvar-Fard et al. 2009b, Bosché 2010, Turkan et al. 2012b, Changmin et al. 2013). The fact that these approaches highly rely on prior BIM information certainly imposes limitations; but these limitations will diminish over time due to rapid adoption of BIM across the industry for building design, construction, and asset management (Bosché et al. 2015). Karsch et al. (2014) presented a constrained-based procedure to improve the image-based 3D reconstruction. More intelligent data collection methods such as (Zollmann et al. 2014) and (Siebert and Teizer 2014) are also proposed that make use of aerial robots for collecting progress images.

The synergy of technologies enables multiple functions to work collaboratively and thus deliver a more effective and seamless working process (Lu et al. 2014). For example, Zhang et al. (2009) developed a collaborative multi-agent system using field data–capturing technologies accompanied by agents, wireless communication technologies to improve real-time monitoring, and planning of construction sites. Tserng et al. (2005) streamlined the information transition process of data identification and acquisition from a job site to a field office by using automated reality capture technologies (laser scanners, bar code scanning, and radio frequency identification).

Raza (2013) propose a state of the art fusion framework of Computer Vision (CV) and RFID to support object recognition and tracking in a three-dimensional space. Su et al. (2014) presented an enhanced boundary condition method integrating RFID and real-time kinematic (RTK) global positioning system (GPS) to control the accuracy of a locating system. In recent attempts, innovative methods are proposed that make use of Xbox Kinect for tracking construction workers and spatial modeling on construction sites (Rafibakhsh et al. 2012, Weerasinghe et al. 2012). Augmented Reality is another ground-breaking technology that has been proposed for tracking construction processes; e.g. (Behzadan and Kamat 2009, Golparvar-Fard et al. 2009b, Dong and Kamat 2013, Wang et al. 2014b).

Use of location-aware technologies also can help in improving the safety of construction resources and processes (Becerik-Gerber et al. 2013). As such, a number of applications have been proposed to reduce hazards and accidents and improve safety; e.g. (Marks and Teizer 2012, Choe et al. 2013, Luo et al. 2013, Park et al. 2015a, Park et al. 2015b, Wang and Razavi 2015). In addition, researchers have studied several emerging technologies for automating project inspection with a focus on different areas including supply chain progress (prefabrication and lay down yards), productivity of workers (through location and action tracking), and tracking structural work progress and qualityusing different technologies: Radio Frequency Identification (RFID) e.g. (Grau et al. 2009), Ultra-Wide Band (UWB) e.g. (Cheng et al. 2011), 2D imaging e.g. (Wu et al. 2009), Photogrammetry e.g. (Brilakis et al. 2010), and three-dimensional (3D) Terrestrial Laser Scanning (TLS) e.g. (Ahmed et al. 2014). Lee et al. (2009) established a safety monitoring system at a site where fall accidents often occurred, based on ultrasonic and infrared sensors, and a wireless telecommunication system. Pena-Mora et al. (2010) presented an information-technology-based collaboration framework to facilitate disaster response operations. The framework incorporated a web collaboration service, RFID tags, a building black box system, a geo-database, and a Geographic Information System (GIS).

Tserng et al. (2005) demonstrated the effectiveness of a bar-code-enabled Personal Digital Assistant (PDA) application to enhance information flow in a construction supply chain environment. Wang (2008) proposed an RFID-based quality management system for monitoring and sharing quality data. The system was applied to the inspection and management of concrete specimens in order to improve automated data collection and information management in a quality test lab. Yin et al. (2009) presented a precast production management system by integrating PDA with RFID. The system encompassed functionalities such as inspection of incoming materials, production process inspection, mold inspection, and specimen strength feedback. Kimoto et al. (2005) developed a mobile computing system with PDA for managers on construction sites. Without relying on any automated identification technology, the system was able to assist construction managers in inspecting finished works, referencing project documents, checking the positions of structural members, and monitoring project progress. Kim et al. (2008)

proposed a PDA-based real time defect management system that for timely performance of corrective actions.

2.5. Cyber-Physical Systems

2.5.1. Information and Communications Technologies (ICT) Use in Construction

Although the uptake of technology in the construction industry is slow in comparison to many other industries, particularly manufacturing, new technologies are making access to real-time data on construction sites. Over the last two decades, the construction industry has started the move towards being more automated. This is because the main reason behind construction projects being overtime and/or over-budget was found to be the gap between project design and actual project execution (Anumba 1996, Repass et al. 2000). In other words, computers and the construction environment have traditionally been highly incompatible. The manual methods of data transfer used were tedious, time-consuming, and prone to error.

Started in earnest in the last three decades of the 20th century, information and communications technologies (ICT) attracted a considerable amount of attention by researchers in the architecture, engineering, and construction (AEC) industry attempting to address a spectrum of operational and managerial issues (Lu et al. 2014). Both technological and managerial advancements of ICT application in the AEC industry and organizations have been significant (Peansupap and Walker 2005). Use of ICT in construction has greatly helped in improvements in different aspect of the industry including across-organizational collaborative design, enterprise-level data-driven decisions, ICT-enabled safety monitoring and control, global virtual working environment, timely and accurate information capture and transmission, massive information collection among organizations, diversified information–based decision making, human knowledge–based decision making and computing or simulation-based decision making (Akinci et al. 2006, Kim et al. 2010, Lu et al. 2014). The automated data transmission and decision making made available through ICT further helps in improvements in different phases of construction projects, from design to construction and lifecycle management (Lu et al. 2014).

Recent research shows the trend of introducing innovative functions through advanced programming, elaborative and interdisciplinary applications to the construction practices. With the availability of advanced technologies, digital information grows rapidly, such as electronic documents and images, 3D or four-dimensional (4D) information, and spatially oriented information archived by global positioning systems or geographic information systems (GIS). Digital information brings critical information to the construction document management sector. For example, Bäckblom et al. (2003) and Hjelt and Björk (2006) investigated electronic document management systems to store, record, and exchange documents produced during a construction project in an electronic and digital manner. Caldas et al. (2002) and Caldas and Soibelman (2003) developed automatic document classification systems to provide easy deployment and scalability to the classification process of digital files, and thus to improve information organization and access in inter-organizational systems.

Smart construction objects (Niu et al. 2015) are other advancement made available in the industry. Smart objects are construction resources (e.g., machinery, tools, device, materials, components, and even temporary or permanent structures) that are made smart through being augmented with sensing, processing, and communication abilities so that they have autonomy and awareness, and can interact with the vicinity to enable better decision making. López et al. (2012) define SOs as objects that are not only capable of providing their unique identification and condition information, but can also perform object-to-object communications, ad hoc networking, and object-centric complex decision making. They sense, log, and interpret the occurrence of themselves and the world, act autonomously, communicate with each other, and exchange information with people.

The application of mobile technologies and automatic knowledge and data transfer becomes more versatile in construction projects every day (e.g., Chen and Kamara 2008, Nourbakhsh et al. 2012, Irizarry and Gill 2009, Lee et al. 2009, Xue et al. 2012, Lim et al. 2014, Zhu et al. 2013, etc.). Tan et al. (2007) proposed a methodology comprising of web-based knowledge base, integrated work-flow system and project knowledge manager as the administrator for the live capture and reuse of project knowledge. Their method, allows project knowledge to be captured live from ongoing projects. Irizarry and Gill (2009) further developed IT applications on iPhone development platform to provide access to safety-related information to the on-site construction personnel. Williams et al. (2007) developed a dynamic path planning system to improve mobile robot navigation in a dynamic building construction site. For this purpose, they made use of mobile robots, an ultra-wideband (UWB) position system, and a portable computer over a WLAN.

A number of methods made use of Building Information Modeling (BIM) and 3D modeling along with sensing technologies and WSN to enhance automation and real-time data transfer in construction sites; e.g. (Arslan et al. 2014, Koseoglu 2011, Goulding et al. 2014, Lee et al. 2011). Motamedi and Hammad (2009) proposed a method for lifecycle management of facility components using RFID tags and BIM. The authors proposed permanently attaching RFID tags to facility components where the memory of the tags is populated with BIM information. There has also been attempts by the industry to integrating field BIM and precast concrete installation using RFID tags (Sawyer 2008).

2.5.2. Cyber Physical Systems

In an environment as data intensive as construction, bi-directional real-time communication and coordination between the constrcutin models and the physical construction on site is an important need for enhancing feedback or controlling processes (Akanmu 2012b). Bi-directional coordination is a two-way integration of models and physical artifacts such that changes in one are automatically reflected in the other. In order to maintain such bi-directional coordination, computational resources are required to tightly integrate the virtual models and the physical construction. This is termed a cyber-physical systems approach.

Cyber-Physical Systems (CPS) refer to the “next generation of engineered systems that require tight integration of computing, communication, and control technologies to achieve stability, performance, reliability, robustness, and efficiency in dealing with physical processes” (Kim and Kumar 2012). CPSs are systems in which physical components and processes (i.e. the physical space) are tightly integrated with computational/control resources (i.e. cyber space) to exhibit a degree of continuous coordination between the two (Krämer 2014, Suh 2014, Krishna 2015). In other words, cyber-physical systems are physical and engineered systems, whose operations are monitored, coordinated, controlled and integrated by a computing and communication core (Karsai and Sztipanovits 2008, Rajkumar et al. 2010, Suh et al. 2014). CPS uses computations and communication deeply embedded in and interacting with physical processes to add new capabilities to physical systems (Krogh et al. 2008).

Integration of physical processes and computing is not new. The term "embedded systems" has been used for some time to describe engineered systems that combine physical processes with computing (Lee 2008a). Cyber-Physical Systems added to the existing embedded systems through interaction and estimation that are intensely embedded in physical processes and components; adding different characteristic and possibilities to them. Physical processes are compositions of many parallel processes operating in continuous time that involves natural or human-made systems and is governed by the laws of physics. Such additions to the physical components help in the automatic control and computation to be performed in cyber space. The cyber space, on the other hand, acts as a central information hub. Data is transferred to the cyber space from every physical component. After data is collected, specific analytics have to be used to extract information that provides better insight over the status of individual components and processes. The design process of a Cyber-Physical system will require an in-depth understanding of the physics of the application area. This means that the cyber and physical part of the system cannot be designed independently. In other words, Cyber-

Physical Systems integrate the dynamics of the physical processes with those of the communication, providing the platform for modeling, design and analysis of all the components as a whole (Shi et al. 2011).

2.5.3. Cyber Physical Systems Applications

Cyber-Physical Systems is changing the way physical operations in different industries interrelate with their planning and control systems. Originated from computer science, CPS have been promoted and applied in a number of fields including manufacturing, aerospace, power grids, agriculture, healthcare, and transportation. In the manufacturing industry, CPS has been deployed to help manage dynamic changes in production e.g. (Kaihara and Yao 2012). In aerospace industry CPS is used for different purposes including automatic pilot avionics, aviation management as well as making an intelligent adaptive cyber-physical ecosystem for the aerospace workforce; e.g. (Noor 2011). Smart grid technology is being developed using CPS applications in power grids (Krogh et al. 2008, Shi et al. 2011). The healthcare industry is also increasingly relying on CPS for networked medical systems and health information networks as well as medical devices; e.g. (Kim et al. 2010, Wu et al. 2011, Lee et al. 2012). Use of CPS in improving agriculture systems includes data management of production experiments, fundamental geographic information of farmland, micro-climate information and other data (e.g. Zhijun et al. 2003, Agnelo et al. 2010).

The application of CPS in Transportation systems has been even more versatile than other industries. In fact, Vehicular Cyber-Physical System (VCPS) is not a new concept. It refers to a wide range of integrated transportation management system which should be real-time, efficient and accurate. Based on modern technologies such as computers, sensors, and networks, the traditional modes of transport are becoming more intelligent. The applications of these smart systems in transportation include but are not limited to promoting the development of intelligent traffic systems, cooperative vehicle safety (CVS), Intelligent Transportation Systems (ITS), connected vehicles, automated vehicles and smart highways, etc. e.g. (Fallah and Sengupta 2012, Wu 2012). Fallah and Sengupta (2012) presented a cyber-physical approach to improving cooperative vehicle safety (CVS) which is based on the cooperation of vehicles in achieving real-time situation awareness for the purpose of safer (and possibly autonomous) driving.

There are methods that tried to move transportation systems towards being smarter using Internet of Things (IoT) concepts leading to safer and smarter network of vehicles under the concept of Internet of Vehicles (Wu 2012). In recent years, there are discussions also to integrate intelligent transportation systems into smart cities, where information and communication technologies (ICT) are used to enhance quality and performance of urban services, to reduce costs and resource consumption, and to engage more effectively and actively with its citizens e.g. (Deakin and Al Wear 2011, Frost and Sullivan 2014).

Similar to other industries, construction can also benefit from the greater project control and monitoring through appropriate integration of automated systems and emerging information and communication technologies in the physical construction process (Anumba et al. 2010). Recently, construction academics started to utilize automatic bi-directional features of CPS in ameliorating construction processes and tracking. These applications include ameliorating different stages of construction projects from the pre-construction stage (Khalid et al. 2014) to improving construction progress monitoring and control in construction phase (Akanmu et al. 2012, Akanmu 2012a, Akanmu et al. 2013a, Akanmu et al. 2013b, Akanmu et al. 2013c, Akanmu and Anumba 2014) and infrastructure health monitoring and control e.g. (Yuan et al. 2014).

Akanmu (2012) and Akanmu et al. (2013) used different case scenarios to illustrate the applicability of cyber-physical systems in realistic construction situations. The scenarios illustrate potential enhancements in the steel erection process made through use of cyber-physical systems approach. In Akanmu et al. (2012, 2014) the authors also presented an approach to component-level CPS integration using light fixtures as an example. Khalid et al. (2014) presented an integration of Cyber-Physical Systems with Augmented Reality (AR) as a decision support tool in the pre-construction stage. Yuan et al. (2014) applied the CPS approach in health monitoring of temporary structures in job sites, including temporary support systems such as earthwork sheeting & shoring, temporary bracing, soil backfill for underground walls, formwork systems, scaffolding, and underpinning of foundations. Turkan (Turkan et al. 2012a) also generated a real-time method to track project earned value throughout project execution.

2.5.4. Features of Cyber-Physical Systems

Advancement of science and engineering is improving the CPS features constantly; thereby dramatically increasing the functionality, reliability, adaptability, autonomy, safety, and usability of Cyber-Physical systems. The main features of CPS systems include (Li et al. 2009, Shi et al. 2011, Kim and Kumar 2012):

- **Closely integrated:** Generation of CPS requires tight integration between computation and physical processes. This makes CPS different from desktop computing, traditional real-time/embedded systems, and today's wireless sensor networks.
- **Cyber capability in every physical component:** The computation processes are embedded in every physical component.
- **Networked at multiple and extreme scales:** Technically, CPS are distributed systems; including various networks namely wireless/wired networks, Bluetooth, GSM, WLAN, etc. The scale and categories of devices vary from one system to another.
- **Complexity:** The dynamics of CPSs is complex, involving the stochastic nature of communication systems, dynamics of computing systems, and continuous dynamics of control systems.
- **Dynamically re-organizing/reconfiguring:** Such versatile and complex systems require highly adaptive capabilities.
- **High degrees of Automation:** As a result of the high level of embedded interaction between components and the need to real-time actions to be taken based on retrieved information, CPSs require automatically advanced feedback control technologies to enhance the automatic data transfer between all components.

2.5.5. Challenges of Cyber-Physical Systems

Cyber-Physical Systems can be widely applied to different areas as mentioned above. Despite its inevitable advantages, designing such systems for different environments has its own challenges. Different studies have investigated the challenges associated with modeling the bi-directional nature of CPS and each of its components e.g. (Lee 2007, Lee 2008a, Derler et al. 2012a, Gujrati 2013). Two main categories of challenges are listed in Figure 4.

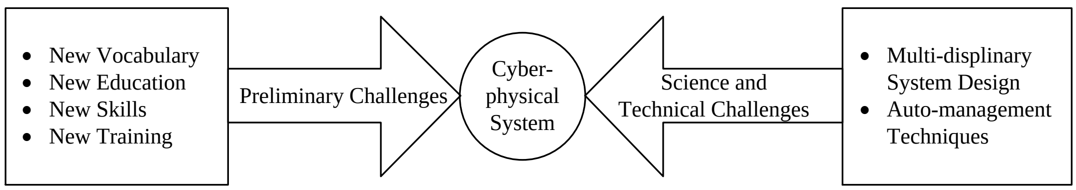

Figure 4:Challenges of Cyber-Physical Systems

- **Preliminary challenges:** In order to start applying such complex systems in different aspects of everyday life, we need professionals with a new set of skills as well as the new vocabulary of components to use for building these complex systems (Lee 2008b). As the complexity of such systems is increasingly concentrated in software and electronics, the traditional disciplinary boundaries need to be realigned in all levels of training and education.
- **Science and technical challenges**: These challenges include but are not limited to sensor data abstraction, pattern discovery, information fusion and classification, multidisciplinary knowledge requirement, modeling and analyzing cross-domain interactions among physical and computational/networking domains as well as communication and networking (Sarkar 2011, Sztipanovits et al. 2012, Hu 2013). Several of the challenges also arise fundamentally from the complexity and heterogeneity of CPS applications. The complexity of models is mitigated by using more specialized, domain-specific models and by using modeling languages with

clear, well-defined semantics (Derler et al. 2012b). These new challenges require a new integrated approach to multi-disciplinary system design trends that take into account factors impacting both the cyber and physical world simultaneously; where computational abstractions need to include physical concepts, such as time and energy.

2.5.6. Cyber Physical System Architecture

As the name is self-explanatory, CPS includes two general spaces, i.e. physical and cyber space. The physical space is the source of information, and the cyber space makes use of the generated information to perform analysis, make a decision, and accordingly optimize and control the physical processes (Sarkar 2011, Krishna 2015). Each of these spaces can be divided into different interactive layers, each comprising of different components needed to get the system to work.

In general terms, layers of a CPS include the physical layer, the computation/control layer, and the application layer (Karsai and Sztipanovits 2008, Lu et al. 2013) as shown in Figure 5. The physical layer falls under the physical space of the system, while computation/control and application layers are forming the cyber space. The key physical components forming the physical system include interacting physical devices such as sensors, sensor devices, actuators, as well as the physical objects of the process under consideration and information and physical laws defining each of these (Kazemi 2010). In other words, the Physical layer consists of natural or human-made systems that are governed by the laws of physics and are operating in continuous time. Sensors and actuators are used as means of interaction between computational/control and physical layers.

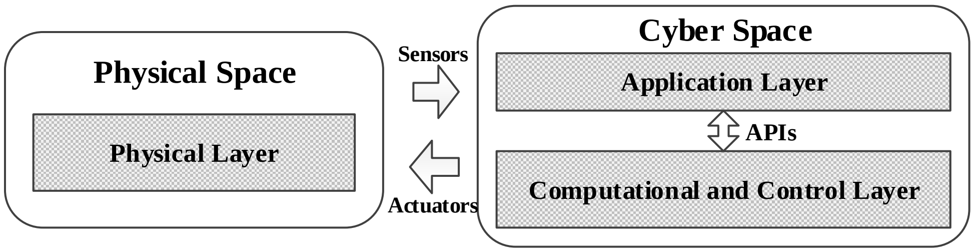

Figure 5: Cyber-Physical System Architecture

The cyber space is defined as a set of computational processes running on computing platforms that is superimposed on the physical space and continuously observes and monitors its changing state. Such observations are made by sensors (a physical measurement device). The data retrieved through sensors is processed, interpreted and fused to generate required information of the physical space (depending on the application) without losing its semantics. The control decisions and required actions are communicated back to the physical space through actuation control. The information communication between the physical and cyber spaces by means of sensors and actuators is achieved through wired or wireless networks based on the application (Sarkar 2011, Gujrati 2013).

The most important aspect of the designing CPS is to discover knowledge about the system from sensor observation and then use the knowledge to adaptively control the underlying physical system. The information retrieved from physical component through sensing process is then transferred to computation/control layer for knowledge discovery/transmission. This is performed in computation/control layer through different elements and processes; leading to control of the whole system and decisions making. The information depicted from the computation/control layer is either transmitted to the physical layer to deploy required changes/modifications, or it is transmitted to the application layer via application program interfaces (API). The application layer serves the purpose of applying the Cyber-Physical System for the domain it is designed for. Further, this layer makes the output of the whole process to be intractable for external agents such as human beings.

2.6. Summary

This chapter presented a review of the literature in the areas related to scheduling and control of construction projects in general and linear projects in particular. The evolution of resource-driven scheduling along with their various applications and expansions for better management of construction projects were also discussed. The moves towards recent trends of real-time project control in construction are also discussed. The literature review helped identify some common assumptions in earlier models along with their advantages and limitations.

Through the comprehensive literature review, following places for improvement were found: The methods presented for scheduling and planning linear projects, consider one productivity rate per each time interval (optimum productivity rate) for the associated activities. This way, other possible productivity rates that can be achieved by their resources at each time interval without delaying activities are not taken into account. As such, space and time flexibilities and constraints of linear activities and other possible productivity rates that can be taken at each time interval are overlooked. This accordingly reduces the flexibility of the generated schedules in responding to unforeseen deviations from the plans. Therefore, and can cause any deviation from the planned productivity to create delays and cost overruns.

Furthermore, the current methods do not account for potential congestion that is likely to happen in the schedules of linear projects due to deviations from the planned productivity rate of the resources. As such, integrating space-time constraints and flexibilities of movement of resources will improve the efficacy of the generated schedules in dealing with not-as-planned situations during construction. In addition, successful, timely, and on-budget implementation of linear projects requires efficient management of sequentially used resources not only in the planning phase, but also throughout the project execution. Current methods do not accommodate real-time bi-directional monitoring of the linear projects based on the actual progress achieved on site during the project execution is another area to be studied further.

As such, this research aims at contributing to the body of knowledge of planning and control of linear projects through addressing the mentioned gaps. For this purpose, an effective schedule optimization framework is proposed. The proposed framework integrates workspaces of linear activities' resources and the inherent uncertainties into their schedule in the planning stage. As such, the present study not only takes all the logical, project-dependent and precedence constraints of activities into account, but also incorporates the space and time constraints that co-exist for the movement of resources of all linear activities. This way, space and time flexibilities and constraints of linear activities are accounted for in the planning phase of linear projects. Potential congestion that is likely to happen due to deviations from the planned productivity rate of the resources are also accounted for and are minimized. The framework is not limited to the planning phase, and further presents a means for bi-directional monitoring and control of linear projects as is discussed in following chapters.

3. Chapter Three: Research Methodology

3.1. Chapter Overview

As it was stated in previous chapters, after thorough review of the state of the art of planning and control of linear projects, a number of potential areas for advancement were found. This research aimed at addressing current needs for advancement. This has been accomplished in different steps, each step delivering a different deliverable, where the problems found in one step were served as the motivation to pursue to the next step to resolve the identified problem. In order to find a solution to the research question of each step, the author has reached out to other disciplines to take benefit of advances in other industries and domains. As such, at each step of the research, a trans-domain search was carried out to discover potential concepts/methods that could be adopted and used for the purpose of this study. The general framework of the research including three development steps and their deliverables in illustrated in Figure 6. This chapter briefly discusses the organization of the research study with due consideration to the sequential steps taken and the developments made in each step. Each step of the research is elaborated in more detail in a separate chapter thereafter.

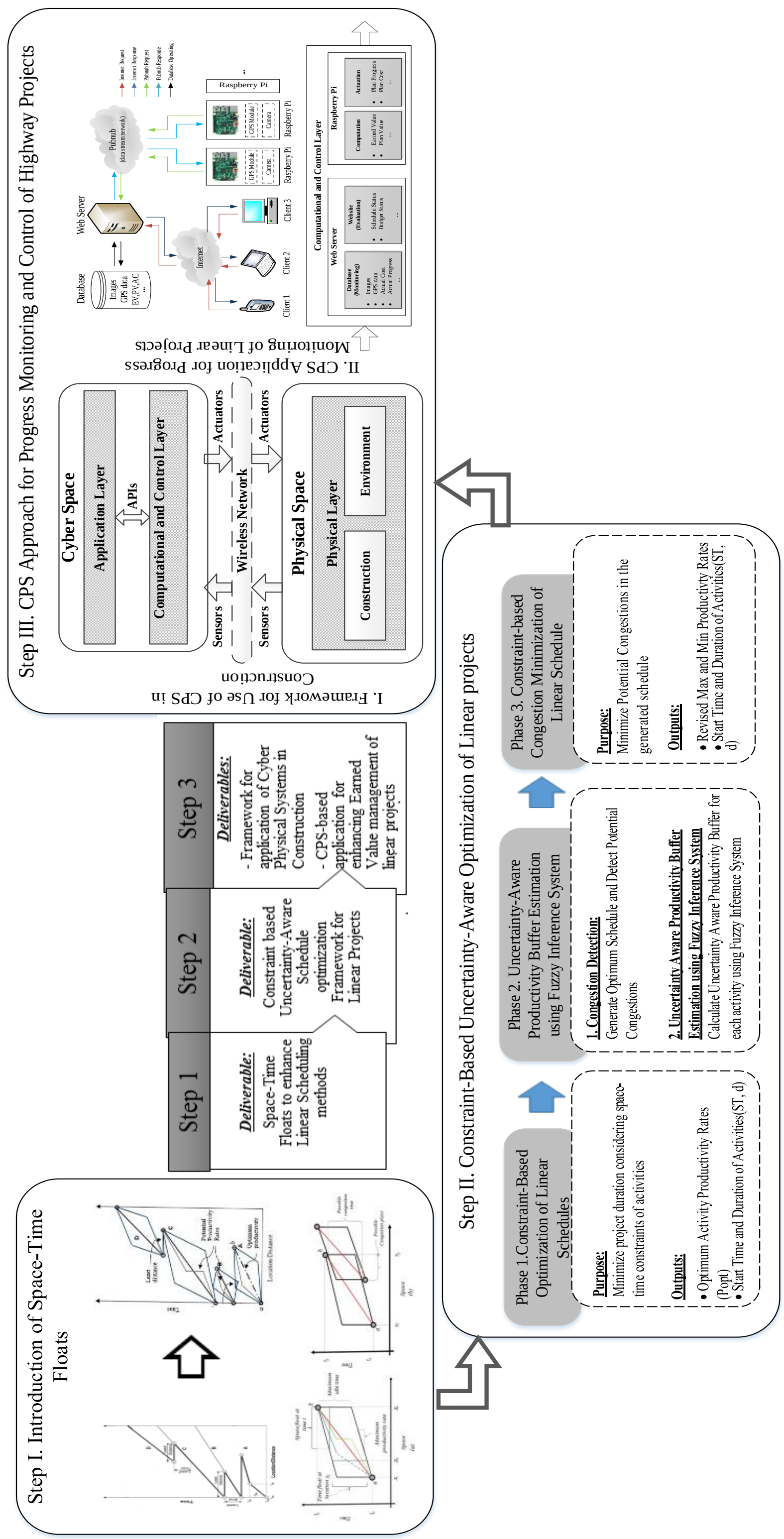

Figure 6: Proposed Planning and Control Framework

3.2. Research Organization

As discussed in previous chapters, the main motivation behind this research study was to advance the current scheduling methods presented for linear projects through incorporating the space and time flexibilities and constraints of the movements of their activities' resources. For this purpose, the research first introduces augmentation to linear scheduling methods through introduction of Space-Time Floats. The notion of space-time floats is introduced in this research as part of a location-aware linear scheduling and control system. A space-time float is an envelope for all possible movement patterns that a linear activity or its associated resources can take considering the time and space constraints of that activity. Use of space-time float and adding it to the schedules of linear projects enables the linear schedules to adapt to variable production rates at each time interval (in essence exchanging time for space and vice versa). As such, the space-time float schedule is not limited to one planned productivity rate per time interval for each activity, but in turn uses the whole range of possible productivity rates that are available to each activity at each point in time and space. Chapter Four presents the details and merits of space-time float based scheduling of linear projects.

Due consideration to space and time flexibilities of linear activities achieved through Space-Time Floats not only helps in generation of more realistic and flexible schedules, but also enables identification and forecasting of potential space-time conflicts/congestions. These congestions are caused as a result of potential deviations from planned productivity rates of activities, frequently happening in construction job sites, and accordingly are called potential congestions. Deviations from planned productivity rates of linear activities may cause their respective resources to be placed at the same space over the same period of time, resulting in congestions in the job site. As a result, pre-identification of places and times where congestions are probable to happen provides a potential to minimize work disruptions and delays caused by such congestions during construction.

To this end, the research was then taken to the next level to optimize the generated schedules and to minimize their potential congestions. For this purpose, an uncertainty-aware schedule optimization framework is proposed. The framework uses constraint satisfaction approach to find the optimum duration of linear projects that also minimizes the potential congestions in their schedule. The proposed schedule optimization method has three essential phases. These phases include: 1) Constraint-Based Optimization of Linear Schedule; 2) Uncertainty-Aware Productivity Buffer Estimation using Fuzzy Inference System 3) Constraint-based Congestion Minimization of Linear Schedule. The details of the proposed uncertainty-aware linear scheduling method are presented in Chapter Five.

Generated linear schedules need to be monitored in real-time to ensure timely implementation of project deliverables and efficient management of sequentially used resources of linear projects. This can be achieved through integration of all project components including project schedules and documents, actual construction processes on site, as well as project management systems and technologies. Such integration offers significant potential for better collaboration, coordination, and communication in all construction projects including linear ones. Effective bi-directional interactions between cyber and physical components and processes of construction projects offered by Cyber Physical Systems can help in achieving this objective.

In order to derive the most benefit from Cyber-Physical Systems in for the purpose of this research, first, a framework for Cyber-Physical Systems approach in Construction Applications is presented in Chapter Six. The proposed framework illustrates the CPS architecture including layers, components and phases as well as their inter-relations to be used in construction applications. Such framework helps in better understanding of Cyber Physical Systems, accordingly leading to taking the most out of CPS-based applications in construction.

The research is then taken into the next level and adds real-time bi-directional control into the generated scheduling framework as discussed in Chapter Six. For this purpose, the proposed CPS-based framework is used to enhance progress monitoring and control of highway and road projects as representative of linear projects. The proposed approach uses a micro-processor to enhance Earned Value management of road and highway construction. Raspberry pi, a simple micro-processor, equipped with different modules is utilized to retrieve the required progress information, perform calculation and analysis and to transfer them to the cyber space of the system. A web server is used to host the cyber space; to store the retrieved information and to transfer the results back to the construction site through the Raspberry Pi.

As such, the framework presented in this study is considered as both a planning and control tool. The method enables detection of potential project delays, space-time congestions, work disruption and resource idling, cost overruns and accordingly suggesting corrective actions throughout project planning and execution. This helps in timely prediction and/or detection of these potential/actual problems and accordingly enables preventing or decreasing their effect on the project budget and time. It should be noted that this research is validated step by step through a number of literature-based and/or field-based case studies. The validation of each developed step is presented at its corresponding chapter.

4. Chapter Four: Introduction of Space-Time Float to Linear Scheduling Method

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4.1. Chapter Overview

As discussed earlier, in the main motivation behind this research study was to augment current linear scheduling methods through addition of space and time flexibilities and constraints of the movements of their resources. To this end, a trans-domain search was carried out. The concept of Time-Geography from human geography domain was found promising in bringing the needed values to linear scheduling methods. As such, the developments made in this study was initially inspired by this concept. Taking benefit of Time Geography concept, the new Space-Time Floats are introduced in this research.

The space-time float is a multi-dimensional float that presents an envelope for all possible movement patterns that an activity or its associated resources can take considering the time and space constraints of that activity. The movement patterns and the location of resources (i.e., crews and equipment) can be used not only for awareness of the status of each activity, but also as a key indicator of resource productivity. This chapter first introduces space-time floats in detail and elaborates their essential features along with their importance in planning linear activities. The potential of space-time floats for tracking linear schedules is then presented. To this end, an input locational data received from location-aware technologies is needed. However, retrieval of the locational data is beyond the scope of this research and as such the tracking part is presented solely as a potential enhancement. The focus here rather is to demonstrate conceptually and numerically the potential of providing a proactive response to delays, eliminating the idle time required for the site data to be transferred to the main office and their corrective decision to be sent to the site.

4.2. Time-Geography

In the 1960s and 1970s, Hägerstrand (Hagerstrad 1970) and his associates at the Lund School, Sweden formed new concepts of space and time with respect to the field of human geography, which became known as time-geography. Powerful in methodological concepts, their work resulted in a better understanding of mapping human movement through space and time (Carlstein et al. 1978). The essence of time geography is the construction of a visually appealing space-time prism to depict and demonstrate the time and space allocation of human activities and movements (Kraak 2003b). This representation in which time is integrated to a 2D geographic plane, offers an alternative view on spatio-temporal movement of human beings (Miller 1991, Kraak 2003b, Delafontaine et al. 2011).

Time-geographic research considers spatial and temporal dimensions for human activity participations. Then it utilizes the key concepts of a space–time path to illustrate how a person navigates through the spatio-temporal environment. The space-time path traces the movement of an individual in space and time (Miller 2005). The faster the individual travels, the more sloped the path segment will be. At higher speeds, the same amount of time can be traded-off for more distance, and at lower speeds the inverse is true. Such path is graphically represented in 3D space by using two spatial coordinates (s1 and s2) and one temporal coordinate (t) as shown in Figure 7(a). The space-time prism is an extension of the space-time path. It gathers all space–time paths an individual might take within a specific time budget. Given a set of spatial and temporal anchors and constraints, a space-time prism is the volume of coordinate triplets where an object could be while still complying with all the movement constraints and fixed events (see Figure 7(b)). The space-time prism also measures the spatio-temporal limits of reachability, the maximum velocity of physical movement, and the minimum time required for an activity. Space-time anchors represent fixed activities, such as going home and work: that is, activities that are relatively difficult to reschedule or relocate. Space-time anchors condition physical accessibility by compelling where and when discretionary travel and activities must start and end, whereas travel velocities determine the trading of time for space in movement between anchors and discretionary activity locations. In other words, movement can be classified as actual and potential. Actual movement is represented by a space-time path, the set of space-time coordinates that describe the trajectory of a moving object. Potential movement is represented by a space-time prism, which consists of the set of space-time coordinates where an entity can potentially be, given a set of constraints.

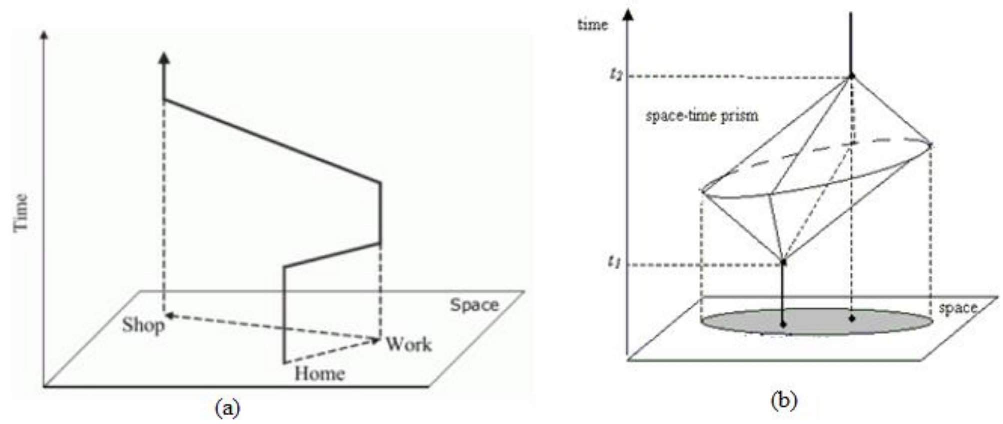


Figure 7: Realization of a) Space-Time Path and b) Space-Time Prism

4.3. Linear Scheduling Enhancement Through Time-Geography

The simple but yet effective ideas of time-geography as explained above are very much comparable to the parameters considered in scheduling linear projects. The space-time anchors are representative of activity start and end location-times that are usually fixed. The space-time paths are representative of resource movement patterns while executing a linear activity, where the slope of the path (the so-called velocity in time-geography) is comparable with productivity rate of activity resources, which is deemed as the main parameter in scheduling linear projects. The potential movements presented by space-time prism also enables due consideration to space and time flexibilities and movement constraints of linear activities. As such, this study takes benefit of these features to augment current linear scheduling methods and accordingly introduces Space-Time Float Prisms to scheduling of linear projects.

4.4. Generation of Space-Time Floats

Construction of space-time prisms is informed by the following considerations. First, spatially dispersed activities have predetermined locations where they must begin or end; these are called spatial anchor points. In the case of linear projects, these spatial anchor points are defined as the pre-planned start and end location of each activity. Second, activities are scheduled to take place at determined times, which implies the existence of predetermined points in time where they should start and end; these are called temporal anchor points. Likewise, these temporal anchor points are translated as start and finish times planned for each construction activity. Finally, activities proceed at a certain speed, which, in the case of construction, is determined by acceptable productivity rates (i.e., physical progress achieved). The slope of a path segment is determined by the productivity rate of the activity. Higher productivity, with faster progress, results in a steeper slope of the path segment because the same amount of time can be traded off for more distance; at lower speeds the inverse is true.

The linearity of the activities implies that they start at a certain location, continuously progressing towards their end location, with a certain productivity rate. This movement also needs to be completed in a predetermined time interval, i.e., the planned duration for the activity. In this case, the start and end locations for all activities correspond to the start and end location for the entire project, which constitutes one section where all activities are to be executed. For larger projects, however, the project is usually divided in different sections that possibly include different activities. As a result, the start and end locations for various activities could be different. The start and end times for different activities can be the same, or might be different. Figure 8 describes the steps of scheduling the project through generation of space-time float prism and potential controlling of its progress at different time intervals.

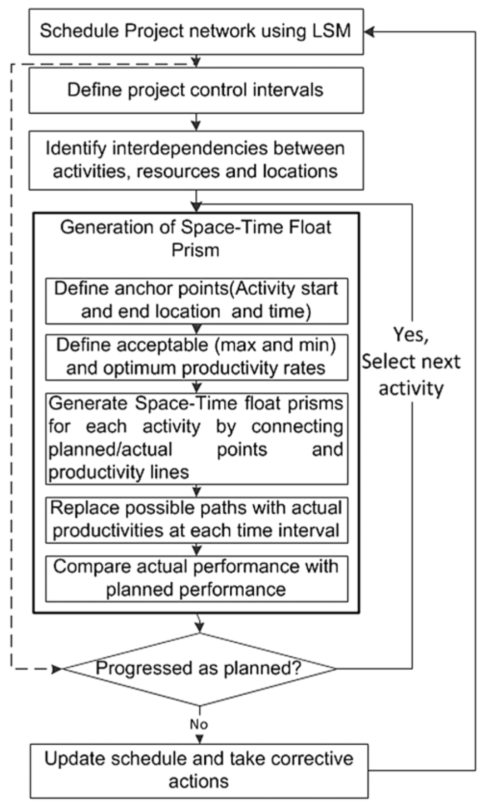


Figure 8: Flowchart of the space-time scheduling and monitoring model

Employing the definitions stated previously, the space-time prism is characterized by an origin (a departure space-time anchor) from which an activity moves towards a destination (a target space- time anchor) at speeds determined by maximum and minimum productivity rates. Figure 9(b) illustrates the elements of a space-time prism. In the figure, point "a" represents the anchor at location (x_i, y_i) and time (t_i) where an identified activity must begin. Likewise, point "b" represents the anchor at location (x_j, y_j) and time (t_j) where the activity must end in order for subsequent activities to begin. The value of (t_j –

t_i) equals the acceptable duration of the activity. The slope of a line is determined by the inverse of the productivity rate for each activity, and therefore a vertical slope represents idle time, meaning that the activity stopped at certain location for some time.

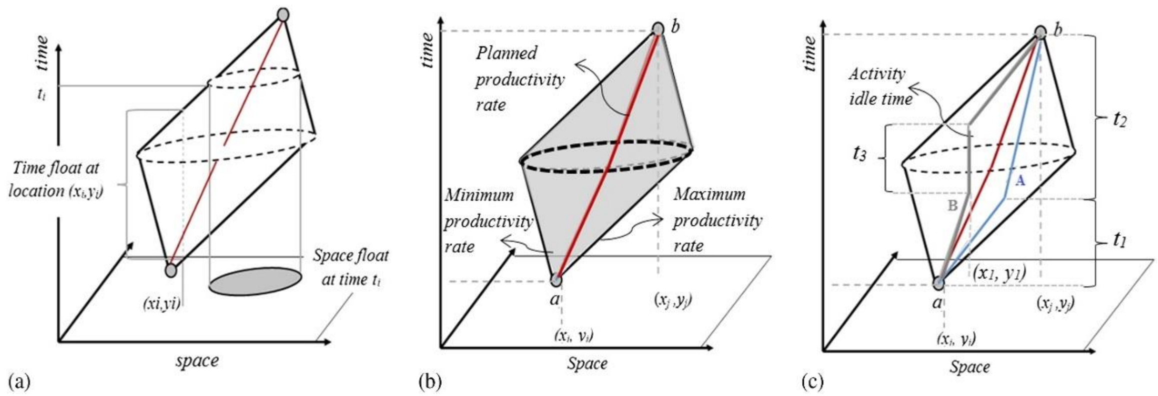


Figure 9: (a) Realization of space and time floats at given times and locations; (b) space-time float prism; (c) realization of different productivity rates within space-time float prism

The slope of space-time paths in each time interval is an indicator of crew productivity in that interval. The actual productivity rate cannot exceed the maximum, and therefore all possible paths are contained within the prism. The preferred path can be identified as the path for which the line slope at each time interval is equal to the planned productivity for that activity during the corresponding time interval. Only forward motion is considered when generating a space-time prism for activity of linear projects. This is because the activities of these projects start from one anchor and progress by moving forward. For detailed calculations of the prism boundaries (maximum and minimum productivities), readers are encouraged to see Lenntorp (1976).

The most important added benefit of addition of Space-Time Float into scheduling linear projects is that it provides a better understanding of the combined space and time floats that are available for each activity. Generation of these prisms permits instantaneous identification of space and time floats that are already used in other methods, but at each time and location. As shown in Figure 9(a), the image of the vertical line connecting boundaries of the prism at a certain location is representative of the time float that is available to the resources of that activity at that specified location (x_i , y_i), i.e., the potential time intervals that an activity's resources would be present at a certain location. Similarly, space floats show the space that is available to the resources of a given activity at a certain time without exceeding the boundaries of productivity for the resources.

Of higher priority is to identify the combination of space-time floats available to each activity at a certain time during its execution based on its current progress. This way, even if an activity has progressed slower than projected, the combination of available space and times is used to continue the activity while still finishing at the preplanned completion date. As shown in Figure 9(c), the space-time prism for an activity comprises different potential paths that represent different production rates for the activity. It also graphically presents the possibility of existence of different production rates within one path. For example, path "A" in Figure 9(c) shows that the activity started with a higher production rate at the beginning (time interval t_1) and slowed down with lower production rate in time interval t_2. Also, path B comprises idle time for the activity, meaning the resources of the activity have been stopped at a location (x_1, y_1) for time interval t_3.

Further, by plotting space-time floats for all activities within a project network, possible areas of space overlap and crew congestion can be detected. In these situations, the space-time floats of those possibly interrupted activities are overlapped. The intersection areas show the locations in time and space where interruptions and congestion are more likely to happen (Figure 10). Zones where the largest overlap between space-time floats of resources required for different activities happens show places where immediate actions should be taken to avoid productivity decreases. Subsequently, management decisions can be taken to minimize such congestions. In this fashion, the planned finish times of those activities might need to be revised, which accordingly influences all successor activities.

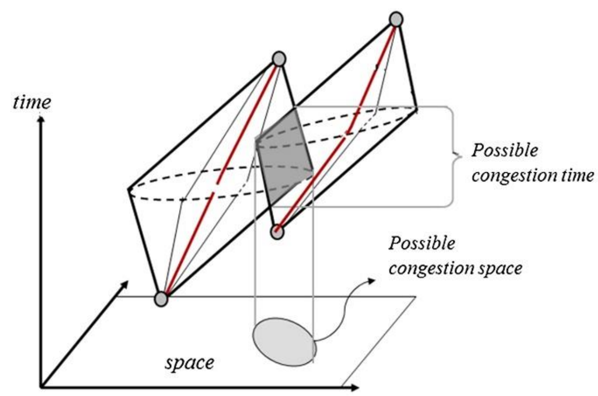


Figure 10: Realization of congestion zones and times between activities

Space and time floats detected separately for each activity thus combine to assist in the identification and control of potential congestions zones. This is done through elimination of floats that would potentially lead to congestion and interactions between resources of succeeding activities. As a result, the space-time floats available for each activity can be recalculated and provided.Figure 10 illustrates the realization of space-time congestions and regeneration of respective activity floats. As seen in the figure, the area under the intersection between the prisms for two succeeding activities illustrates the possible space in which congestion is likely to occur between the two activities in case of any deviation from their planned productivity rates. The time that such congestion is likely to happen is also detected. The three-dimensional (3D) prism (the congestion prism) formed from such intersection also shows locations and times that the congestion is possibly happening by deviating from planned productivities.

4.5. Location-Aware Control Using Space-Time Float

Actual paths can then be identified based on spatial information of resources collected during the location-sensing process. As seen in Figure 11, actual movement patterns are updated based on tracked movements of resources at different time intervals and can be compared with the planned paths. The dashed line in the figure shows the actual path for the activity. In the example shown in Figure 11, because the observed productivity is less than the projected productivity, a correction (i.e., increase in productivity) is required in the following time interval if the activity is to finish within its time budget. In contrast, the dotted line indicates that the productivity rate has been higher than projected and therefore resources may be reallocated or a float introduced to avoid finishing before the next activity can possibly begin. These data are then transferred to the project scheduling and control system to update the schedule and plan for corrective actions as needed.

The potential location-aware control made available through generation of space-time floats uses locational data as an input to identify the location of construction resources including material, crews, and equipment (Roofigari Esfahan et al. 2013, Roofigari-Esfahan et al. 2015). The method is implemented in MATLAB environment to demonstrate its capabilities. It should be noted that in case of linear projects, because of one dimensional progress of the project alongside the direction of the project, space-time floats can be presented in 2D, respectively called space-time float polygon. To enable schedule generation using space-time floats and potential controlling of the generated schedule, first, project activities are classified as repetitive and non-repetitive activities. The repetitive activities are then saved and a monitoring time interval is set based on the nature of each activity. Other time intervals are also set as general monitoring times based on the overall scheme of the project schedule and interdependencies between activities. These time intervals are used to track the status of the project. After the location information of the required resources is identified, the data are transferred to the scheduling and control system and the project schedule is updated accordingly. The updated schedule is then compared with the original schedule to determine the current status of the project. Based on the tracked movements of resources and comparing gained productivity rate with planned productivities, different corrective strategies are applied.

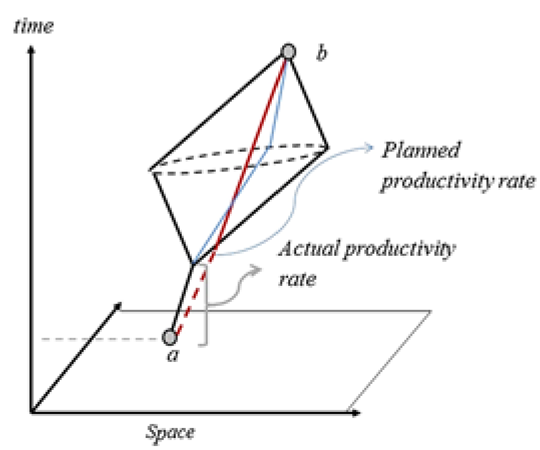


Figure 11: Updating space-time prisms using actual productivities

These strategies include but are not limited to the following: Observed productivities can be used as a measure to calculate finish time of activities. Therefore, possible delayed activities are detected and corrective actions can be taken. Also, in the case in which the actual movement pattern shows that an activity is idle, scheduled start and finish times of that activity and the overall project can be revised. In such a case, in order to better manage the project's crew continuity and resource control, the crews of the idle activity can be reassigned to nearby activities.

As expected, by increasing the number of activities more space-time float prisms will be added to the scheduling process. Alternatively, the number of operations can be reduced by bundling related activities through work packaging. The same can also be done in case of existence of different resources executing the same activity; a space-time prism is generated for each resource, and then all the prisms for different resources are bundled, leading to the overall schedule for that activity. Bundling resources or activities is a topic of study for the future work. Figure 12 shows application of the proposed method to a simple numerical example and compares it with the LSM schedule generated for the same example. The start and end times of different activities need not to be the same, meaning each can start and finish at any point during a project life cycle. The figure shows that although considering only the optimum productivity rates does not show any congestion between activities, by considering space-time float prisms a better realization of potential congestions is provided.

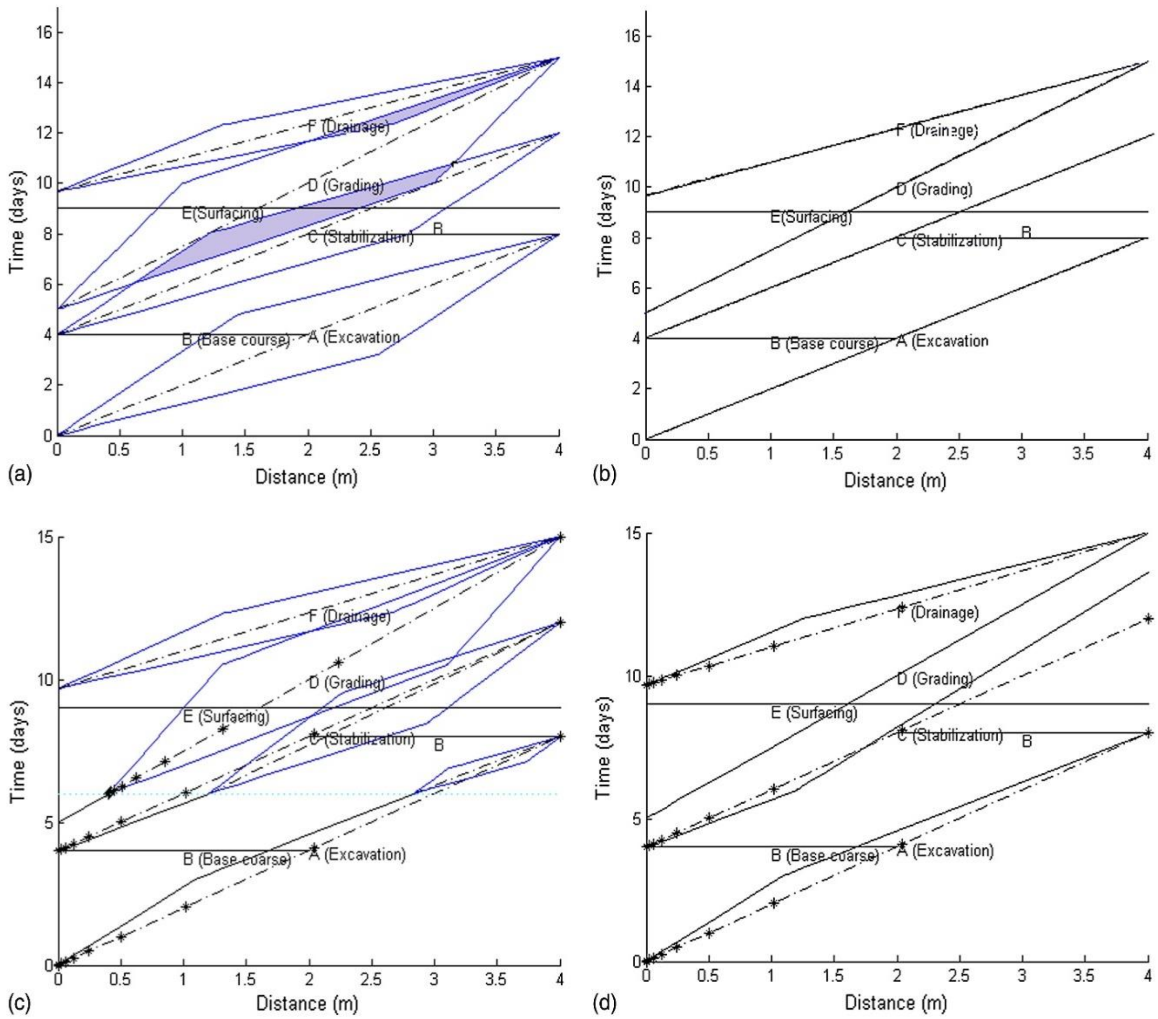


Figure 12: Case example: (a) baseline schedule using space-time float prism; (b) baseline schedule using LSM method; (c) tracked schedule and revised prisms at t = 6 days; (d) as-built schedule at t = 15 days

5. Chapter Five: Constraint-Based Uncertainty-Aware Optimization of Linear projects

5.1. Chapter Overview

After the linear schedule is generated using space-time floats, the proposed framework goes though the next step to optimize the generated schedule and to minimize its potential congestions. For this purpose, an uncertainty-aware schedule optimization method is proposed. The three essential phases of the proposed uncertainty-aware schedule optimization method include: 1) Constraint-Based Optimization of Linear Schedule; 2) Uncertainty-Aware Productivity Buffer Estimation using Fuzzy Inference System; and 3) Constraint-based Congestion Minimization of Linear Schedule (see Figure 13). The schedule optimization framework uses different tools to achieve the optimum duration of linear projects that is associated with the least potential congestions. These tools include 1) Space-time float; (2) Constraint-Satisfaction optimization and (3) Fuzzy Inference Systems.

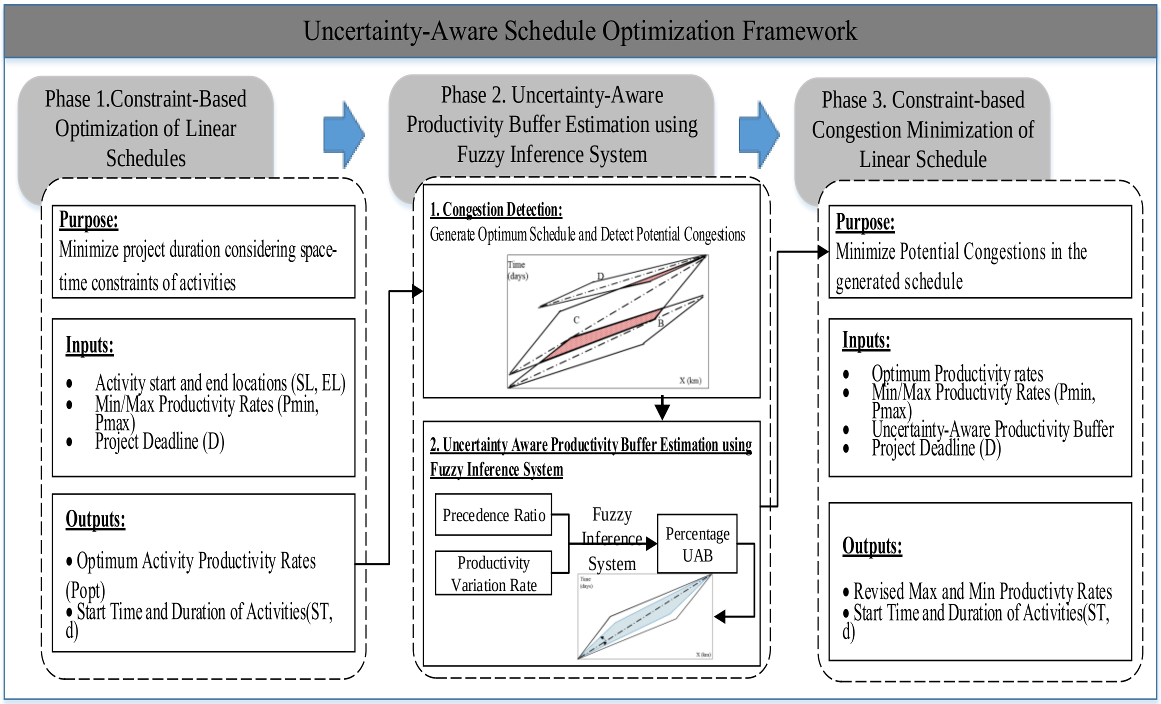


Figure 13: Uncertainty-Aware schedule optimization method

5.2. Phase I. Constraint-Based Optimization of Linear Schedules

The first phase of the proposed schedule optimization method is a Constraint Satisfaction Problem (CSP)-based optimization model. This phase establishes minimum-duration linear schedule with due consideration to all space-time constraints and flexibilities of linear activities. To facilitate the use of CP algorithms in scheduling problems, a powerful optimization package, termed IBM ILOG CPLEX Optimization Studio (Beck et al. 2011), was developed incorporating a CP optimizer engine that offers features specially adapted to solving scheduling problems. ILOG CPLEX Optimization Studio was used and the ILOG OPL language was adopted here as the model formulation language.

5.2.1. Constraint Programming

Constraint programming (CP) is a programming paradigm for solving Constraint Satisfaction Problems (CSPs) through using a combination of mathematics, artificial intelligence, and operations research techniques (Chan and Hu 2002; Liu and Wang 2012, Tang et al., 2014b). Constraint Satisfaction Problems are defined by a set of variables, X_1; X_2; …; X_n, and a set of constraints, C_1; C_2; …; C_m. Each variable X_i has a non-empty domain D_i of possible values. Each constraint C_i involves some subset of the variables and specifies the allowable combinations of values for that subset. A state of the problem is defined by an assignment of values to some or all of the variables. An assignment that does not violate any constraints is called a consistent assignment. A complete assignment is one in which every variable is mentioned, and a solution to a CSP is a complete assignment that satisfies all the constraints.

When solving an optimization CSP problem, the objective function in the problem is treated as a constraint and this additional constraint forces the new feasible schedule to have a better objective value than the current schedule. The upper or lower bounds of the constraint are replaced as soon as a better objective function value is found. The propagation mechanism narrows the domains of decision variables to reduce the size of the search space while recording the current best schedule. The search terminates when no feasible solution is found (Pinedo 2008; Liu and Wang 2008).

Apart from being applicable to solving a variety of problems, constraint programming has particular advantages in solving scheduling problems (Chan and Hu 2002; Heipcke

1999, Menesi et al., 2013) due to: (1) its efficient solution search mechanism, (2) flexibility to consider a variety of constraint types, and (3) convenience of model formulation. As such, constraint programming is suitable for modeling and solution finding of the project scheduling optimization of linear projects and accordingly has been selected to be used for the purpose of this study.

5.2.2. Constraint-Based Duration Optimization of Linear Projects

In the problem specification stage of the optimization, the objective and the variables are determined. The object of this phase is to minimize duration and the decision variables include the start time (ST) and optimum productivity rates (P_{opt}) of all activities. The search engine then explores these options and finds the productivity rate for each activity that minimizes the overall project duration. It should be noted that the method at this stage is generated in 2D. The following constants, variables, constraints, and objectives were adopted in the construction of the first phase of the CSP-based model:

Constants:

The values of constants will not change during problem solving of the CSP; these constants include:

SL_i *Start location of activity i;*

EL_i *End location of activity i;*

$P_{min,i}$ *Minimum productivity rate of activity i;*

$P_{max,i}$ *Maximum productivity rate of activity i;*

Ltmini,j *Minimum time required between activity i and activity j;*

Ltmaxi,j *Maximum time required between activity i and activity j;*

D *Project deadline;*

Where; i, j ∈{0..n} , n: number of project activities;

Decision variables:

Popti *Optimum resource productivity rate of activity i;*

$P_{opti} \in \{P_{mini}, P_{maxi}\}$;

ST_i *Start time of activity i;*

$ST_i \in [0, D]$;

Where; P_{opti}*: Optimum productivity rate of activity i and* ST_i *Start time of activity i;* P_{mini}*: Minimum productivity rate of activity i;* P_{maxi}*: maximum productivity rate of activity i;*

Constraints:

The precedence relationships between activities are considered as the main constraints applied to the optimization model. In this study, all types of precedence relations are taken into account, namely: Finish to Start (FT), Start to Finish (SF), Finish to Finish (FF) and Start to Start (SS). In addition, the model is not limited to the constraints between succeeding activities. Accordingly, any type of constraint between any two activities is taken into account. The minimum and maximum times required between subsequent activities are also accounted for when considering the precedence relationships between succeeding activities. Following fixed constraints are also applied to the optimization model.

Fixed Constraints:

$ST_i \geq 0$;

$ET_i \leq D$;

$ET_{la} \leq D$;

$ST_{fa} = 0$;

Where; ETi = End time of Activity i; la = Last activity of the project and fa= First activity of the project;

Objective Function:

$$\text{Minimize (Max } (ET_i)), \text{ For all } i \in \{1..n\}; \quad (1)$$

$$ET_i = ST_i + \frac{EL_i - SL_i}{P_{opti}} \quad (2)$$

The output of this phase is the start time and the optimum productivity rates for all project activities which lead to the minimum project duration. Activity durations are then calculated through Equation 3;

$$d_i = ET_i - ST_i; \quad (3)$$

The start and end coordinates, i.e. start and end location and times, of all activities along with their maximum and minimum productivity rates are then used in the second phase to generate the schedule in form of Space-Time Float polygons and to calculate Uncertainty-Aware Productivity Buffers.

5.3. Phase II. Uncertainty-Aware Productivity Buffer Estimation Using Fuzzy Inference System

After the schedule is optimized in the first phase and optimum project duration along with the optimum productivity rates for each activity are identified, the schedule is generated in this phase. The second phase is modeled in a MATLAB environment. In order to transfer the data generated in the previous phase, a spreadsheet interface is used between the CPLEX and MATLAB environments. The data transferred include number of project activities, activity IDs and the information required to generate Space-Time Float polygons for each activity as shown in Figure 14. This information includes the start and end coordinates of all activities in form of (SL, ST) and (EL, ET), respectively, their optimum productivity rates as well as minimum and maximum productivity rates (polygon boundaries). The potential congestions in the generated schedule is then detected as follows.

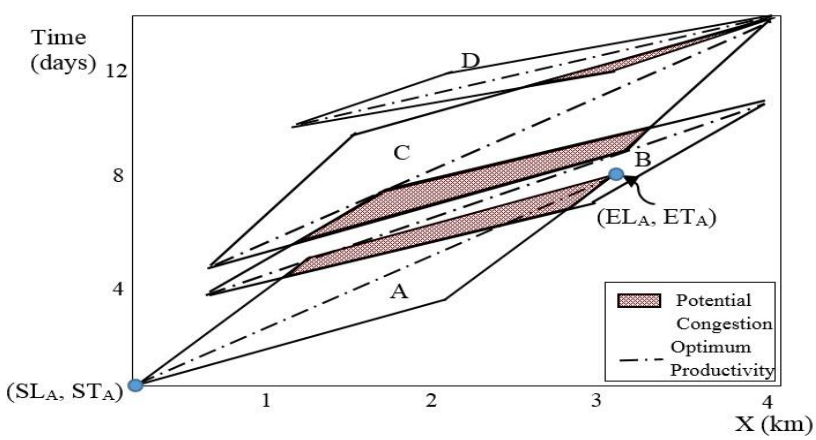


Figure 14: Detection of Potential Congestions between Activities

5.3.1. Space-Time Congestions

As it is shown in Figure 14, the generated schedule may contain overlaps between Space-Time Float polygons of succeeding activities. Such overlaps accordingly demonstrate the potential congestion between resources of the overlapping activities caused by deviation from planned productivities. Deviations from planned productivity rates of linear activities cause their respective resources to be placed at the same space over the same period of time, resulting in congestions in the job site. Such deviations mainly occur due to uncertainties in weather, design, labor efficiency, equipment efficiency, site conditions, etc. These unforeseen uncertainties need to be anticipated and accounted for upfront, in the planning stage, to be able to address any changes occurring during execution. This will subsequently enable identification of places and times where congestions are probable to happen; providing a potential to minimize delays caused by such congestions. To this end, the method presented here introduces a novel approach to account for uncertainties associated with planned productivities of linear projects in activity level. For this purpose, a new type of buffer named Uncertainty-Aware Productivity Buffer is introduced and estimated using Fuzzy Inference System as described in the next section.

5.3.2. Uncertainty-Aware Productivity Buffer

The Uncertainty-Aware Productivity Buffer (UAB) presented in this study is defined as the maximum tolerable (vs. potential) deviation (uncertainty) from planned productivity rate where the impact on the schedule needs to be minimized (Figure 15). In other words, a certain percentage deviation from planned productivity is accepted to occur when planning activities. Any congestion within the accepted buffer, as presented by red-shaded areas in Figure 15, needs to be prevented from occurring through improvement of the schedule. In contrary to the other methods that model uncertainty buffer associated with activity duration, the UAB considers the uncertainty associated with planned productivity rates of the linear activities. This buffer also enables due consideration to both time and space uncertainties. It should be mentioned that Uncertainty-Aware Productivity Buffer is considered here in activity level, and is different from one activity to another. A fuzzy inference system is proposed to be used for calculation of the buffer for individual project activities.

Different project-based and activity-based factors can affect the uncertainty buffer that needs to be considered for each linear activity. For this framework, contextual information about precedence relationships and productivity variation of the activities are used to form the input variables of the fuzzy inference system, and the activities' uncertainty-aware buffer is the output. Although these contextual variables have effect on the amount of uncertainty buffer, their boundaries as well as contribution to the buffer are fuzzy as they are highly dependent on the activity itself as well as the project conditions. These boundaries need to be estimated by experts through judgmental statements that are vague and imprecise. As such, fuzzy inference system was selected as a means for formulating the mapping from these input variables to the output using fuzzy logic. Consequently, uncertainty is captured by the notion of "belonging" to a range. The fuzzy system design parameters, their definitions, and the inference rules are explained subsequently.

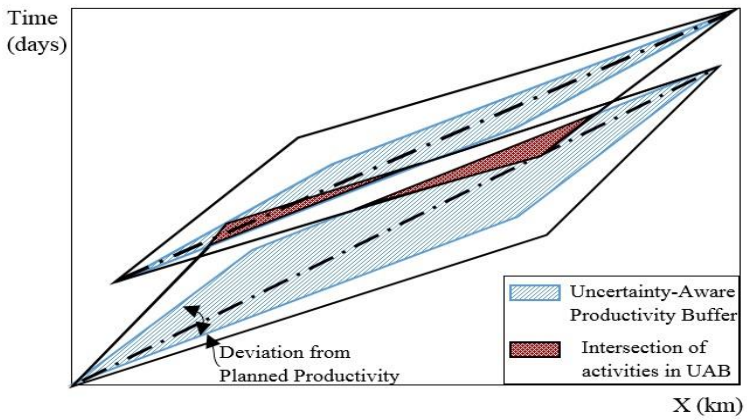


Figure 15: Uncertainty-Aware Productivity Buffer

5.3.2.1. Fuzzy Input Variables

To better account for the inherent uncertainties and to more accurately define the buffer size, it is crucial to factor in various distinctive project attributes. In order to calculate the UAB size for individual activities, first the factors that introduce uncertainties need to be identified. In this study, Precedence Ratio (PR) and Productivity Variation Rate (PVR) are considered as the two factors that can define the tolerability in deviation from planned productivity. These variables are defined as follows and can be arbitrarily used on the basis of availability and management judgment.

- **Precedence Ratio**

The contextual variable Precedence Ratio implies the relevance of a particular activity with other activities in the project network. When an activity has more number of successor activities in the project, its uncertainties and as a result delays and distortions is more likely to influence its succeeding activities and result in delays in the project.

Thus, a smaller uncertainty-aware productivity buffer is desirable for this activity. The PR can be measured using Equation 4:

$$PR_i = {}^{N_{Succ,i}}\!\big/_{N_{A,i}} \qquad (4)$$

Where; $N_{succ,i}$ = number of the successors of activity i; and $N_{A,i}$ = number of activities in the path(s) that contains activity i. The PR fuzzy variable can have values of High, Medium and Low, depending on the ratio. Figure 16 (a) shows the membership function for this input variable.

- **Productivity Variation Rate**

The contextual variable Productivity Variation Rate (PVR) is directly related to the Space-Time float of the activity and represents the flexibility of a particular activity. The flexibility of a linear activity here is defined as its productivity boundaries from minimum to maximum productivity rates, used to generate Space-Time Float Prism of that activity. In other words, linear activity flexibilities are presented by the possible variation from optimum productivity rate of an activity within its productivity boundaries. Prior research has shown that activities with less flexibility are less likely to be completed on time (Yang et al. 2009) and therefore require larger buffers. The value of the PVR of activity i can be determined as shown by Equation 5:

$$PVR_i = \frac{P_{max,i} - P_{min,i}}{P_{opt,i}} \qquad (5)$$

Where; PVR_i is the Productivity Variation Rate for Activity i; $P_{max,i}$, $P_{min,i}$ and $P_{opt,i}$ are maximum, minimum and optimum productivity rates of activity i, respectively. Consequently, when activity i has low flexibility and thus small space-time float, it imposes higher risk on the on-time completion of successive activities and accordingly requests for higher buffer. In contrast, when activity i has high flexibility and thus large space-time float, it is less likely to delay successive activities, and accordingly less buffer need to be assigned. In this fuzzy inference system, PVR can have the values of High, Medium and Low depending on the flexibility of the activity. Figure 16(b) presents the membership function for this input variable.

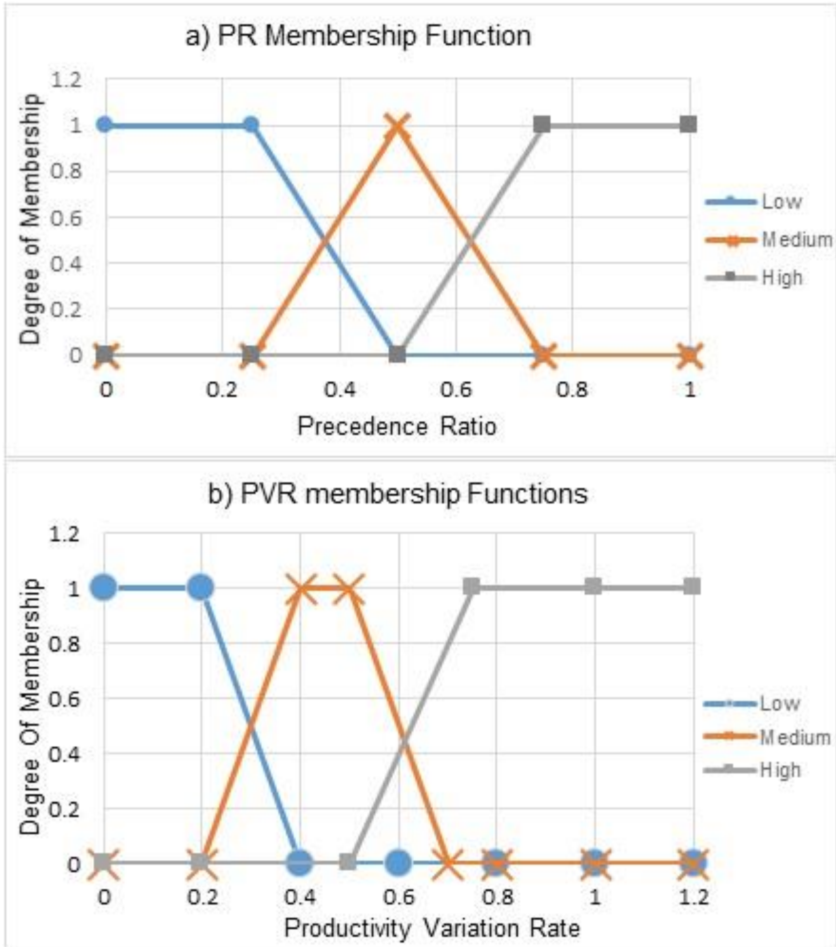


Figure 16: Fuzzy Input Variable Membership Function

5.3.2.2. Fuzzy Output Variable

The output variable is the uncertainty-aware buffer size that is presented in terms of percentage variation from optimum productivity rate and is calculated based on the contextual data described above. This UAB size can have the fuzzy values of Low, Medium and High. Figure 17 presents the membership function for the fuzzy output variable and its three fuzzy values.

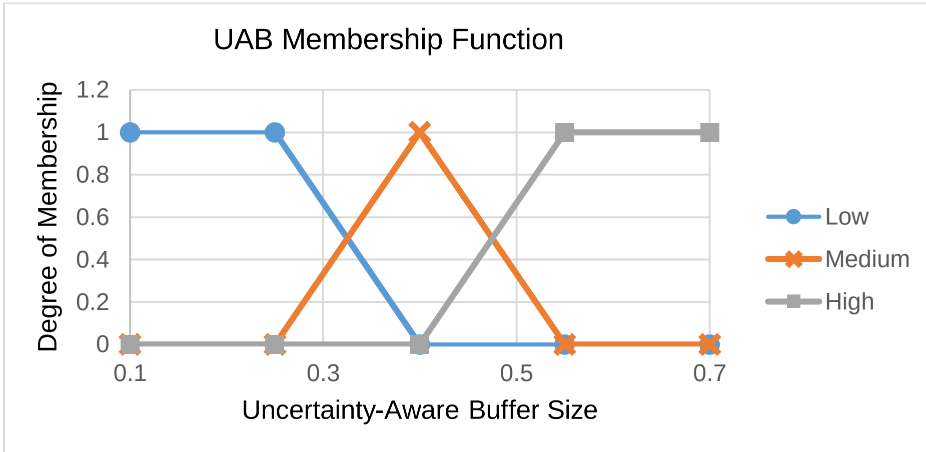


Figure 17: Fuzzy Output Variable Membership Function

5.3.2.3. Fuzzy Inference Rules

Fuzzy inference rules bridge the gap between the input and output variables. These rules show the perception or the knowledge of the expert and are in the form of if-then logical statements. As discussed earlier, both factors in this study have inverse relationship with the final result. In other words, the more successors an activity has, the less buffer should be assigned to that activity. Likewise, the more flexible an activity is, the less uncertainty buffer is required for that activity. A sample rule from the fuzzy inference rules engine follows: “If (PR is Low) or (PVR is Low) then (UAB is High)”. After firing the fuzzy rules of inference, the final output is defuzzified to give an absolute number in the “Buffer range” for the activity. The surface generated from fuzzy inference system rules is illustrated in Figures 18.

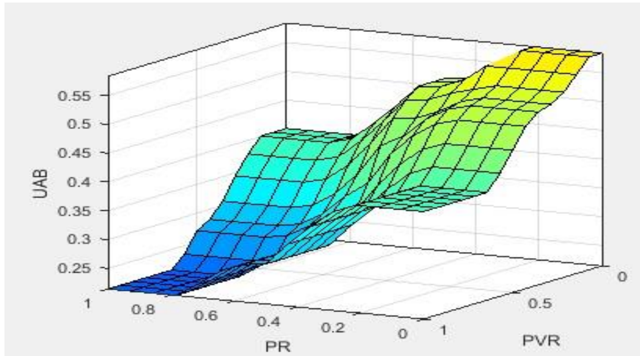


Figure 18: Fuzzy Inference System Output Surface

5.3.2.4. Defuzzification

Conceptually, defuzzification is a method for converting a fuzzy value to a crisp number. For the present application, fuzzy terms are illustrative but not adequate for calculating the required uncertainty-aware buffer size. The crisp buffer size (in terms of percentage) is further used in the third phase for minimizing potential congestions in the generated schedule. There are three methods of defuzzification: center of gravity, center of sums, or mean of maxima. Because of the simplicity of calculation, the simple center of gravity or centroid method was chosen for use in this research.

The output of the second phase identifies the Uncertainty-Aware Buffer size for each activity. After the Uncertainty-Aware Buffers are calculated for all activities in this phase, this data is transferred to the third phase to be used as one of the constraints applied to the congestion minimization model. The schedule is then revised and improved to minimize the detected congestions.

5.4. Phase III. Constraint-based Congestion Minimization of Linear Schedules

The purpose of the third phase is to minimize the summation of potential congestion areas between all activities. For this purpose, the optimization results of the first phase, i.e. optimum productivity rates of activities and their respective time interval as well as the Uncertainty-Aware Productivity Buffers calculated in second phase are transferred and used as known information. This information is used to re-optimize the schedule generated in the first phase in order to minimize the detected congestions between activities in the second phase and avoid congestions in the Uncertainty-Aware Productivity buffer areas.

As discussed in section 5.3 and shown in Figure 14, the overlaps of Space-Time float polygons, i.e. potential congestion between activities, are detected in the MATLAB model. In order to detect and quantify the potential congestion between activities, a matrix is generated in which the overlap areas are calculated. In that matrix, if the element a_{ij} is non-zero, it means there exist potential congestion between activities i and j. Essentially, the element a_{ij} will be equal to zero if no potential congestion exists between the two activities i and j.

In this optimization phase, decision variables include polygon boundaries, i.e. min and max productivity rates of activities, as well as start time of activities. In order to minimize the potential congestion (overlap areas) between activities, the Space-Time Float polygon for the either of the overlapping activities (or both) becomes narrower on the congested side; or the start time of the activities is moved. Changing the boundaries of the prism on the congested side only, provides the advantage of not reducing the overall space-time floats available to activities where it is not necessary. Therefore, the floats are only compensated where their existence leads to occurrence of congestion between activities. The optimization inputs and outputs are listed below:

Constants:

SL_i *Start location of activity i;*

EL_i *End location of activity i;*

$Popt_i$ *Optimum resource production rate of activity i (achieved from phase1);*

$Ltmin_{i,j}$ *Minimum time required between activity i and activity j;*

$Ltmax_{i,j}$ *Maximum time required between activity i and activity j;*

UAB_i *Uncertainty-Aware Productivity Buffer for activity i (in percentage)*

D Project deadline

Decision variables:

$P1_{min,i}$ *Minimum productivity rate of activity i which minimizes congestions;*

$P1_{min,i} \in [P_{min,i}, P_{opt,i}]$

$P1_{max,i}$ *Maximum productivity rate of activity i which minimizes congestions;*

$P1_{max,i} \in [P_{opt,i}, P_{max,i}]$

ST_i *Start time of activity i;*

$ST_i \in [0, D]$

Constraints:

The precedence relationships between activities are again considered as the main constraints applied to the optimization model. The Uncertainty-Aware Productivity Buffers are also the hard constraints added to the optimization model. For this purpose, first the area of the UAB for each activity is realized, and accordingly no overlap is allowed to occur within the UAB area. To do so, $A_{UABi,j}$ is calculated as the summation of uncertainty buffer overlap areas between activities i and j. Then the total Uncertainty buffer congestion areas in the schedule (AUAB), calculated using Equation 6, is set to zero to prevent these congestions from happening.

$$A_{UAB} = \sum_{j=1}^{n} \sum_{i=1}^{n} A_{UABi,j} \;\; ; \; i,j \in \{1..n\} \qquad (6)$$

Objective Function:

After all the constraints are defined, the total congestion area in the schedule is calculated and minimized using Equation 7:

$$min(A_{cong} = \sum_{j=1}^{n} \sum_{i=1}^{n} A_{congi,j}) \;\; ; \; i,j \in \{1..n\} \qquad (7)$$

Where; $A_{cong\ i,j}$ is the congestion area between Space-Time Float polygons of activities i and j and A_{cong} is the total congestion area available in the generated optimum schedule.

The congestion areas used in Equations 6 and 7 are calculated as the area of a polygon formed by the overlap between activity Space-Time Float polygons or Uncertainty-Aware Buffer Areas. As such, the algebraic area calculation formula for closed polygons with known coordinates of vertices is used as shown in Equation 8.

$$A = \left|\frac{(x_1y_2 - y_1x_2) + (x_2y_3 - y_2x_3) + \cdots + (x_ny_1 - y_nx_1)}{2}\right| \quad (8)$$

Where x_1 is the x coordinate of vertex 1 and y_n is the y coordinates of the n[th] vertex. The vertices are numbered in order, going either clockwise or counter-clockwise, starting at any vertex. Examples of triangular and rectangular intersections are depicted in Figure 19. The coordinate of the intersection vertices are presented in (x_i,t_i) format. However, in order to use in the optimization model, the vertices need to be formulated using decision variables, i.e. $P_{1min,i}$, $_{P1max,i}$ and ST_i. This is done through generating parametric system of linear equations for the intersecting sides of the activity polygons as shown in Equations 9-10:

$$\begin{cases} x_i - SL_i = P1_{min,i}(t_i - ST_i & (9) \\ x_i - SL_j = P1_{max,j}(t_i - ST_j) & (10) \end{cases}$$

After solving the parametric system of linear equations, the intersection points are identified in terms of start time (ST) and minimum and maximum productivity rates ($P_{1,min}$ and $P_{1,max}$) of the intersecting polygons. The coordinates of the intersection points are then used in Equations 8 to calculate the congestions in the schedule. Similarly, the congestions areas within the identified Uncertainty-Aware Buffers of activities are calculated and formulated using Equations 8-10. This area is then set to zero to prevent overlaps from occurring within the uncertainty buffers of activities. The optimization process then optimizes the schedule by minimizing the total congestion in the project network.

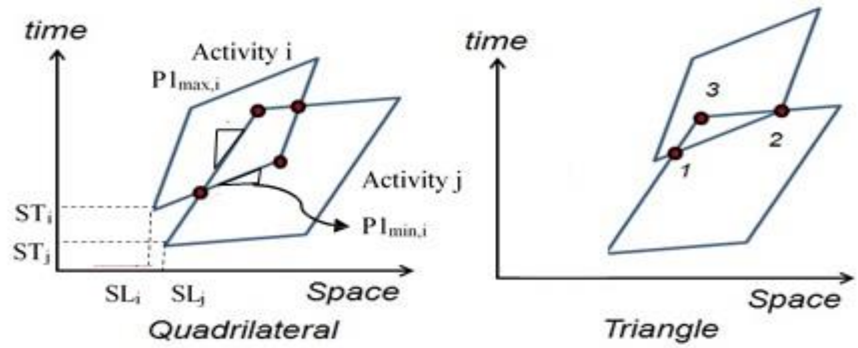


Figure 19: Different congestion areas between polygons

The output of this phase, i.e. the revised minimum and maximum productivity rates of activities (revised polygon boundaries) and start and end time of activities, is then used to generate the revised schedule. The step by step application of the proposed framework to a numerical example drawn from literature follows.

5.5. Case Studies

The optimization method presented here was applied to two case studies from the literature to verify the proposed method. The first case study examines the efficacy of the first stage of the optimization framework in generating optimum duration for linear projects with due consideration to their space-time flexibilities and constraints. The second case study examines the three-phase optimization framework in practically optimizing schedules of linear projects.

5.5.1. Case study 1: Validating Duration Optimization

The first example is previously presented in the literature (Mattila and Abraham 1998, Tang et al. 2014a). The minimum and maximum productivities are calculated from the minimum and maximum resources available in the original example. The project network of this example consists of 9 activities. The project included widening of a segment of U.S. Route 41, located in northern Michigan. Major activities consist of removal of existing concrete paving, ditch excavation, embankment, sub-base, gravel, and bituminous paving. The duration presented in the literature for this example is 38 days. The description of each activity as well as inputs and outputs of the first optimization phase are listed in Table 1.

As it is shown in Table 1, the input data of the optimization process includes Activity IDs, start and end locations, minimum and maximum achievable productivity rates and successors of all activities. This information is used in the first phase to look for the minimum duration of the project. If some activities are required to start or finish at a certain day, this information is also included as constraints. The output of this process identifies optimum the productivity rates as well as the start and end times of all activities. The optimum durations for each activity are then calculated from the optimum productivities attained in the optimization process. The calculated optimum duration for the project is 36 days which is 2 days shorter than the other methods shown in Table 3 (Mattila and Abraham, 1998, Tang et al., 2014a). The achieved optimum productivity rates are listed in Table 2.

Table 1: Input data to the optimization process

No. of Tasks 9						
Deadline 38						
Input						
Task Name	Task	succsId	SL	EL	Pmin	Pmax
Ditch excavation	1	2,3	0	50	3.3	10
Culvert installation	2		0	50	1	5
Concrete pavement removal	3	4,5	0	50	1.67	5.83
Peat excavation and swamp backfill	4	5	30	50	8	12
Embankment	5	6	0	50	2.5	8.75
Utility work	6	7	30	50	10	15
Sub-base	7	8	0	50	2.56	6.41
Gravel	8	9	0	50	5	12.5
Paving	9		0	50	8.33	20.83

Table 2 shows the comparison of the activity durations and productivities of the initial schedule presented by other methods with the optimized schedule obtained in this study. Table 3 also presents the comparison of durations achieved previously for this example versus the results of this study. By considering the whole range of possible productivity rates for each activity, the current method was able to relax some activities, causing less required resources per day. It should be noted that in relaxing of activities, daily fluctuation of the resources is also taken into account. If non-repetitive activities also exist in the project, the start time is calculated based on the precedence relationships with their predecessors and successors.

Table 2: Output of the optimization

Output			
Start	End	Duration	OptPro
0	12	12	4.17
0	4	4	2.00
3	24	21	2.38
5	7	2	6.00
7	26	19	2.63
26	28	2	10.00
12	32	20	2.50
24	34	10	5.00
30	36	6	8.33

This simple example demonstrates the ability of the proposed method to derive alternative plans in order to meet project deadlines. The generated optimized schedule shows that generating schedules with due consideration of the Space-Time Float for each activity, enable better scheduling and control of these projects.

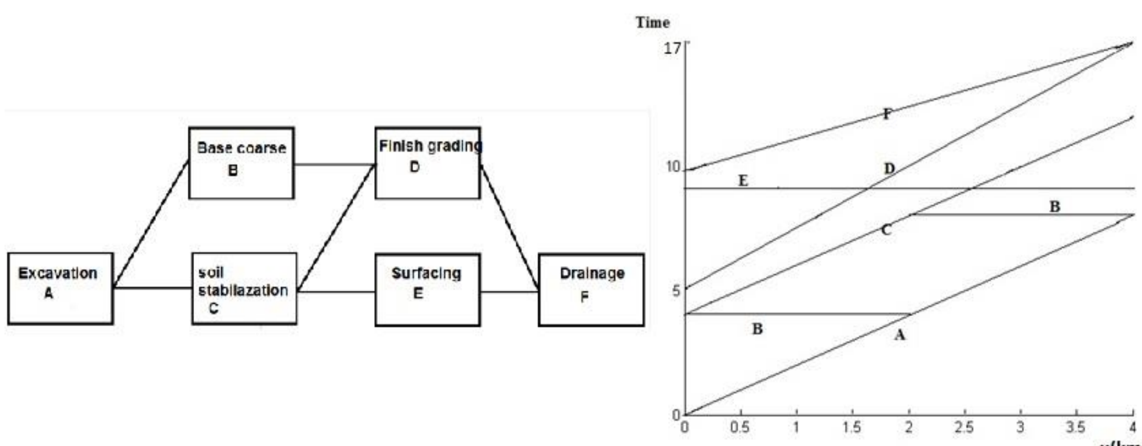
Table 3: Comparison of the results

Method	Study by Mattila and Abraham (1998)	Study by Georgy (2008)	Study by Tang et al. (2014)	Current study
Total duration (days)	38	38	38	36

5.5.2. Case study 2: Validating 3 Phases of the Optimization Method

The second case study is adopted from the literature and modified to verify the developed method. In this example, the minimum and maximum productivity rates are hypothetical. However, in the real-world examples, the information about activity productivity ranges as well as specific project and activity constraints can be obtained from the project team. The project includes construction of a 4-kilometer altering access road. Four activities (A, C, D and F) are assumed to be linear activities while the other two (B and E) were considered to be delivery of the required material. Activities B and E are therefore assumed non-repetitive and as such, are represented by horizontal lines. Activity B is delivery of base coarse aggregates and is planned to be delivered in two steps, at days 4 and 8 and is illustrated with two horizontal lines. The CPM network of the project in addition to the original linear schedule is presented in Figure 20. The description of each activity along with inputs and outputs of the optimization process are included in Table 4.

The project was initially scheduled to be completed in 17 days. Using the proposed optimization framework, an optimum duration equal to 15 days was achieved from the first phase of optimization. The results of the first phase, i.e. optimum productivity rates and durations, were used to generate schedule using Space-Time Float polygons and to calculate Uncertainty-Aware Buffers for the activities in the second phase.



(a) (b)

Figure 20: CPM network and b) Original LSM schedule

Table 4: Input of the Optimization Process

NbTasks	6
Deadline	17

Initial Schedule							
Task	SL	EL	Pmin	Pmax	SuccsId	Duration	productivity
A	0	4	0.3	0.9	{2,3}	8	0.5
B	0	4	Non repetitive	Non repetitive	{4}	Non repetitive	Non repetitive
C	0	4	0.3	0.8	{4,5}	8	0.5
D	0	4	0.2	0.7	{6}	10	0.4
E	0	4	Non repetitive	Non repetitive	{6}	Non repetitive	Non repetitive
F	0	4	0.5	1	-	6	0.75

As it is illustrated in Figure 21(a), there exist overlaps between Space-time Float polygons which accordingly represent potential congestions in the generated schedule. As seen in Figure 21(a), potential congestion exists between activities C and D, as well as between activities D and F. This calls for minimizing these congestions in the third optimization phase. To this end, first the uncertainty-aware productivity buffer sizes are calculated for all linear activities using the generated Fuzzy Inference system. The inputs and output of the Fuzzy inference system are listed in Table 5. Figure 22 also shows example fuzzy rules for activity D. As shown in Figure 21(a), there exists overlap between uncertainty-aware buffer of activities C and D that should be completely eliminated.

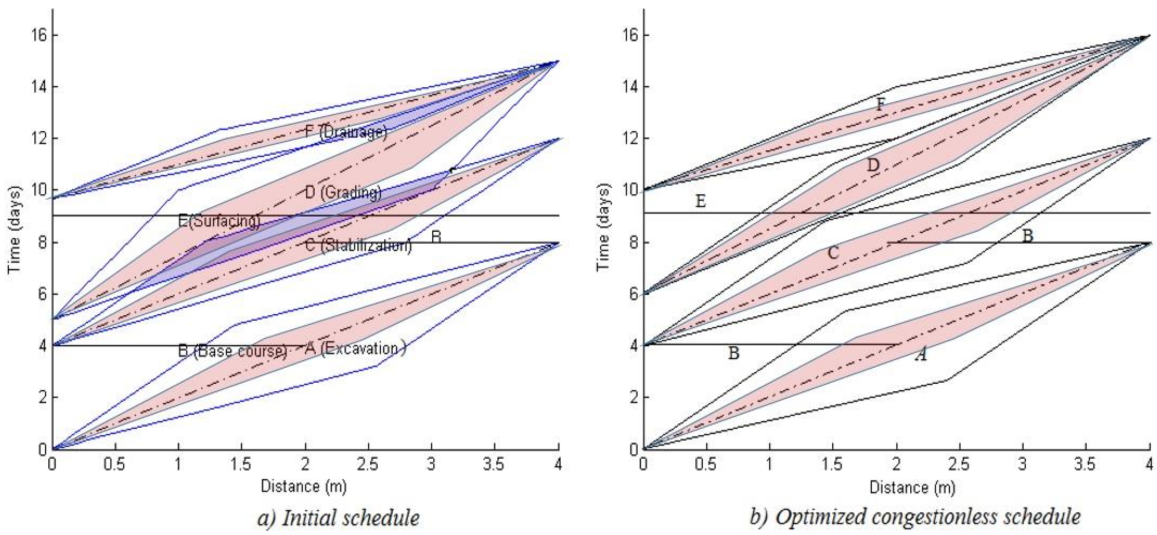


Figure 21: a)Initial schedule visualized in second phase vs b) the schedule with minimized-congestion

Table 5: Uncertainty-Aware Productivity Buffers

Task	PR	PVR	UAB(%)
A	0.83	1.2	21.5
B	-	-	-
C	0.6	1	27.6
D	0.2	1.25	40
E	-	-	-
F	0	0.67	43

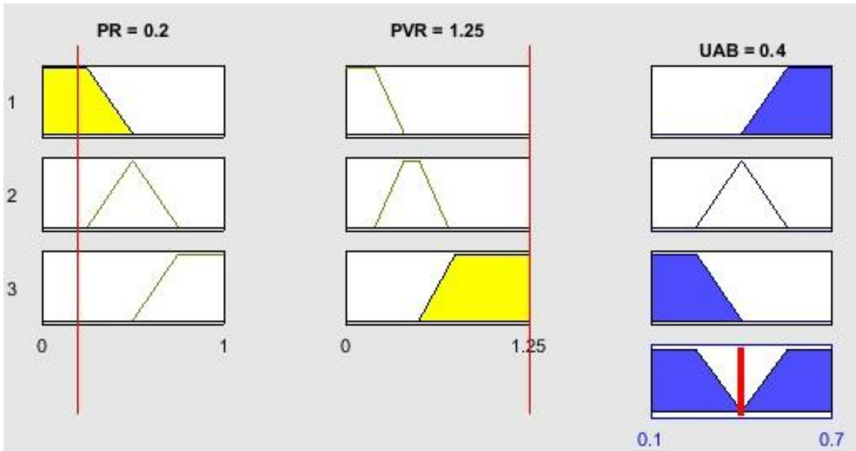


Figure 22: Example Fuzzy Rules

The output of this phase is then used in the third phase to minimize existing potential congestions in the schedule. This input data includes Activity IDs, their start and end locations, successors, minimum and maximum productivity rates, as well as optimum productivity rates from the first phase and uncertainty buffers form the second phase. This information is used to search for the optimum duration for the project that is associated with the least potential congestion in the schedule. Project deadline (17 days) and Uncertainty-Aware Buffers are inputted as hard constraints that cannot be violated. The output of this process includes optimum minimum and maximum productivity rates for all repetitive activities as well as start and end times of all the activities. The optimum duration achieved in this process might be longer than the previously determined duration for the project, but still satisfies the deadline constraint. Figure 11shows the schedule generated in the second phase, using optimization output from first phase and activity productivity boundaries along with the optimum schedule from the third phase. As seen in

Figure 21(b), all the potential congestions detected in the second phase are eliminated in the optimum schedule achieved from the third phase.

Table 5 shows the results of the schedule after the proposed three phase optimization process. It can be inferred from the table 5 that the scheme of the schedule generated is significantly different from that of the initial schedule in which congestion was not considered. The final schedule finishes at 16 days which still satisfies the 17 days deadline constraint. Although the achieved duration is 1 days longer than the previously achieved minimum duration, the total area of potential congestions is reduced to zero in the optimized schedule. For this purpose, as can be seen in Table 5 and Figure 21(b), activities D and F are moved by one day, i.e. from day 5 to 6 and 9 to 10, respectively. Also, the available productivity interval for activity D (its minimum and maximum productivity rates) is reduced from [0.2, 0.7] to [0.3, 0.5], which practically means less float will be available to the resources of this activity. The result attained through this example ensures the efficacy of the method in optimizing schedules of linear projects.

Table 6: Optimization Output

Optimum Schedule					
Activity	Pmin(opt)	Pmax(opt)	ST	ET	Duration
A	0.3	0.9	0	8	8
C	0.3	0.8	4	12	8
D	0.3	0.5	6	16	10
F	0.5	1	10	16	6

6. Chapter Six: CPS Approach for Progress Monitoring and Control of Highway Projects

6.1. Chapter Overview

As discussed earlier, the integration between computational/control and the physical construction gained through Cyber-Physical Systems can significantly improve information handling in difference stages of construction projects; hence enhancing the control of the construction processes. With CPS, data from both the physical and cyber domains flow automatically in real-time. The next step of this study takes benefit of real-time bi-directional control features of Cyber-Physical Systems to enhance the generated framework for linear projects. In this chapter, first, a framework for use of cyber physical systems in construction applications is proposed. A sample CPS application for enhancing Earned Value (EV) management of highway and road construction projects using Raspberry Pi micro-processor is then presented. The application and significance of each of the CPS layers in the proposed control and monitoring application is discussed to improve future outcomes. Finally, a case study is presented to demonstrate the efficacy of the proposed CPS approach. The case study evaluates different features of the proposed approach through three scenarios.

6.2. Cyber-Physical Systems Framework for Construction Applications

In order to derive the most benefit from Cyber-Physical Systems in any domain, CPS architecture including layers, components and phases as well as their inter-relations must be understood; construction is not an exception. Therefore, this study first presents a framework for Cyber-Physical Systems approach in construction applications. The goal of the proposed framework is to enable rapid design and deployment of integrated computational and physical systems for different phases of construction projects; from planning and design to construction and facility management. Figure 23 depicts the main elements of the proposed framework. The framework presented in the Figure 23 consists of three main layers of the Cyber-Physical architecture adapted for construction operations and environment.

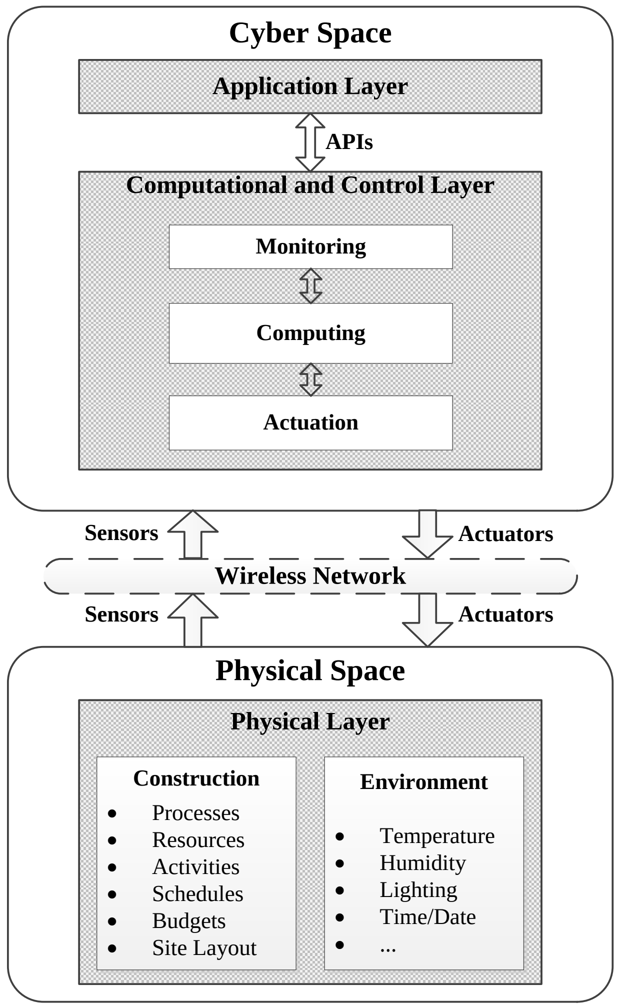


Figure 23: Cyber-Physical Systems Framework for Construction Projects

6.2.1. Physical Layer

The physical layer in construction applications is a combination of physical systems and components inherent in the construction environment and processes. The physical systems and components include construction resources, activities, processes and operations throughout the project life cycle as well as project information such as specifications, costs, schedules and other related information in each process. Data from the physical layer is collected through different types of sensors and sensing devices

(Dasgupta et al. 2014, Ali et al. 2015). Different types of data acquired through sensors include but is not limited to: human activity sensing (e.g. motion detection, surveillance camera, brain activity sensors, etc.); infrastructural sensing (e.g. water pressure, corrosions and vibration, flood/water leakage, contact sensing, etc.); environmental sensing (e.g. temperature, humidity, pressure, soil, wind, etc.); vehicular sensing (e.g. location, speed, acceleration, path planning, etc.) and many others.

6.2.2. Computation and Control Layer

The collected data from the physical layer needs to be interactively transferred and made available in real-time to the computation/control layer for knowledge discovery/transmission. Different phases take place in the computation/control layer to achieve the goal of a CPS, based on the planned application. These phases can be generally divided into the following:

6.2.2.1. Monitoring

The essential function of CPS is to monitor and examine the components and processes in the physical space. The monitoring phase is helpful in giving feedback about the physical and environmental data received from the physical layer through sensors. This will allow for improved performance and well-informed actions in the future. In construction, different stages of a project need to be monitored and controlled constantly not only to acquire data about their status but also to ensure timely and proper performance and quality of the outcomes of each process. As a result, monitoring would be an essential phase in construction for which this phase provides the substance.

6.2.2.2. Computing

This phase investigates and analyse the data obtained from the monitoring phase, which is gathered through the networks. Different computational algorithms and data types can be used in this phase depending on the application. These algorithms could be performed to accomplish different goals including: comparing as-built with the planned, ascertain timely achievement of milestones, update and optimize processes considering different criteria, calculate lost time/cost and the value earned, control the flow of work, ascertain the safety of processes, assess and minimize the risks, and others.

6.2.2.3. Actuation

This phase transforms and transfers the results and decisions obtained in the computing phase to other layers to apply required changes or to store necessary information. The actuation will be carried out by actuators.

6.2.3. Application Layer

The information generated in the computation/control layer through analysing the collected data needs to be available to the corresponding physical components and processes in real-time. Furthermore, this information needs to be available and understandable to the user. As a result, the analyzed information should be communicated to both the application and physical layers. The data is communicated to the physical layer via actuators and to the application layer via application program interfaces (API).

The application layer is designed based on the goal of the system. This Cyber Physical System approach is applicable to different phases of construction throughout the lifecycle of the project. Examples of application of such CPS approach include but are not limited to progress monitoring and project control, Earned Value monitoring, as-built and workflow documentation, deficiency detection and health monitoring, safety and risk management. The application layer in each case should reflect the designed purpose.

6.2.4. Communication

Sensors and actuators are used as means of interaction between cyber space and physical space. Sensors and sensing devices with diverse capabilities and complexities are major elements in a Cyber-Physical system. Using the acquired data from sensors, knowledge can be generated to populate the knowledge base. The actual data collection and dissemination is done through networks. In order for bi-directional communication between physical and cyber spaces to work properly, all the components should be connected and able to communicate with each other. For this purpose, the sensors used on physical components need to be connected to each other and to the cyber space through wired or wireless networks. The acquired data is then used to produce instantaneous information. Different network configurations and set ups can be used depending on the data to be acquired as well as the flow of information and type of application. Similarly, different sensors can be used to produce a large variety of data that should be collected or disseminated to serve the purpose of monitoring different physical processes. At the same time, various technologies have to be included in order to provide proper communication between all the stated components.

To further discuss the proposed CPS framework and to demonstrate the benefits of using CPS approach in construction, an application of CPS in progress monitoring and control of road and highway projects using Earned Value method (EV) is presented.

6.3. CPS Application for Earned Value Management of Highway Projects Using Raspberry Pi

A CPS application is presented here that uses a micro-processor to enhance project control of road and highway projects as a representative of linear construction projects. Raspberry pi, a simple micro-processor, equipped with different modules is used to retrieve the required progress information, perform calculation and analysis and to transfer them to the cyber space of the system. A web server is used to host the cyber space; to store the retrieved information and to transfer the results back to the construction site through the Raspberry Pi. Figure 24 schematically demonstrates the network diagram of the proposed application.

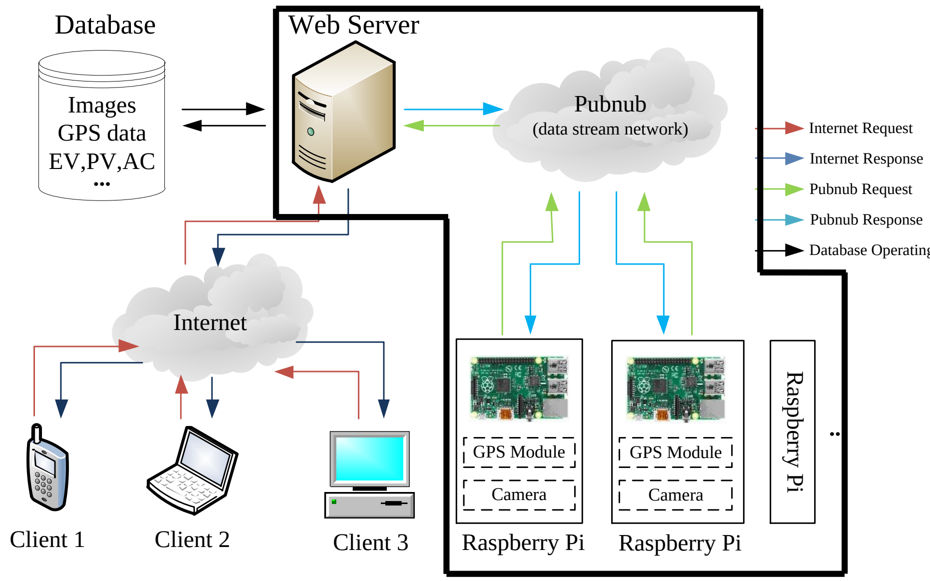


Figure 24: Network Diagram of the Proposed Application

As discussed earlier, due to repeated movement of linear activities' resources, it is important not only to continuously integrate this movement into the progress monitoring and control systems of linear projects, but also to reflect any change in the schedule of the activities on the job site to make necessary adjustments. The application proposed here tends to fulfill this demand by generating a bi-directional data transfer framework for control and monitoring of highway projects.

6.3.1. Physical Layer

The physical layer of the proposed application consists of all the physical components required for tracking the progress of highway activities. These components include the project activities and the resources needed for carrying out each activity, the sensors used to retrieve progress data from those resources, project drawings, specifications, schedule and budget. The moving resources, i.e. equipment, play an important role in this framework as their movement while carrying out an activity, e.g. asphalting, is used as a means of retrieving the necessary information regarding the progress of the activity.

Due to the fact that progress of highway project activities is dependent upon the movement of its resources, the most important data to be retrieved is the continuous locational and speed data of the equipment or workers executing the activity. Furthermore, time-lapse progress images can provide a visual sense of the activity's progress over time. Raspberry Pi equipped with different sensing modules is another physical component of this framework that is used not only to continuously retrieve progress data, but also to use this data in the computation/control layer to extract the required monitoring and control information and to transfer data between cyber and physical spaces.

6.3.2. Sensing

Raspberry Pi 2 Model B equipped with GPS, cellular and camera modules was used as the primary sensing device. Such sensing device is capable of real-time project data acquisition, processing and analysis as well as transferring progress information to the cloud server and receiving information or instruction. GPS and camera modules are used for capturing location and project images and the mini cellular GSM module is utilized to communicate this data to the cloud server/cyber layer in real-time. In such system, a piece of equipment performing a critical activity, e.g. asphalt paver, is equipped with this sensing device. Figure 25 illustrates the sensing device assembled for this study.

It should be noted that the accuracy of the GPS module is approximately 1.5m for lower speeds on jobsites (2-10 km/h) and 3m for higher speeds on roads and highways. The cellular module transmits the locational data along with the calculated distances and speeds to the server every five seconds. The progress images are also taken and sent to the server every five minutes. A GPS antenna is also added to aid in receiving the satellite signals and make the module usable in low signal environments. This data is used by the Raspberry Pi to automatically update the progress information on the server and website accordingly. In addition, two indicator LEDs are added to the device to represent the status of the GPS and the Internet connection as well as to inform the personnel and workers on site of changes/updates in the computational/control layer in real-time. The continuous green light is representative of presence of internet connection and GPS signal respectively, while continuous red light is representative of connection lost. Similarly, flashing red light on the GPS indicator LED is representative of data transmission to the server while flashing red light on the internet indicator LED is representative of changes on the website.

6.3.2.1. Raspberry Pi MicroProcessor

Raspberry Pi is a credit card–sized mini-computer developed in the UK in 2012 with the intention of promoting the teaching of basic computer science in schools. Since its introduction, Raspberry Pi has been applied in other sectors because of its customizable nature. The invention of these small size personal computers has caused a new revolution in the Information Technology (IT) industry. There are several advantages in using these small inexpensive computers in tracking of construction processes and to use them as an integral part of any CPS application in Construction. These advantages include:

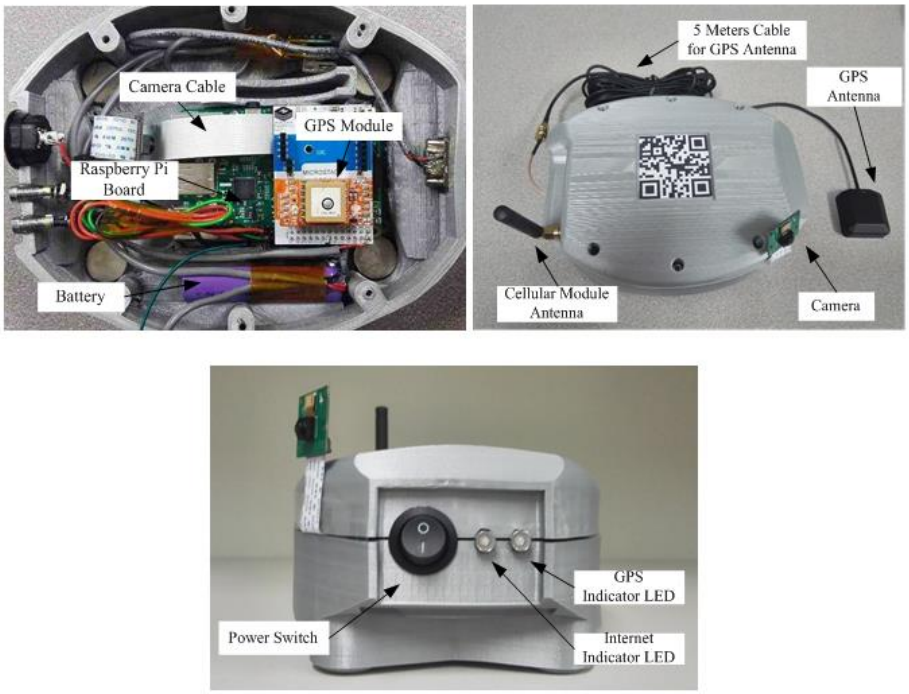


Figure 25: The Sensing Device using Raspberry Pi

Cost: Despite being as small as the size of a credit card, Raspberry Pi works as a normal computer at a relatively low price. Compared to other mobile devices such as cellphones and tablets, Raspberry Pi is offering much more with much lower price.

Computational capabilities: The Raspberry Pi's computational resources are equal to the average desktop or laptop, therefore suitable for high-performance computing. This surely makes Raspberry Pi a good alternative for being used where computation needs to be embedded in each component.

Expansion capabilities: There are numerous modules available to expand the Raspberry Pi's capabilities; all at very affordable prices. Everything from an I/O boards (GPIO) to cameras and different sensors and cellular modules can be added based on the application. There are also a number of status lights available to Raspberry Pis that can be used to report on the status of different sensors. Opposite to cellphones and other mobile technologies that are bounded to their specifications and are costly to adapt in order to achieve needed specs, expansions to the Raspberry Pi are selected based on the required accuracy and can be changed as required at very low cost.

Control actuation: Raspberry Pi can send control signals with its onboard pins. This makes it achievable to drive motors, power switches, and others in the physical layer. Compared with cellphones, tablets and other mobile devices, the onboard pins of Raspberry Pi not only make it easy to acquire information from different sensors but also help to execute the commands sent from the cyber layer.

Small form factor: The Raspberry Pi (with a case) can be held in one's hand. This means the Raspberry Pi can be integrated inside of devices and attached to different equipment without adding any weight. Next generation of Raspberry Pis are expected to be even smaller than the one used in this study.

Multiple uses: Having the storage on an SD card makes it easy to swap with other SD cards running other GNU/Linux distributions to quickly and easily change the functionality of the Raspberry Pi.

Energy consumption: The energy consumption of a Raspberry Pi with different expansions is much less than other mobile devices. As a result, different batteries can be used to charge the Raspberry Pi according to the application, with an average 6-15 hours of continuous use to one week of standby status; which is enough for this application in construction.

All the advantages stated above makes Raspberry Pi a good alternative for other mobile technologies currently used in construction including cellphones, tablets, etc.

6.3.3. Computational and Control Layer

The computational/control layer in the generated framework is responsible for monitoring the progress data received from the construction site, carrying out the required calculations and evaluations and transferring back the results to the physical components through actuation or to the application layer through API. The data flow in computational and control layer is showed in Figure 26.

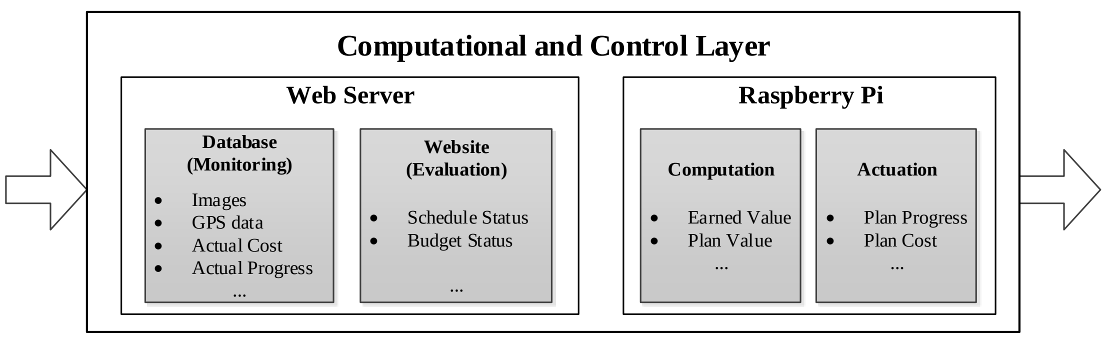


Figure 26: Computational and Control Layer for Highway Projects

A web server is used to host the database that is used to store the retrieved data and the website designed to be used as user interface (as described later in the application layer). Accordingly, the web server continuously receives the sensed data from the physical components through Raspberry Pi and stores it in the database. The data transmitted includes not only the raw locational information and images, but also the progress information calculated by the Raspberry Pi itself, as Raspberry Pi is also an active component of this layer; including total traveled distance from the beginning of the day (the progress of the activity), travel distance between each two data transfers, the speed of the equipment and the earned value calculations based on the actual progress.

6.3.3.1. Monitoring

The aim of the monitoring phase of the computation/control layer is to oversee the locational data retrieved from resources through the sensing process to evaluate the progress of activities. This accordingly paves the way for performing Earned Value calculation (using Equations 11-15). The cellular network provides the means for bi-directional communication between Raspberry Pis attached to the resources, the server and the application website. Correspondingly, the Raspberry Pi is constantly connected to the server through cellular network and transmits and receives data to/from it. The Web site is also designed as a user interface to enable demonstration of the acquired progress data and EV monitoring and additionally enable user data update input to modify the calculations in real-time based on the most recent project design/schedule/budget. This is elaborated in more detail in the application layer.

6.3.3.2. Computation: Earned Value Management of Highway Projects

Earned Value Method (EV) is the most commonly used method for project control in the construction industry. It provides an early warning of performance problems when properly applied (Acebes et al. 2013). The EV technique is usually used for cost and schedule control because it combines technical performance, schedule performance, and cost performance within a single framework (El-Omari and Moselhi 2011). Contractors typically state a clear preference for EV progress tracking over design object oriented quantity (progress) tracking for buildings and industrial facilities. As a result, integrating this well-accepted and commonly used technique with the CPS approach will facilitate timely control of the project and progress analysis. In the EV method, project progress is evaluated in an objective manner using three measures (Rose 2013) as shown in Figure 27:

Budgeted cost of work scheduled (BCWS) or Planned Value (PV): measures the work that is planned to be completed in terms of the budgeted cost.

Budgeted cost of work performed (BCWP) or Earned Value (EV): measures the work that has actually been accomplished to date in terms of the budgeted cost.

Actual cost of work performed (ACWP) or Actual Cost (AC): measures the work that has been accomplished to date in terms of the actual cost.

The significance of these three values is that they distinguish the schedule and cost performances of the project at successive reporting periods. The following performance indicators are calculated based on these three values:

Cost variance (CV): $CV=BCWP-ACWP$, with $CV>0$ indicating cost savings;

Schedule variance (SV): $SV=BCWP-BCWS$, with $SV>0$ indicating schedule advantage;

Cost Performance Index CPI: $CPI=BCWP/ACWP$, with $CPI>1.0$ indicating cost savings;

Schedule Performance Index (SPI): $SPI=BCWP/BCWS$, with $SPI>1.0$ indicating schedule advantage.

As stated earlier, in highways and road projects, the movement of certain resources while on work can be considered as a measure of progress of the associated activity (Roofigari-

Esfahan et al. 2015). As a result, the EV calculations are adjusted here based on the distance paved by the resources. These adjusted equations are then used to update EV measurements on the site in real-time.

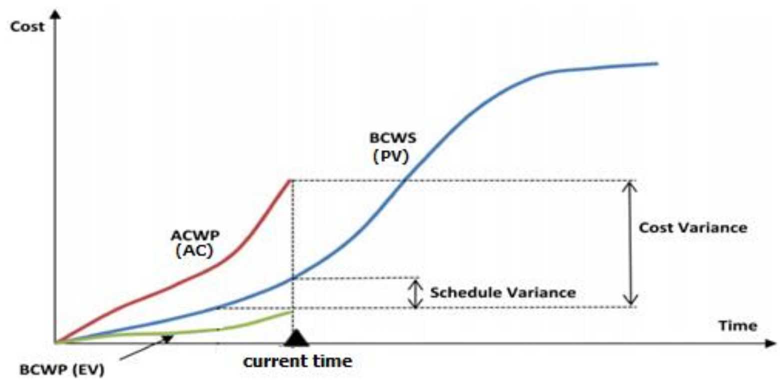


Figure 27: Earned Value Measurements

$$Planned\ Progress = \frac{Planned\ kilometers}{Total\ activity\ kilometers} \quad (11)$$

$$Actual\ Progress = \frac{Actual\ kilometers}{Total\ activity\ kilometers} \quad (12)$$

$$PV = Planned\ \ value = \frac{\sum_{i=1}^{n} Planned\ kilometers \times Planned\ cost}{\sum_{i=1}^{n} Total\ activity\ kilometers} \quad (13)$$

$$EV = Earned\ \ value = \frac{\sum_{i=1}^{n} actual\ kilometers \times Planned\ cost}{\sum_{i=1}^{n} Total\ activity\ kilometers} \quad (14)$$

$$AC = Actual\ cost = \sum_{i=1}^{n} actual\ kilometers \times Actual\ cost \quad (15)$$

Subsequently, the earned value calculations are updated continuously according to the data received. This, however, is not enough and in order to create the bi-directional data communication, the system needs to be able to accept input from the project management team and to apply their changes/suggestions in the calculation in real-time. Respectively, the main purpose of the application layer is to concede such data entry/update and to bounce this information back to the computation phase for updating calculations as discussed in the application layer.

The result is demonstrated on the web site in terms of Budget and schedule performance indicators; i.e. whether the project is ahead/behind schedule and or under/over budget. Such result is representative of the project status in terms of schedule and cost; i.e. informs the user if the project is under/over budget and ahead/behind schedule based on the progress monitored from the beginning of the activity/project to the end of that day.

6.3.3.3. Actuation

The actuation or the control component of this layer is achieved by using the Pubnub Network (data stream network) as demonstrated through a box in Figure 24. The main advantage of Pubnub Network is to build the real-time communication between the website and Raspberry Pi without knowing the IP addresses of both sides. After all the necessary calculation has been performed in the computation phase, the actuation allows reflecting decisions and/or changes in the plans. This is carried out through the actuation phase which uses the Raspberry Pi as well. In any of these cases the changes are automatically notified on the Raspberry Pi through status lights. The user then is able to retrieve the changed information through scanning the barcode designed for the Raspberry Pi (as shown in Figure 25), which automatically directs him/her to the website where changes are visible.

The control component is designed to allow user input to make sure the Earned Value calculations are carried out based on the most recent project information. These inputs include but are not limited to any change in the planned schedule/budget for the project/activity and the actual costs occurred to date. The changes in the planned data could be resulted from late delivery of material, weather/site conditions, changes in service/material pricing, change orders, etc. The actual cost also needs to be updated based on the costs actually occurred on a daily basis. As shown in Figure 19, any change in these control parameters is sent to Raspberry Pi in real-time, and then the corresponding calculation is changed. In addition, the preferred numbers of progress photos that are required to be shown in the website can also be entered.

6.3.3.4. Database

In order to achieve the real-time realization of the project status as described in the previous sections, a dynamic connection is required between the website and the database. The database interface and the architecture of operation database are shown in Figure 28. All the images, GPS data, calculated parameters are uploaded in the database which will provide corresponding information upon the request received from the designed website.

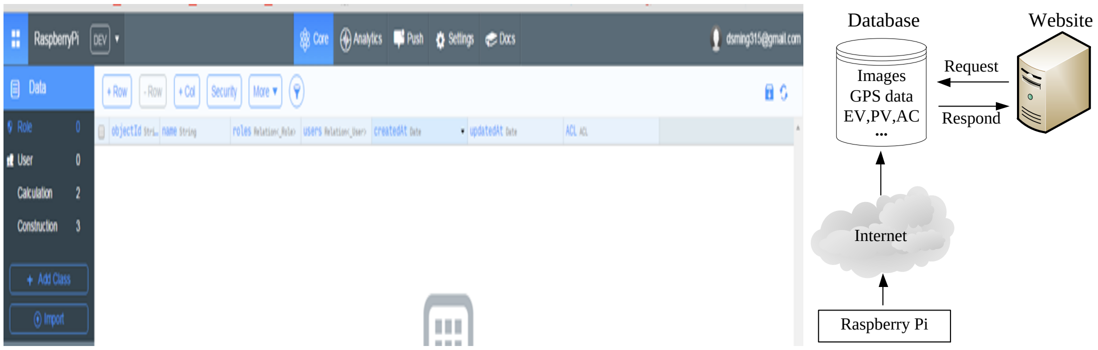


Figure 28: Database Interface and Data Transfer

To store the images, they are Base64 encoded in Raspberry Pi using Python language. By sending the HTTP request to database, the connection between Raspberry Pi and database is established. The encoded images are sent to the database using their ImageID and corresponding ImageData (Figure 29(a)). The encoded data is then decoded in the website, and displayed. The GPS and calculation parameters are also stored separately in the database (Figure 29(b)).

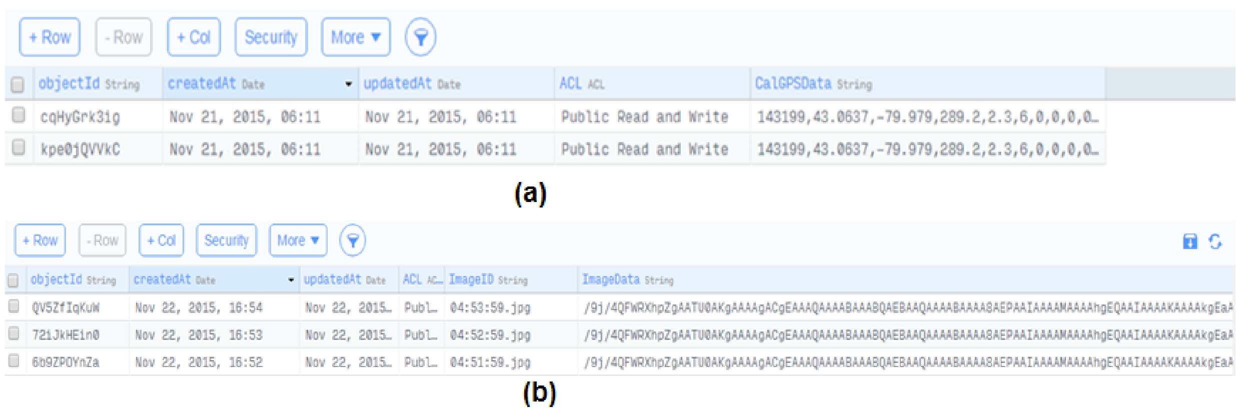


Figure 29: Storage of (a) Images and (b) GPS Data and Calculated Parameters in the Database

6.3.4. Application Layer

The main purpose of the application layer is to provide an interface for demonstrating the actual progress on the site to the user, project management team and other project participants in this case, and to let data entry/update from the user in real-time. For this purpose, a website was designed using JavaScript. The website is connected to the server and the database. As a result, each data entry/update automatically is sent back to the computation phase to update calculations. Furthermore, any input/change in the website is simultaneously transferred to the Raspberry Pi and accordingly indicated on the job site through the status lights (LEDs). Figure 30 illustrates a snapshot of the designed website.

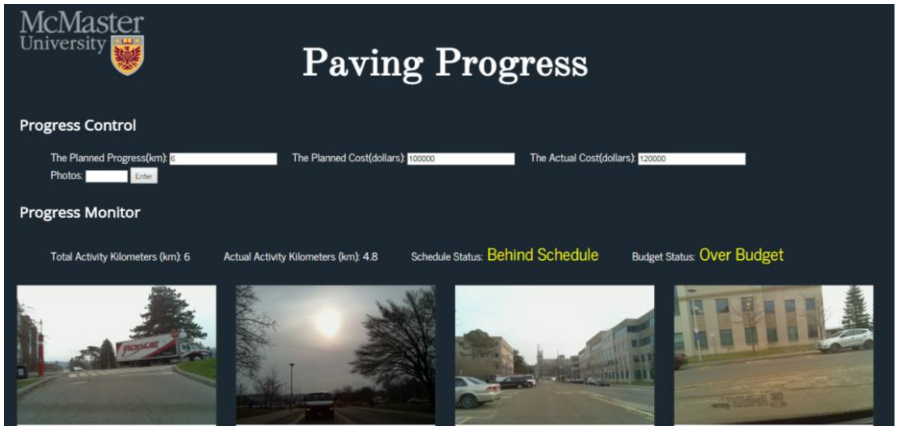


Figure 30: Generated Application Website

As shown in Figure 30, there are three main components in the website: progress control (control phase), progress monitoring (monitoring phase) and visual progress view. In addition to the control and monitoring parameters, the progress on site is visually demonstrated on the web site through different figures. The time-lapse images of each day are used to generate a video of the construction progress in that day. The updated Earned Value plots can be generated at the end of each day or at any time during the day by downloading the progress information that is stored in the database in real time. For this purpose, a MATLAB code is written to decode the stored data and to generate Earned Value plots up to the time data is downloaded.

6.4. Case Study

The field experiment aims to demonstrate the applicability and feasibility of the developed system for real applications. For this purpose, three scenarios were designed and carried out, to facilitate evaluation of different components pertinent to real-time bi-directional earned value management of road and highway projects. To this end, a vehicle was utilized and was driven on arterial roads of McMaster University's main Campus to simulate asphalt paving activity. The equipment was driven with low speed (approximately 2km/hr) comparable to real construction condition. The experiment was carried out in two consecutive days and the real-time progress information was collected.

In order to carry out Earned Value calculations, the initial planned measures need to be known. Assumed initial measures include: the total of three kilometers is planned to be asphalted in two days, four working hours per day, total cost is $100,000 per day and is assumed to be distributed linearly over the 1.5km progress planned for each day. In order to retrieve real-time information of activity progress including location and site images, the Raspberry Pi was mounted on the back of the vehicle. Different data transfer intervals of five seconds and five minutes were selected to send retrieved data of the location and progress images using the cellular module. The locational coordinates (longitude, latitude and altitude) of the vehicle retrieved through GPS module, is received and used to calculate travel distance, total distance, and earned value, schedule and cost variances in real-time. The raw and calculated locational data is send to the database every 5 seconds, to be stored and presented on the website accordingly. The status of the project is estimated using the schedule and cost variances and is shown on the website as ahead/behind schedule and under/over budget (see Figure 30). The progress images taken are also stored in the database and updated on the website every 5 minutes as shown in Figure 30.

Three scenarios were set up within 8 hours' experiment; first, two hours' experiment was carried out to investigate effects of changes in speed of the equipment in accurate real-time data collection. The next four hours' experiment was performed in two consecutive days, two hours each day to examine continuous data collection and how the tracked performance was compared to the plan. The last experiment was performed with the aim to examine the bi-directional real-time data communication of the application as described in detail in the following sections.

6.4.1. Scenario 1

In order to examine the accuracy of the collected data and its relevance to the speed of the equipment and data communication, the experiment was done for two hours with different speeds ranging from 0 (complete stops for a period of time) to 15 km/h. the results are shown in Figure 31. It was found that the developed framework is able to realize the varied movement patterns of the equipment with good accuracy. As it is shown in Figure 31(b), the vehicle had two complete stops between minutes 42 to 50 and 85-110. Although the variation in travel distance in each 5 second interval is well demonstrated, the accuracy of detected distance is less on higher speeds i.e. where higher slope is demonstrated in Figure 31(b) (the circles on the diagram). In speeds comparable to construction paving speeds, the detected travel distance is within 1-2 meters' accuracy. Also, in areas with less cellular network strength, the data transmission might take between 5-10 seconds and consequently, the measured travel distance would appear to be more than the actual (see Figure 31(a)).

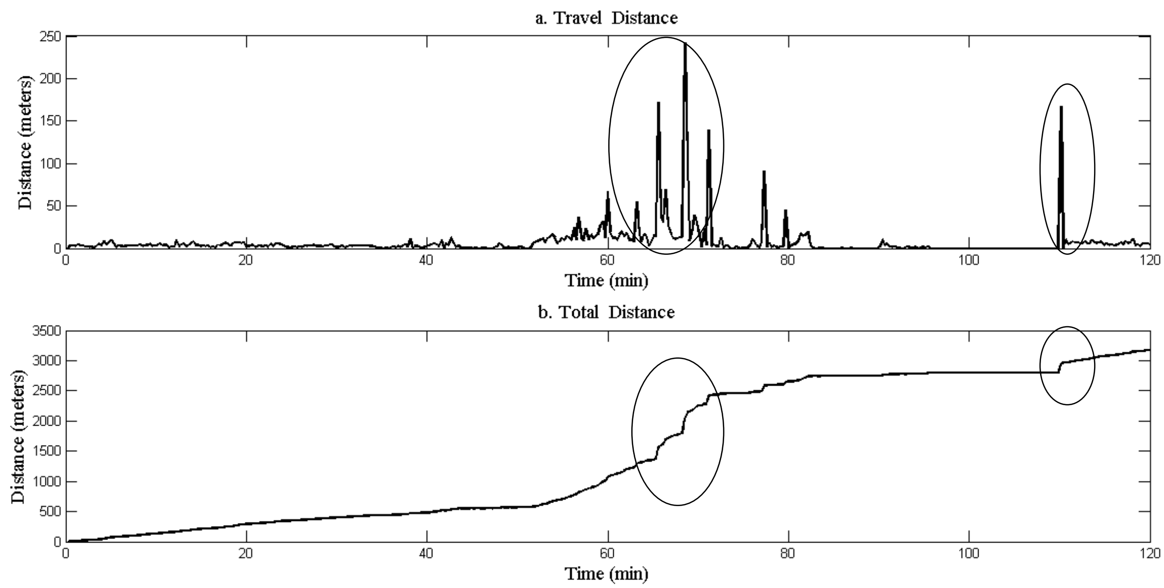


Figure 31: (a) Real-Time Travel Distance and (b) Total Distance Paved for Scenario 1

As stated earlier, earned value calculations was also performed in real-time on the Raspberry Pi and was sent to the database along with the raw locational data (see Figure 32). The respective Earned Value charts were generated afterwards from the data stored on the database for each scenario; comparing planned values at each point in time with the actually achieved progress. As anticipated, the earned progress was more than planned as the average speed was higher than the plan. As a result, the status of the project was reported as ahead of schedule and over budget on the website.

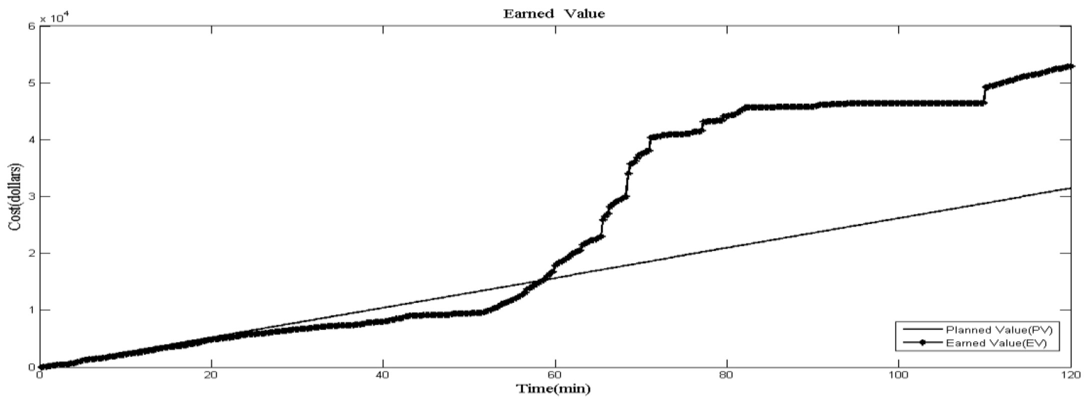


Figure 32: Earned Value for Scenario 1

6.4.2. Scenario 2

The second scenario was carried out in two days, two hours each day, to examine efficacy of the proposed framework in continuous real-time earned value monitoring of the road and highway projects. As a result, the speed was selected to be constant with average of 1.5-2 km/h. As demonstrated on Figure 33, the total paved distance (Figure 33(a)) and earned value (Figure 33(b)) curves were smooth and with small variations from planned. Total of 1.5 kilometers was paved which is according to the plan. As a result, this scenario was finished on time and budget, which was demonstrated on the website.

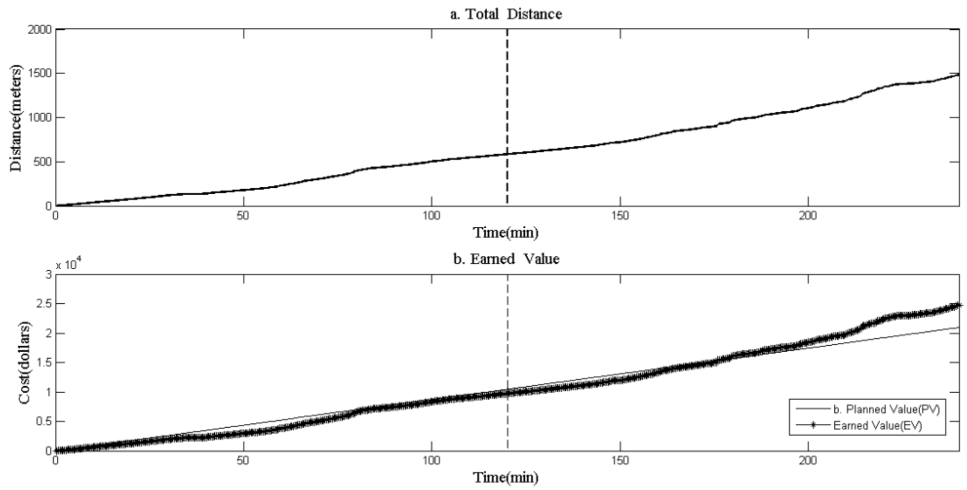


Figure 33: (a) Real-Time Total Distance and (b) Earned value for Scenario 2

6.4.3. Scenario 3

The last scenario was carried out to examine the important real-time bi-directional data communication between the website and the jobsite. Although the one-way real-time data communication (from construction site to the website and as a result to the project office) was examined through the first two scenarios, the bi-directional communication should exist as preliminary requirement for a Cyber-Physical system in this context. For this purpose, the third scenario was designed to examine the capability of the proposed application in real-time communication from website to the job site. In this scenario, the value of planned progress and planned cost were changed (and stated by authorized users on the website) while the activity was undergoing on the jobsite. As a result, the updated planned information was communicated to the Raspberry Pi on the jobsite and was used to calculate the rest of the calculations.

In order to examine this capability, first, the project planned cost was changed from \$100,000/day to \$120,000/day half way through the experiment. As a result, the updated calculations of equations 1-5 were undertaken using the updated value and therefore a jump appeared in the real-time tracked earned value as well as on the planned value curve. The planned project cost then was reduced from \$120,000 per day to \$90,000 per day and immediate changes appeared on both planned value and earned value curves as shown in Figure 34(b). In addition, less progress (approximately half kilometer) was achieved in this scenario as seen in Figure 34(a). As a result, the scenario was reported behind schedule and over budget.

The scenarios demonstrated promising results in putting in place real-time bi-directional communication between the physical and cyber worlds of such example. The real-time earned value generated for each scenario also effectively illustrates the progress on site, calling for just in time corrective actions when necessary.

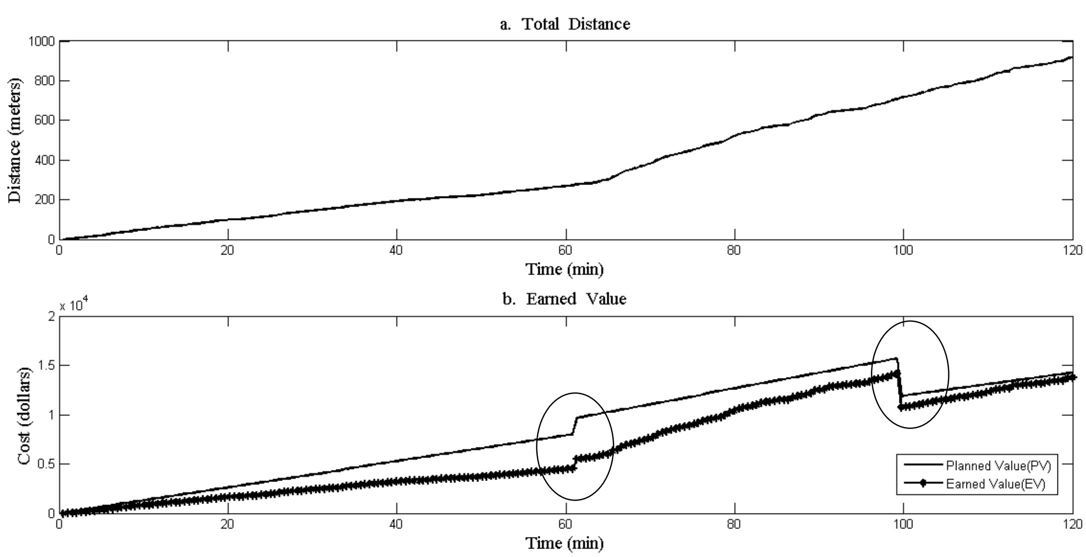


Figure 34: Real-Time (a) Total Distance and (b) Real-time Earned Value

7. Chapter Seven: Conclusions and Future Work

7.1. Chapter Overview

This research was inspired by studies that suggested linear repetitive projects need more careful consideration in the selection of proper planning and control methods. Through the course of this dissertation, a number of achievements were obtained. This chapter first summarizes the different steps of the research along with the main achievements obtained. The main contributions of this research to the body of knowledge of planning and control of linear projects are then presented. The limitations of the research and possible paths for future works then follow.

7.2. Summary and Concluding Remarks

The end product of the study presented in this dissertation is an advanced planning and control framework for linear projects that not only accommodates all logical and spatio-temporal requirements but also provides the latest technological developments as an embedded tool. Through comprehensive literature review, it was found that the space and time allocated to the movement of linear activities' resources play an important role in the productivity achieved from resources and accordingly needs to be undertaken when planning these projects. This leads to the need for developing methods that take into account the combined effect of space and time flexibilities and constraints of linear activities' resources.

To meet this need, this research has accomplished three major objectives by development of the new planning and control framework for linear projects. The first of these objectives was to outline a planning tool that takes into account space and time flexibilities and constraints of linear activities, in the planning phase. The first objective resulted in introducing the novel notion of space-time float for linear scheduling and control. Such an integration of space-time constraints and flexibilities to linear schedules, through the use of space-time float, improves the way linear projects are scheduled and controlled. In addition, using space-time floats for scheduling linear activities enables forecasting potential areas and times of congestion between activities; detection of activity idle times; and actual and/or potential delays. Therefore, using space-time floats for scheduling linear activities provides the means for avoiding these unfavorable situations in the planning phase of linear projects before execution starts.

Subsequently, the second objective was to generate an optimization method to optimize the generated schedules and to minimize their potential congestions. For this purpose, an uncertainty-aware schedule optimization framework was proposed. The optimization method uses uncertainty-aware constraint satisfaction approach to find the optimum duration of linear projects that also minimizes the potential congestions in their schedule. The uncertainties inherent in linear activities are also accounted in the developed optimization method. For this purpose, a new type of buffer, Uncertainty-Aware Productivity Buffer, was introduced and used. This uncertainty buffer identifies the amount of uncertainty in productivity rates of linear activities that the schedule can manage without causing negative impact. This way, the uncertainty and potential congestions in linear projects are accounted for in the planning stage and their negative effects can be eliminated before occurring.

Further, the construction sites are frequently encountering different conditions which make them fall behind schedule and/or over budget. Such cases are often causes for claims and disputes. To avoid the above-mentioned unfavourable situations, generated schedules need to be monitored in real-time to ensure timely implementation of project deliverables and efficient management of sequentially used resources of linear projects. To this end, the third objective of this study was to propose a means for real-time bi-directional monitoring and control of the linear schedules generated. The framework made use of effective bi-directional interactions between cyber and physical components and processes of construction projects offered by Cyber Physical Systems to achieve this objective. Consequently, a framework for use of Cyber Physical Systems in construction in general, and an application for improving progress monitoring and control of highway projects, as representative of linear projects, in particular were then presented. The bi-directional real-time monitoring features of the proposed framework offers significant potential for better collaboration, coordination, and communication in all construction projects including linear ones. The framework accordingly enhances construction progress monitoring and control by allowing real-time feedback loops and enabling right-on-the-spot corrective actions. It also facilitates the communication between the construction site personnel with various project parties as they are all involved in the generation of the up-to-date information in real-time.

As a result, the developments made through the course of this study propose an improvement over current linear scheduling approaches. The proposed planning and control framework allows the scheduler and planners of linear projects to predict and visualize deviations from plans and take corrective actions both during planning and construction phases of linear projects. This provides the project team with the ability to better understand the unplanned changes in the project and their impact on productivity, time, space and cost. The framework also depicts and analyzes the real-time changes in activities' progress on site and enables on-time corrective actions. The graphical format also allows the construction team to visualize the actual progress as well as alternative plans when discrepancies occur.

A significant advantage of the proposed framework is that it can comprehensively convey a detailed work schedule that can be used by construction managers in making project-wide decisions and by field staff in day-to-day operations.

7.3. Contributions

The developments presented in this study, aimed to add to the current scheduling and planning methods for linear construction projects while keeping their essential benefits. As such, this research has contributed to the body of knowledge of scheduling and control of linear projects. The framework presented here contributed to and augmented the conventional methods presented for linear scheduling in the following areas:

Space-Time Floats

The proposed approach represents a relatively simple but powerful alternative to methods in current use that define and use space and time floats separately. Simultaneous consideration of the two floats makes it simple to assess potential space versus time trade-offs and can help to prevent, reduce, or eliminate congestion and delays. Through accounting for the space-time flexibilities and constraints that are practically available to linear activities, use of space-time floats also enables detection of potential delays/congestion before they actually occur.

Uncertainty-Aware Productivity Buffer

In contrary to the conventional scheduling methods that model uncertainty buffer associated with activity duration, the Uncertainty-Aware Productivity Buffer considers the uncertainty associated with planned productivity rates of the linear activities. As a result, this new type of buffer is realized both in terms of time and space that is more suitable to the nature of linear schedules. Furthermore, due consideration to the uncertainties associated with linear activities provides a means to account for unforeseen deviations from plans and preventing their negative effect on the linear schedules.

Planning and Control Features Combined

The approach presented functions both as a planning and a control tool. It helps to identify issues in the planning phase to make management decisions and take preventive actions, thus leading to more efficient project Planning. On the other hand, the real-time bi-directional earned value monitoring method provides an efficient means for keeping track of project progress in real-time. This subsequently aids contractors and project managers of linear projects to closely track the progress of their construction projects and steer their projects back on schedule when actual progress deviates from projections due to resource unavailability or productivity reduction.

Cyber Physical Systems Approach to Linear Project Monitoring and Control

This research has shown how cyber-physical systems can be applied in construction for enhancing bi-directional coordination between project offices and the physical construction through the development and implementation of an application for improving earned value management of linear projects. The developed system illustrates how the current construction practices can be modified and also shows the benefits of the proposed approach for the construction industry. These broader impacts and benefits include access to real-time progress information and potentials for enhancing real-time communication and collaboration between the personnel on the job site and the office. By demonstrating the potential of the cyber-physical systems integration approach, this study helps to open the door to new CPS applications in the construction industry.

7.4. Limitations and Challenges

The method presented here only addresses the duration and congestion objectives in the optimization process, using space and time factors. The cost aspect is not directly integrated into the optimization method. The output still helps the management teams of liner projects to prevent cost overruns through efficiently planning their activities and decreasing potential delays. As an improvement, the cost factor can be added directly into the optimization method to improve the decisions made. In addition, only literature-based testing was possible during the implementation time for evaluating the planning part of the framework. It is recognized that real-life implementation of this system may require adjustment or modifications based on the factors affecting productivity of resources. The productivity ranges are also calculated based on potential duration range of activities as historical data is missing for productivity ranges of all resources of linear activities.

Only limited field/outdoor testing of the CPS system was undertaken. There is a need to demonstrate the practical functionality of the systems on a real construction site before robust conclusions can be drawn on the suitability of the approach to full scale construction projects. This would also help to establish the organizational, contractual and other project-specific constraints that will need to be addressed. The cyber physical systems application presented in this study at its current format is also designed to track one activity on the jobsite at this stage to demonstrate the efficacy of the proposed application. Future advancements of this framework can consider more than one activity to also take into account relationships between activities and their interaction.

In addition, similar to any other ground-breaking technology, bringing CPS approach to the construction industry, which is slow to adopt technology, would carry a number of challenges. The uncertainty and lag from a real-time physical system to discrete-time digital control is an obstacle that must be overcome. Synchronization within the system and over-complexity of the system itself are also obstacles that must be taken into consideration in order for the CPS to be applied to construction processes. Management and analysis of the intensive data collected from the physical construction processes and the required interoperability between all physical and computational components of the system are other key challenges that need to be addressed to efficiently set up the integrated system. Overcoming these challenges opens infinite potentials for use of CPS to enhance different construction processes and facilitate real-time management throughout the life cycle of construction projects.

7.5. Outlook and Future Work

This research has laid a foundation for developing planning and control tools for linear projects that take into account project and activity level requirements. Further research could expand upon three major areas: data collection and analytics for additional site specific or project specific considerations, expanding the capability of the proposed monitoring tool, and expanding the scope to include all types of linear projects. Generation of databases of historical data about productivity ranges of different resources working on different linear activities and in different types of linear projects can significantly help in generation of more reliable schedules; accordingly leading to more reliable space-time configuration. In such a database, effects of learning, site conditions, and geotechnical data need also to be taken into account. This information would help to broaden the useful range of the productivity rates and allow for a higher accuracy in predicting the productivity rates achieved in the field.

The monitoring phase can also be adopted to be applied to different types of linear projects. For this purpose, different means of progress tracking can be utilized to effectively monitor each type of linear project. Furthermore, construction sites are often affected by different environmental conditions including extreme weather, humidity, etc.; which correspondingly affect their performance, subsequently impacting project monitoring and control. Therefore, additional types of data also should be collected, managed and analyzed to better represent real site condition and consider their impact on project progress. These conditions need to be communicated in real-time, in order to decrease the amount of disputes. The ability to incorporating non-linear activities into the progress monitoring model are some of the other outlooks of this study.

8. Bibliography

Acebes, F., Pajares, J., Galán, J. M. and López-Paredes, A. (2013). "Beyond earned value management: A graphical framework for integrated cost, schedule and risk monitoring." *Procedia - Social and Behavioral Sciences* 74(0): 181-189.

Aduagyei, F. (2008). "Optimization of resources in construction work area through effective process planning". Civil Engineering. Calgary, Al, Canada, University of Calgary. Master of Science.

Agrama, F. A. (2014). "Multi-objective genetic optimization for scheduling a multi-storey building." *Automation in Construction* 44: 119-128.

Ahmed, M., Haas, C. and Haas, R. (2014). "Automatic detection of cylindrical objects in built facilities." *Journal of Computing in Civil Engineering* 28(3): 04014009.

Ahuja, H. N. (1976). "Construction performance control by networks", New York; Toronto: Wiley.

Ahuja, H. N. and Nandakumar, V. (1985). "Simulation model to forecast project completion time." *Journal of Construction Engineering and Management* 111(4): 325-342.

Akanmu, A. and Anumba, C. (2014). "Experimental investigation of chirp spread spectrum-based swarm sensors for construction resource tracking". Computing in civil and building engineering (2014), American Society of Civil Engineers: 1086-1093.

Akanmu, A., Anumba, C. and Messner, J. (2013a). "Active monitoring and control of light fixtures during building construction and operation: Cyber-physical systems approach." *Journal of Architectural Engineering* 20(2): 04013008.

Akanmu, A., Anumba, C. and Messner, J. (2013b). "Scenarios for cyber-physical systems integration in construction." *ITcon* 18: 240-260.

Akanmu, A., Anumba, C., Messner, J. and Lee, S. (2012). "Component level cyber-physical systems integration: A light fixtures example". Computing in civil engineering (2012), American Society of Civil Engineers**:** 437-444**.**

Akanmu, A., Rasheed, S. and Qader, I. (2013c). "Spatial mapping approach to component tracking using rtls system". Aei 2013, American Society of Civil Engineers**:** 364-376**.**

Akanmu, A. A. (2012a). "Towards cyber-physical systems integration in construction". Ann Arbor, The Pennsylvania State University. 3521212**:** 220**.**

Akanmu, A. A. (2012b). "Towards cyber-physical systems integration in construction", Architectural Engineering**.**

Akinci, B., Fischen, M., Levitt, R. and Carlson, R. (2002). "Formalization and automation of time-space conflict analysis." *Journal of Computing in Civil Engineering* 16(2): 124-134**.**

Akinci, B., Kiziltas, S., Ergen, E., Karaesmen, I. Z. and Keceli, F. (2006). "Modeling and analyzing the impact of technology on data capture and transfer processes at construction sites: A case study." *Journal of Construction Engineering and Management* 132(11): 1148-1157**.**

Ali, S., Qaisar, S. B., Saeed, H., Khan, M. F., Naeem, M. and Anpalagan, A. (2015). "Network challenges for cyber physical systems with tiny wireless devices: A case study on reliable pipeline condition monitoring." *Sensors* 15(4): 7172-7205**.**

Andayesh, M. and Sadeghpour, F. (2014). "The time dimension in site layout planning." *Automation in Construction* 44: 129-139**.**

Andoh, A., Su, X. and Cai, H. (2012). "A framework of rfid and gps for tracking construction site dynamics". Construction research congress 2012, American Society of Civil Engineers**:** 818-827**.**

Andoh, A. R. (2012). "Tracking construction site dynamics using rfid and gps", PURDUE UNIVERSITY.

Anumba, C. (1996). "Functional integration in cad systems." *Advances in engineering software* 25(2): 103-109.

Anumba, C., Akanmu, A. and Messner, J. (2010). "Towards a cyber-physical systems approach to construction". 2010 Construction Research Congress, Banff, Alberta.

Arditi, D. (1985). "Construction productivity improvement." *Journal of Construction Engineering and Management* 111(1): 1-14.

Arditi, D. and Albulak, M. Z. (1986). "Line-of-balance scheduling in pavement construction." *Journal of Construction Engineering and Management* 112(3): 411-424.

Arslan, M., Riaz, Z., Kiani, A. K. and Azhar, S. (2014). "Real-time environmental monitoring, visualization and notification system for construction h&s management." *ITcon* 19: 72-91.

Bae, H., Golparvar-Fard, M. and White, J. (2013). "High-precision vision-based mobile augmented reality system for context-aware architectural, engineering, construction and facility management (aec/fm) applications." *Visualization in Engineering* 1(1): 1-13.

Bakry, I., Moselhi, O. and Zayed, T. (2013). "Fuzzy dynamic programming for optimized scheduling of repetitive construction projects". IFSA World Congress and NAFIPS Annual Meeting (IFSA/NAFIPS), 2013 Joint, IEEE.

Bakry, I., Moselhi, O. and Zayed, T. (2014). "Optimized acceleration of repetitive construction projects." *Automation in Construction* 39: 145-151.

Bansal, V. (2011). "Use of gis and topology in the identification and resolution of space conflicts." *Journal of Computing in Civil Engineering* 25(2): 159-171.

Baqerin, M., Shafahi, Y. and Kashani, H. (2015). "Application of weibull analysis to evaluate and forecast schedule performance in repetitive projects." *Journal of Construction Engineering and Management*: 04015058.

Becerik-Gerber, B., Siddiqui, M., Brilakis, I., El-Anwar, O., El-Gohary, N., Mahfouz, T., Jog, G., Li, S. and Kandil, A. (2013). "Civil engineering grand challenges: Opportunities for data sensing, information analysis, and knowledge discovery." *Journal of Computing in Civil Engineering* 28(4): 04014013.

Behzadan, A. and Kamat, V. (2009). "Automated generation of operations level construction animations in outdoor augmented reality." *Journal of Computing in Civil Engineering* 23(6): 405-417.

Behzadan, A. H., Aziz, Z., Anumba, C. J. and Kamat, V. R. (2008). "Ubiquitous location tracking for context-specific information delivery on construction sites." *Automation in Construction* 17(6): 737-748.

Bosché, F. (2010). "Automated recognition of 3d cad model objects in laser scans and calculation of as-built dimensions for dimensional compliance control in construction." *Advanced Engineering Informatics* 24(1): 107-118.

Bosché, F., Ahmed, M., Turkan, Y., Haas, C. T. and Haas, R. (2015). "The value of integrating scan-to-bim and scan-vs-bim techniques for construction monitoring using laser scanning and bim: The case of cylindrical mep components." *Automation in Construction* 49, Part B: 201-213.

Bowden, S., Dorr, A., Thorpe, T. and Anumba, C. (2006). "Mobile ict support for construction process improvement." *Automation in Construction* 15(5): 664-676.

Brilakis, I., Fathi, H. and Rashidi, A. (2011). "Progressive 3d reconstruction of infrastructure with videogrammetry." *Automation in Construction* 20(7): 884-895.

Brilakis, I., Lourakis, M., Sacks, R., Savarese, S., Christodoulou, S., Teizer, J. and Makhmalbaf, A. (2010). "Toward automated generation of parametric bims based on hybrid video and laser scanning data." *Advanced Engineering Informatics* 24(4): 456-465.

Carlstein, T., Parkes, D. and Thrift, N. (1978). "Timing space and spacing time: Human activity and time geography". London, Edward Arnold.

Caron, F., Razavi, S. N., Song, J., Vanheeghe, P., Duflos, E., Caldas, C. and Haas, C. (2007). "Locating sensor nodes on construction projects." *Autonomous Robots* 22(3): 255-263.

Chan, W.-T., Chua, D. K. and Kannan, G. (1996). "Construction resource scheduling with genetic algorithms." *Journal of Construction Engineering and Management* 122(2): 125-132.

Changmin, K., Hyojoo, S. and Changwan, K. (2013). "Automated construction progress measurement using a 4d building information model and 3d data." *Automation in Construction* 31: 75-82.

Chen, P.-H. and Shahandashti, S. M. (2009). "Hybrid of genetic algorithm and simulated annealing for multiple project scheduling with multiple resource constraints." *Automation in Construction* 18(4): 434-443.

Chen, Y. and Kamara, J. M. (2011). "A framework for using mobile computing for information management on construction sites." *Automation in Construction* 20(7): 776-788.

Cheng, T., Venugopal, M., Teizer, J. and Vela, P. A. (2011). "Performance evaluation of ultra wideband technology for construction resource location tracking in harsh environments." *Automation in Construction* 20(8): 1173-1184.

Cho, K., Hong, T. and Hyun, C. T. (2013). "Space zoning concept-based scheduling model for repetitive construction process." *Journal of Civil Engineering and Management* 19(3): 409-421.

Choe, S., Leite, F., Seedah, D. and Caldas, C. (2013). "Application of sensing technology in the prevention of backing accidents in construction work zones". Computing in civil engineering (2013), American Society of Civil Engineers**:** 557-564.

Choi, B., Lee, H., Park, M., Cho, Y. and Kim, H. (2014). "Framework for work-space planning using four-dimensional bim in construction projects." *Journal of Construction Engineering and Management* 0(0): 04014041.

Chrzanowski Jr, E. N. and Johnston, D. W. (1986). "Application of linear scheduling." *Journal of Construction Engineering and Management* 112(4): 476-491.

Chua, D., Yeoh, K. and Song, Y. (2010). "Quantification of spatial temporal congestion in four-dimensional computer-aided design." *Journal of Construction Engineering and Management* 136(6): 641-649.

Cosma, C. (2003). "Development of a systematic approach for uncertainty assessment in scheduling multiple repetitive construction processes by using fuzzy set theory".

Costin, A., Pradhananga, N. and Teizer, J. (2014). "Passive rfid and bim for real-time visualization and location tracking". Construction research congress 2014, American Society of Civil Engineers**:** 169-178.

Costin, A. and Teizer, J. (2014). "Utilizing bim for real-time visualization and indoor localization of resources". Computing in civil and building engineering (2014), American Society of Civil Engineers**:** 649-656.

Dasgupta, R., Chattopadhyay, D., Pal, A. and Chakravarty, T. (2014). "A comprehensive seven layer sensor model: Cyber-physical system". Sensing technology: Current status and future trends i. A. Mason, S. C. Mukhopadhyay, K. P. Jayasundera and N. Bhattacharyya, Springer International Publishing. 7**:** 57-81.

Dawood, N. and Mallasi, Z. (2006). "Construction workspace planning: Assignment and analysis utilizing 4d visualization technologies." *Computer-Aided Civil and Infrastructure Engineering* 21(7): 498-513.

Delafontaine, M., Neutens, T. and Van De Weghe, N. (2011). "Modeling potential movement in constrained travel environments using rough space-time prisms." *International Journal of Geographical Information Systems* 25(9): 1389-1411.

Derler, P., Lee, E. A. and Vincentelli, A. S. (2012a). "Modeling cyber physical systems." *Proceedings of the IEEE* 100(1): 13-28.

Derler, P., Lee, E. A. and Vincentelli, A. S. (2012b). "Modeling cyber–physical systems." *Proceedings of the IEEE* 100(1): 13-28.

Dong, A., Maher, M. L., Kim, M. J., Gu, N. and Wang, X. (2009). "Construction defect management using a telematic digital workbench." *Automation in Construction* 18(6): 814-824.

Dong, S. and Kamat, V. R. (2013). "Smart: Scalable and modular augmented reality template for rapid development of engineering visualization applications." *Visualization in Engineering* 1(1): 1-17.

Duffy, G., Oberlender, G. and Seok Jeong, D. (2011). "Linear scheduling model with varying production rates." *Journal of Construction Engineering and Management* 137(8): 574-582.

Duffy, G. A. (2009). "Linear scheduling of pipeline construction projects with varying production rates". Civil Engineering. Stillwater, Oklahoma, Oklahoma State University. DOCTOR OF PHILOSOPHY

Dzeng, R.-J., Lin, C.-W. and Hsiao, F.-Y. (2014). "Application of rfid tracking to the optimization of function-space assignment in buildings." *Automation in Construction* 40: 68-83.

El-Omari, S. and Moselhi, O. (2008). "Integrating 3d laser scanning and photogrammetry for progress measurement of construction work." *Automation in Construction* 18(1): 1-9.

El-Omari, S. and Moselhi, O. (2011). "Integrating automated data acquisition technologies for progress reporting of construction projects." *Automation in Construction* 20(6): 699-705.

El-Rayes, K. and Kandil, A. (2005). "Time-cost-quality trade-off analysis for highway construction." *Journal of Construction Engineering and Management* 131(4): 477-486.

El-Rayes, K. and Moselhi, O. (2001). "Optimizing resource utilization for repetitive construction projects." *Journal of Construction Engineering and Management* 127(1): 18-27.

El-Sayegh, S. M. (1998). "Linear construction planning model (lcpm): A new model for planning and scheduling linear construction projects".

Eldin, N. N. and Senouci, A. B. (1994). "Scheduling and control of linear projects." *Canadian journal of civil engineering* 21(2): 219-230.

Erdogan, B., Anumba, C., Bouchlaghem, D. and Nielsen, Y. (2008). "Collaboration environments for construction: Implementation case studies." *Journal of Management in Engineering* 24(4): 234-244.

Ergun, H. and Pradhananga, N. (2015). "Real-time location data for automated learning curve analysis of linear repetitive construction activities". Computing in civil engineering 2015, American Society of Civil Engineers: 107-114.

Ezeldin, A. and Soliman, A. (2009). "Hybrid time-cost optimization of nonserial repetitive construction projects." *Journal of Construction Engineering and Management* 135(1): 42-55.

Fallah, Y. P. and Sengupta, R. (2012). "A cyber-physical systems approach to the design of vehicle safety networks". Distributed Computing Systems Workshops (ICDCSW), 2012 32nd International Conference on, IEEE.

Fan, S. and Lin, Y. (2007). "Time-cost trade-off in repetitive projects with soft logic". Computing in civil engineering (2007)**:** 83-90**.**

Georgy, M. E. (2008). "Evolutionary resource scheduler for linear projects." *Automation in Construction* 17(5): 573-583**.**

Golparvar-Fard, M., Pena-Mora, F. and Savares, S. (2009a). "D4ar – a 4-dimensional augmented reality model for automating construction progress monitoring data collection, processing and communication " *Journal of Information Technology in Construction* 14: 129-153**.**

Golparvar-Fard, M., Peña-Mora, F. and Savarese, S. (2009b). "D4ar–a 4-dimensional augmented reality model for automating construction progress monitoring data collection, processing and communication." *Journal of Information Technology in Construction* 14: 129-153**.**

Golparvar-Fard, M., Peña-Mora, F. and Savarese, S. (2011). "Integrated sequential as-built and as-planned representation with d4ar tools in support of decision-making tasks in the aec/fm industry." *Journal of Construction Engineering and Management* 137(12): 1099-1116**.**

Gong, D. and Hugsted, R. (1993). "Time-uncertainty analysis in project networks with a new merge-event time-estimation technique." *International Journal of Project Management* 11(3): 165-173**.**

Gonzalez, V., Alarcon, L. F. and Yiu, T. W. (2013). "Integrated methodology to design and manage work-in-process buffers in repetitive building projects." *Journal of the Operational Research Society* 64(8): 1182-1193**.**

Gore, S., Song, L. and Eldin, N. (2011). "Photo-modeling for construction site space planning." *University of Houston*.

Grau, D., Caldas, C. H., Haas, C. T., Goodrum, P. M. and Gong, J. (2009). "Assessing the impact of materials tracking technologies on construction craft productivity." *Automation in Construction* 18(7): 903-911.

Gujrati, S. (2013). "Models and algorithms for cyber-physical systems". Ann Arbor, Kansas State University. 3609428: 159.

Guo, Q. L., Maher, M. and Wamuziri, S. (2001). "Risk analysis in construction networks using a modified stochastic assignment model." *CIVIL ENGINEERING SYSTEMS* 18(3): 215-241.

Guo, S. (2002). "Identification and resolution of work space conflicts in building construction." *Journal of Construction Engineering and Management* 128(4): 287-295.

Hägerstraand, T. (1970). "What about people in regional science?" *Papers in regional science* 24(1): 7-24.

Hagerstrad, T. (1970). "What about people in regional science?" *Papers in Rigional Science* 24: 6-21.

Hammad, A., Akbarnezhad, A., Rey, D. and Waller, S. (2015). "A computational method for estimating travel frequencies in site layout planning." *Journal of Construction Engineering and Management*: 04015102.

Handa, V. and Barcia, R. (1986). "Linear scheduling using optimal control theory." *Journal of Construction Engineering and Management* 112(3): 387-393.

Harmelink, D. and Rowings, J. (1998). "Linear scheduling model: Development of controlling activity path." *Journal of Construction Engineering and Management* 124(4): 263-268.

Harmelink, D. J. (1995). "Linear scheduling model: The development of a linear scheduling model with micro computer applications for highway construction project control."

Harris, R. and Ioannou, P. (1998). "Scheduling projects with repeating activities." *Journal of Construction Engineering and Management* 124(4): 269-278.

Hassanein, A. (2003). "Planning and scheduling highway construction using gis and dynamic programming". Building, Civil and Environmental Engineering. Montreal, Quebec, Canada, Concordia University. Doctor of Philosophy.

Hassanein, A. and Moselhi, O. (2005). "Accelerating linear projects." *Construction Management and Economics* 23(4): 377-385.

Hegazy, T. (1999). "Optimization of construction time-cost trade-off analysis using genetic algorithms." *Canadian journal of civil engineering* 26(6): 685-697.

Hegazy, T. (2005). "Computerized system for efficient scheduling of highway construction." *Transportation Research Record: Journal of the Transportation Research Board*(1907): 8-14.

Hegazy, T. and Ersahin, T. (2001). "Simplified spreadsheet solutions. Ii: Overall schedule optimization." *Journal of Construction Engineering and Management* 127(6): 469-475.

Hegazy, T. and Kamarah, E. (2008). "Efficient repetitive scheduling for high-rise construction." *Journal of Construction Engineering and Management* 134(4): 253-264.

Hegazy, T. and Wassef, N. (2001). "Cost optimization in projects with repetitive nonserial activities." *Journal of Construction Engineering and Management* 127(3): 183-191.

Herbsman, Z. J. (1999). "The application of linear scheduling in the fdot construction operation".

Hildum, D. W. and Smith, S. F. (2007). "Constructing conflict-free schedules in space and time". ICAPS 2007, 17th International Conference on Automated Planning and Scheduling, September 22, 2007 - September 26, 2007, Providence, RI, United states, Curran Associates Inc.

Hiyassat, M. a. S. (2000). "Modification of minimum moment approach in resource leveling." *Journal of Construction Engineering and Management* 126(4): 278-284.

Hossain, L. and Ruwanpura, J. (2010). "An optimization model for dynamic multi-project environment in construction". Construction research congress 2010, American Society of Civil Engineers: 277-287.

Hu, F. (2013). "Cyber-physical systems: Integrated computing and engineering design". London, GBR, CRC Press.

Hyari, K. and El-Rayes, K. (2006). "Optimal planning and scheduling for repetitive construction projects." *Journal of Management in Engineering* 22(1): 11-19.

Ibrahim, M. and Moselhi, O. (2015). "Enhanced localization for indoor construction." *Procedia Engineering* 123: 241-249.

Ioannou, P. and Yang, I. (2016). "Repetitive scheduling method: Requirements, modeling, and implementation." *Journal of Construction Engineering and Management*: 04016002.

Ioannou, P. G. and Srisuwanrat, C. (2006). "Sequence step algorithm for continuous resource utilization in probabilistic repetitive projects". Proceedings of the 38th conference on Winter simulation, Winter Simulation Conference.

Ioannou, P. G. and Srisuwanrat, C. (2007a). "Optimal work breaks in deterministic and probabilistic repetitive projects". Simulation Conference, 2007 Winter, IEEE.

Ioannou, P. G. and Srisuwanrat, C. (2007b). "Probabilistic scheduling for repetitive projects". Proceedings of the 15th Annual Conference of the International Group for Lean Construction.

Ipsilandis, P. (2007). "Multiobjective linear programming model for scheduling linear repetitive projects." *Journal of Construction Engineering and Management* 133(6): 417-424.

Irizarry, J., Gheisari, M., Williams, G. and Walker, B. N. (2013). "Infospot: A mobile augmented reality method for accessing building information through a situation awareness approach." *Automation in Construction* 33: 11-23.

Irizarry, J. and Gill, T. (2009). "Mobile applications for information access on construction jobsites". Computing in civil engineering (2009), American Society of Civil Engineers: 176-185.

Jiang, Y. and Wu, H. (2007). "Production rates of highway construction activities." *International Journal of Construction Education and Research* 3(2): 81-98.

Johnston, D. W. (1981). "Linear scheduling method for highway construction." *Journal of the Construction Division* 107(2): 247-261.

Jongeling, R. and Olofsson, T. (2007). "A method for planning of work-flow by combined use of location-based scheduling and 4d cad." *Automation in Construction* 16(2): 189-198.

Jun, D. H. (2010a). "Multi-objective optimization for resource driven scheduling in construction projects", University of Illinois at Urbana-Champaign.

Jun, D. H. (2010b). "Multi-objective optimization for resource driven scheduling in construction projects". Ann Arbor, University of Illinois at Urbana-Champaign. 3452182: 246.

Kaihara, T. and Yao, Y. (2012). "A new approach on cps-based scheduling and wip control in process industries". Simulation Conference (WSC), Proceedings of the 2012 Winter, IEEE.

Karan, E. and Ardeshir, A. (2008). "Safety assessment of construction site layout using geographic information system". Aei 2008: 1-14.

Karsai, G. and Sztipanovits, J. (2008). "Model-integrated development of cyber-physical systems". Software technologies for embedded and ubiquitous systems, Springer: 46-54.

Karsch, K., Golparvar-Fard, M. and Forsyth, D. (2014). "Constructaide: Analyzing and visualizing construction sites through photographs and building models." *ACM Transactions on Graphics (TOG)* 33(6): 176.

Khan, W. Z., Xiang, Y., Aalsalem, M. Y. and Arshad, Q. (2013). "Mobile phone sensing systems: A survey." *IEEE Communications Surveys & Tutorials* 15(1): 402-427.

Khoury, H., Chdid, D., Oueis, R., Elhajj, I. and Asmar, D. (2015). "Infrastructureless approach for ubiquitous user location tracking in construction environments." *Automation in Construction* 56: 47-66.

Khoury, H. M. and Kamat, V. R. (2007). "Wlan based user position tracking for contextual information access in indoor construction environments". Proceedings of the 2007 ASCE International Workshop on Computing in Civil Engineering. Pittsburgh, Pennsylvania, USA.

Kim, C., Kim, H., Ryu, J. and Kim, C. (2010). "Ubiquitous sensor network for construction material monitoring." *Journal of Construction Engineering and Management* 137(2): 158-165.

Kim, C., Park, T., Lim, H. and Kim, H. (2013). "On-site construction management using mobile computing technology." *Automation in Construction* 35: 415-423.

Kim, K.-D. and Kumar, P. R. (2012). "Cyber–physical systems: A perspective at the centennial." *Proceedings of the IEEE* 100(Special Centennial Issue): 1287-1308.

Kim, T. W., Kim, Y., Cha, S. H. and Fischer, M. (2015). "Automated updating of space design requirements connecting user activities and space types." *Automation in Construction* 50(0): 102-110.

Kim, Y. S., Oh, S. W., Cho, Y. K. and Seo, J. W. (2008). "A pda and wireless web-integrated system for quality inspection and defect management of apartment housing projects." *Automation in Construction* 17(2): 163-179.

Kimoto, K., Endo, K., Iwashita, S. and Fujiwara, M. (2005). "The application of pda as mobile computing system on construction management." *Automation in Construction* 14(4): 500-511.

Koo, B., Kim, J. and Kim, J.-I. (2013). "An empirical study of mep workspace modeling approaches for 4d model-based time-space conflict analyses: Case study on the international linear collider project." *KSCE Journal of Civil Engineering* 17(4): 627-637.

Kraak, M.-J. (2003a). "The space-time cube revisited from a geovisualization perspective". Proc. 21st International Cartographic Conference.

Kraak, M. J. (2003b). "The space-time-cube revisited from a geovisualisation perspective". 21st International Cartographic Conference (ICC), Durban, South Africa.

Krämer, B. J. (2014). "Evolution of cyber-physical systems: A brief review". Applied cyber-physical systems, Springer: 1-3.

Krishna, P. V., Saritha, V., Sultana., H. P. (2015). "Challenges, opportunities, and dimensions of cyber-physical systems", IGI Global.

Krogh, B., Lee, E., Lee, I., Mok, A., Rajkumar, R., Sha, L., Vincentelli, A., Shin, K., Stankovic, J. and Sztipanovits, J. (2008). "Cyber-physical systems, executive summary." *CPS Steering Group, Washington DC*.

Kumar, B. and Sommerville, J. (2012). "A model for rfid-based 3d location of buried assets." *Automation in Construction* 21: 121-131.

Kuo, Y.-C. (2004). "Highway earthwork and pavement production rates for construction time estimation". Ann Arbor, The University of Texas at Austin. 3143291: 359-359 p.

Lee, D.-E. and Arditi, D. (2006). "Automated statistical analysis in stochastic project scheduling simulation." *Journal of Construction Engineering and Management* 132(3): 268-277.

Lee, E. A. (2007). "Computing foundations and practice for cyber-physical systems: A preliminary report." *University of California, Berkeley, Tech. Rep. UCB/EECS-2007-72*.

Lee, E. A. (2008a). "Cyber physical systems: Design challenges". 11th IEEE Symposium on Object/Component/Service-Oriented Real-Time Distributed Computing, ISORC 2008, May 5, 2008 - May 7, 2008, Orlando, FL, United states, Inst. of Elec. and Elec. Eng. Computer Society.

Lee, E. A. (2008b). "Cyber physical systems: Design challenges". Object Oriented Real-Time Distributed Computing (ISORC), 2008 11th IEEE International Symposium on.

Lee, I., Sokolsky, O., Chen, S., Hatcliff, J., Jee, E., Kim, B., King, A., Mullen-Fortino, M., Park, S. and Roederer, A. (2012). "Challenges and research directions in medical cyber–physical systems." *Proceedings of the IEEE* 100(1): 75-90.

Lee, U.-K., Kim, J.-H., Cho, H. and Kang, K.-I. (2009). "Development of a mobile safety monitoring system for construction sites." *Automation in Construction* 18(3): 258-264.

Leu, S.-S. and Yang, C.-H. (1999). "Ga-based multicriteria optimal model for construction scheduling." *Journal of Construction Engineering and Management* 125(6): 420-427.

Li, H., Chan, G., Wong, J. K. W. and Skitmore, M. (2016). "Real-time locating systems applications in construction." *Automation in Construction* 63: 37-47.

Li , J. Z., Gao, H. and Yu, B. (2009). "Concepts, features, challenges, and research progresses of cpss". Development Report of China Computer Science in 2009**:** 1-17.

Li, N., Becerik-Gerber, B., Krishnamachari, B. and Soibelman, L. (2014). "A bim centered indoor localization algorithm to support building fire emergency response operations." *Automation in Construction* 42: 78-89.

Li, N., Li, S., Becerik-Gerber, B. and Calis, G. (2011). "Deployment strategies and performance evaluation of a virtual-tag-enabled indoor location sensing approach." *Journal of Computing in Civil Engineering* 26(5): 574-583.

Lipman, R. R. (2004). "Mobile 3d visualization for steel structures." *Automation in Construction* 13(1): 119-125.

Liu, S.-S. (1999). "Resource-constrained scheduling of linear projects: A heuristic approach using tabu search heuristics."

Lluch, J. (2009). "Visualization of repetitive construction activities in excel". Computing in civil engineering (2009)**:** 603-612.

Lu, T., Xu, B., Guo, X., Zhao, L. and Xie, F. (2013). "A new multilevel framework for cyber-physical system security", TerraSwarm.

Lu, Y., Li, Y., Skibniewski, M., Wu, Z., Wang, R. and Le, Y. (2014). "Information and communication technology applications in architecture, engineering, and construction organizations: A 15-year review." *Journal of Management in Engineering* 31(1): A4014010.

Lucko, G. (2008). "Productivity scheduling method compared to linear and repetitive project scheduling methods." *Journal of Construction Engineering and Management* 134(9): 711-720.

Lucko, G. (2010a). "Integrating efficient resource optimization and linear schedule analysis with singularity functions." *Journal of Construction Engineering and Management* 137(1): 45-55.

Lucko, G. (2010b). "Optimizing cash flows for linear schedules modeled with singularity functions by simulated annealing." *Journal of Construction Engineering and Management* 137(7): 523-535.

Lucko, G., Araújo, L. and Cates, G. (2015). "Slip chart–inspired project schedule diagramming: Origins, buffers, and extension to linear schedules." *Journal of Construction Engineering and Management*: 04015101.

Lucko, G., Said, H. M. M. and Bouferguene, A. (2014). "Construction spatial modeling and scheduling with three-dimensional singularity functions." *Automation in Construction* 43: 132-143.

Lukman Khalid, C. M., Fathi, M. S. and Mohamed, Z. (2014). "Integration of cyber-physical systems technology with augmented reality in the pre-construction stage". Technology, Informatics, Management, Engineering, and Environment (TIME-E), 2014 2nd International Conference on.

Lumsden, P. (1968). "The line-of-balance method", Pergamon Press Limited.

Luo, X., O'brien, W. and Leite, F. (2013). "Evaluating the impact of location-aware sensor data imperfections on autonomous jobsite safety monitoring". Computing in civil engineering (2013), American Society of Civil Engineers: 573-580.

Maalek, R., Lichti, D. and Ruwanpura, J. (2015). "Development of an automated 3d/4d as-built model generation system for construction progress monitoring and quality control."

Mallasi, Z. (2006). "Dynamic quantification and analysis of the construction workspace congestion utilising 4d visualisation." *Automation in Construction* 15(5): 640-655.

Marks, E. and Teizer, J. (2012). "Proximity sensing and warning technology for heavy construction equipment operation". Construction research congress 2012, American Society of Civil Engineers: 981-990.

Mattila, K. and Abraham, D. (1998). "Resource leveling of linear schedules using integer linear programming." *Journal of Construction Engineering and Management* 124(3): 232-244.

Menesi, W., Golzarpoor, B. and Hegazy, T. (2013). "Fast and near-optimum schedule optimization for large-scale projects." *Journal of Construction Engineering and Management* 139(9): 1117-1124.

Miller, H. J. (1991). "Modeling accessibility using time space prism concepts within geographical information systems." *International Journal of Geographical Information Systems* 5: 287-301.

Miller, H. J. (2005). "A measurement theory for time geography." *Geographical Analysis* 37: 17-45.

Mingozzi, A., Maniezzo, V., Ricciardelli, S. and Bianco, L. (1998). "An exact algorithm for the resource-constrained project scheduling problem based on a new mathematical formulation." *Management Science* 44(5): 714-729.

Moon, H., Dawood, N. and Kang, L. (2014). "Development of workspace conflict visualization system using 4d object of work schedule." *Advanced Engineering Informatics* 28(1): 50-65.

Moon, H., Kim, H., Kamat, V. and Kang, L. (2013). "Bim-based construction scheduling method using optimization theory for reducing activity overlaps." *Journal of Computing in Civil Engineering* 29(3): 04014048.

Moselhi, O. and Hassanein, A. (2003). "Optimized scheduling of linear projects." *Journal of Construction Engineering and Management* 129(6): 664-673.

Moussourakis, J. and Haksever, C. (2004). "Flexible model for time/cost tradeoff problem." *Journal of Construction Engineering and Management* 130(3): 307-314.

Niu, Y., Lu, W., Chen, K., Huang, G. and Anumba, C. (2015). "Smart construction objects." *Journal of Computing in Civil Engineering*: 04015070.

Noor, A. (2011). "Intelligent adaptive cyber-physical ecosystem for aerospace engineering education, training, and accelerated workforce development." *Journal of Aerospace Engineering* 24(4): 403-408.

O'brien, J. J. (1975). "Vpm scheduling for high-rise buildings." *American Society of Civil Engineers, Journal of the Construction Division* 101(4): 895-905.

O'connor, J. T. and Huh, Y. (2005). "Crew production rates for contract time estimation: Bent footing, column, and cap of highway bridges." *Journal of Construction Engineering and Management* 131(9): 1013-1020.

Park, J., Marks, E., Cho, Y. and Suryanto, W. (2015a). "Mobile proximity sensing technologies for personnel and equipment safety in work zones". Computing in civil engineering 2015, American Society of Civil Engineers: 41-48.

Park, J., Marks, E., Cho, Y. and Suryanto, W. (2015b). "Performance test of wireless technologies for personnel and equipment proximity sensing in work zones." *Journal of Construction Engineering and Management* 142(1): 04015049.

Peansupap, V. and Walker, D. (2005). "Factors affecting ict diffusion: A case study of three large australian construction contractors." *Engineering, construction and architectural management* 12(1): 21-37.

Peña-Mora, F., Chen, A. Y., Aziz, Z., Soibelman, L., Liu, L. Y., El-Rayes, K., Arboleda, C. A., Lantz Jr, T. S., Plans, A. P. and Lakhera, S. (2010). "Mobile ad hoc network-enabled collaboration framework supporting civil engineering emergency response operations." *Journal of Computing in Civil Engineering* 24(3): 302-312.

Penã-Mora, F. and Dwivedi, G. (2002). "Multiple device collaborative and real time analysis system for project management in civil engineering." *Journal of Computing in Civil Engineering* 16(1): 23-38.

Polat, G., Buyuksaracoglu, Y. and Damci, A. (2009). "Scheduling asphalt highway construction operations using the combination of line-of-balance and discrete event simulation techniques". 2009 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM 2009), 8-11 Dec. 2009, Piscataway, NJ, USA, IEEE.

Pradhananga, N. and Teizer, J. (2014). "Congestion analysis for construction site layout planning using real-time data and cell-based simulation model". Computing in civil and building engineering (2014): 681-688.

Rafibakhsh, N., Gong, J., Siddiqui, M., Gordon, C. and Lee, H. (2012). "Analysis of xbox kinect sensor data for use on construction sites : Depth accuracy and sensor interference assessment". Construction research congress 2012, American Society of Civil Engineers: 848-857.

Rahbar, F. F. and Rowings, J. E. (1992). "Repetitive activity scheduling process." *AACE International Transactions* 2: O. 5.1.

Rajkumar, R. R., Lee, I., Sha, L. and Stankovic, J. (2010). "Cyber-physical systems: The next computing revolution". Proceedings of the 47th Design Automation Conference, ACM.

Raza, R. H. (2013). "Three dimensional localization and tracking for site safety using fusion of computer vision and rfid". Electrical Engineering, Michigan State University. Doctor of Philosophy.

Razavi, S. N. and Haas, C. T. (2010). "Multisensor data fusion for on-site materials tracking in construction." *Automation in Construction* 19(8): 1037-1046.

Reinhardt, J., Garrett Jr, J. H. and Akinci, B. (2005). "Framework for providing customized data representations for effective and efficient interaction with mobile computing solutions on construction sites." *Journal of Computing in Civil Engineering* 19(2): 109-118.

Repass, K., Garza, J. and Thabet, W. (2000). "Mobile schedule tracking technology at the jobsite". Construction congress vi, American Society of Civil Engineers: 204-213.

Rezazadeh Azar, E. and Mccabe, B. (2011). "Automated visual recognition of dump trucks in construction videos." *Journal of Computing in Civil Engineering* 26(6): 769-781.

Riaz, Z., Arslan, M. and Peña-Mora, F. (2015). "Challenges in data management when monitoring confined spaces using bim and wireless sensor technology". Computing in civil engineering 2015, American Society of Civil Engineers: 123-130.

Riley, D. and Sanvido, V. (1995). "Patterns of construction-space use in multistory buildings." *Journal of Construction Engineering and Management* 121(4): 464-473.

Roofigari-Esfahan, N., Paez, A. and N.Razavi, S. (2015). "Location-aware scheduling and control of linear projects: Introducing space-time float prisms." *Journal of Construction Engineering and Management* 141(1): 06014008.

Roofigari Esfahan, N., Páez, A. and Razavi, S. (2013). "Spatio-temporal progress estimation for highway construction". Computing in civil engineering (2013), American Society of Civil Engineers**:** 541-548.

Rose, K. H. (2013). "A guide to the project management body of knowledge (pmbok® guide)—fifth edition." *Project Management Journal* 44(3): e1-e1.

Russell, A. and Caselton, W. (1988). "Extensions to linear scheduling optimization." *Journal of Construction Engineering and Management* 114(1): 36-52.

Sarkar, S. (2011). "Autonomous perception and decision making in cyber-physical systems". Ann Arbor, The Pennsylvania State University. 3483818**:** 227-n/a.

Senouci, A. and Eldin, N. (1996). "Dynamic programming approach to scheduling of nonserial linear project." *Journal of Computing in Civil Engineering* 10(2): 106-114.

Shah, R. K. (2014). "A new approach for automation of location-based earthwork scheduling in road construction projects." *Automation in Construction* 43: 156-169.

Shi, J., Wan, J., Yan, H. and Suo, H. (2011). "A survey of cyber-physical systems". Wireless Communications and Signal Processing (WCSP), 2011 International Conference on, IEEE.

Shu-Shun, L. and Chang-Jung, W. (2007). "Optimization model for resource assignment problems of linear construction projects." *Automation in Construction* 16(4): 460-473.

Siddiqui, M. (2014). "Taxonomy of work spaces for sensor-driven jobsite management". Computing in civil and building engineering (2014), American Society of Civil Engineers: 1070-1077.

Siebert, S. and Teizer, J. (2014). "Mobile 3d mapping for surveying earthwork projects using an unmanned aerial vehicle (uav) system." *Automation in Construction* 41: 1-14.

Son, H., Park, Y., Kim, C. and Chou, J.-S. (2012). "Toward an understanding of construction professionals' acceptance of mobile computing devices in south korea: An extension of the technology acceptance model." *Automation in Construction* 28: 82-90.

Son, J. and Mattila, K. G. (2004). "Binary resource leveling model: Activity splitting allowed." *Journal of Construction Engineering and Management* 130(6): 887-894.

Son, J. and Skibniewski, M. J. (1999). "Multiheuristic approach for resource leveling problem in construction engineering: Hybrid approach." *Journal of Construction Engineering and Management* 125(1): 23-31.

Song, L., Cooper, C. and Lee, S.-H. (2009). "Real-time simulation for look-ahead scheduling of heavy construction projects". 2009 Construction Research Congress - Building a Sustainable Future, April 5, 2009 - April 7, 2009, Seattle, WA, United states, American Society of Civil Engineers.

Srisuwanrat, C. (2009). "The sequence step algorithm: A simulation-based scheduling algorithm for repetitive projects with probabilistic activity durations". Civil Engineering, University of Michigan. Doctor of Philosophy.

Srisuwanrat, C. and Ioannou, P. G. (2007). "Optimal scheduling of probabilistic repetitive projects using completed unit and genetic algorithms". Proceedings of the 39th conference on Winter simulation: 40 years! The best is yet to come, IEEE Press.

Staub-French, S., Russell, A. and Tran, N. (2008). "Linear scheduling and 4d visualization." *Journal of Computing in Civil Engineering* 22(3): 192-205.

Stradal, O. and Cacha, J. (1982). "Time space scheduling method." *Journal of the Construction Division* 108(CO3): 445-457.

Su, X. and Cai, H. (2013). "A 4d cpm-based graphic scheduling system". Computing in civil engineering (2013)**:** 786-793.

Su, X., Li, S., Yuan, C., Cai, H. and Kamat, V. (2014). "Enhanced boundary condition–based approach for construction location sensing using rfid and rtk gps." *Journal of Construction Engineering and Management* 140(10): 04014048.

Suh, S. C. (2014). "Applied cyber-physical systems".

Suh, S. C., Tanik, U. J., Carbone, J. N. and Eroglu, A. (2014). "Applied cyber-physical systems." *Springer* 2: 27.

Sztipanovits, J., Koutsoukos, X., Karsai, G., Kottenstette, N., Antsaklis, P., Gupta, V., Goodwine, B., Baras, J. and Wang, S. (2012). "Toward a science of cyber–physical system integration." *Proceedings of the IEEE* 100(1): 29-44.

Tang, Y., Liu, R. and Sun, Q. (2014a). "Schedule control model for linear projects based on linear scheduling method and constraint programming." *Automation in Construction* 37: 22-37.

Tang, Y., Liu, R. and Sun, Q. (2014b). "Two-stage scheduling model for resource leveling of linear projects." *Journal of Construction Engineering and Management* 140(7): 04014022.

Teizer, J. (2008). "3d range imaging camera sensing for active safety in construction." *J. Inf. Technol. Constr* 13: 103-117.

Teizer, J., Caldas, C. H. and Haas, C. T. (2007). "Real-time three-dimensional occupancy grid modeling for the detection and tracking of construction resources." *Journal of Construction Engineering and Management* 133(11): 880-888.

Teizer, J., Cheng, T. and Fang, Y. (2013). "Location tracking and data visualization technology to advance construction ironworkers' education and training in safety and productivity." *Automation in Construction* 35: 53-68.

Teizer, J. and Vela, P. A. (2009). "Personnel tracking on construction sites using video cameras." *Advanced Engineering Informatics* 23(4): 452-462.

Teizer, J., Venugopal, M. and Walia, A. (2008). "Ultrawideband for automated real-time three-dimensional location sensing for workforce, equipment, and material positioning and tracking." *Transportation Research Record: Journal of the Transportation Research Board*(2081): 56-64.

Thabet, W. and Beliveau, Y. (1997a). "Modeling work space to schedule repetitive floors in multistory buildings." *Journal of Construction Engineering and Management* 120(1): 96-116.

Thabet, W. and Beliveau, Y. (1997b). "Scarc: Space-constrained resource-constrained scheduling system." *Journal of Computing in Civil Engineering* 11(1): 48-59.

Thabet, W. Y. (1992). "A space-constrained resource-constrained scheduling system for multi-story buildings".

Thabet, W. Y. and Beliveau, Y. J. (1994). "Hvls: Horizontal and vertical logic scheduling for multistory projects." *Journal of Construction Engineering and Management* 120(4): 875-892.

Tokdemir, O. B. (2003). "Aliss: Advanced linear scheduling system". Civil Engineering. Chicago, Illinois, Illinois Institute of Technology. Doctor of Philosophy.

Tomé, A., Kuipers, M., Pinheiro, T., Nunes, M. and Heitor, T. (2015). "Space–use analysis through computer vision." *Automation in Construction* 57: 80-97.

Torrent, D. G. and Caldas, C. H. (2009). "Methodology for automating the identification and localization of construction components on industrial projects." *Journal of Computing in Civil Engineering* 23(1): 3-13.

Tserng, H. P., Dzeng, R.-J., Lin, Y.-C. and Lin, S.-T. (2005). "Mobile construction supply chain management using pda and bar codes." *Computer-Aided Civil and Infrastructure Engineering* 20(4): 242-264.

Turkan, Y., Bosché, F., Haas, C. and Haas, R. (2012a). "Toward automated earned value tracking using 3d imaging tools." *Journal of Construction Engineering and Management* 139(4): 423-433.

Turkan, Y., Bosche, F., Haas, C. T. and Haas, R. (2012b). "Automated progress tracking using 4d schedule and 3d sensing technologies." *Automation in Construction* 22: 414-421.

Uslu, B., Golparvar-Fard, M. and De La Garza, J. M. (2011). "Image-based 3d reconstruction and recognition for enhanced highway condition assessment". Proc., Proceedings of the 2011 ASCE Intl. Workshop on Computing in Civil Engineering, Miami, FL.

Vanhoucke, M. (2006). "Work continuity constraints in project scheduling." *Journal of Construction Engineering and Management* 132(1): 14-25.

Vorster, M., Beliveau, Y. J. and Bafna, T. (1992). "Linear scheduling and visualization." *Transportation Research Record*(1351).

Wang, J. and Razavi, S. (2015). "Low false alarm rate model for unsafe-proximity detection in construction." *Journal of Computing in Civil Engineering* 30(2): 04015005.

Wang, L.-C. (2008). "Enhancing construction quality inspection and management using rfid technology." *Automation in Construction* 17(4): 467-479.

Wang, W.-C., Weng, S.-W., Wang, S.-H. and Chen, C.-Y. (2014a). "Integrating building information models with construction process simulations for project scheduling support." *Automation in Construction* 37: 68-80.

Wang, X., Truijens, M., Hou, L., Wang, Y. and Zhou, Y. (2014b). "Integrating augmented reality with building information modeling: Onsite construction process controlling for liquefied natural gas industry." *Automation in Construction* 40: 96-105.

Wang, X., Yung, P., Luo, H. and Truijens, M. (2014c). "An innovative method for project control in lng project through 5d cad: A case study." *Automation in Construction* 45(0): 126-135.

Watkins, M., Mukherjee, A., Onder, N. and Mattila, K. (2009). "Using agent-based modeling to study construction labor productivity as an emergent property of individual and crew interactions." *Journal of Construction Engineering and Management* 135(7): 657-667.

Weerasinghe, I., Ruwanpura, J., Boyd, J. and Habib, A. (2012). "Application of microsoft kinect sensor for tracking construction workers". Construction research congress 2012, American Society of Civil Engineers: 858-867.

Winch, G. and North, S. (2006). "Critical space analysis." *Journal of Construction Engineering and Management* 132(5): 473-481.

Woldesenbet, A., Jeong, D. H. S. and Oberlender, G. D. (2012). "Daily work reports-based production rate estimation for highway projects." *Journal of Construction Engineering and Management* 138(4): 481-490.

Wu, B. (2012). "Internet-of-vehicles based on technologies of internet-of-things". Iclem 2012, American Society of Civil Engineers: 348-356.

Wu, F.-J., Kao, Y.-F. and Tseng, Y.-C. (2011). "From wireless sensor networks towards cyber physical systems." *Pervasive and Mobile Computing* 7(4): 397-413.

Wu, Y., Kim, H., Kim, C. and Han, S. (2009). "Object recognition in construction-site images using 3d cad-based filtering." *Journal of Computing in Civil Engineering* 24(1): 56-64.

Xu, R., Liu, J., Zhu, J. and Jiang, X. (2015). "The design and construction of wlan-based indoor navigation system". 2nd International Conference on Geo-Informatics in Resource Management and Sustainable Ecosystem, GRMSE 2014, October 3, 2014 - October 5, 2014, Ypsilanti, MI, United states, Springer Verlag.

Yamin, R. A. (2001). "Cumulative effect of productivity rates in linear schedules".

Yang, I. T. and Chi-Yi, C. (2005). "Stochastic resource-constrained scheduling for repetitive construction projects with uncertain supply of resources and funding." *International Journal of Project Management* 23(7): 546-553.

Yang, J., Park, M.-W., Vela, P. A. and Golparvar-Fard, M. (2015). "Construction performance monitoring via still images, time-lapse photos, and video streams: Now, tomorrow, and the future." *Advanced Engineering Informatics* 29(2): 211-224.

Yang, J., Vela, P., Teizer, J. and Shi, Z. (2011). "Vision-based crane tracking for understanding construction activity". Computing in civil engineering (2011), American Society of Civil Engineers: 258-265.

Yin, S. Y. L., Tserng, H. P., Wang, J. C. and Tsai, S. C. (2009). "Developing a precast production management system using rfid technology." *Automation in Construction* 18(5): 677-691.

Yuan, C. (2014). "Tracking dynamic construction objects ---a key node modeling approach using color-depth cameras". Civil Engineering. West Lafayette, Indiana, Perdue University. Master of Science.

Yuan, X., Parfitt, K. and Anumba, C. J. (2014). "The use of cyber-physical systems in temporary structures–an exploratory study." *Computing in Civil and Building Engineering. ASCE, Florida, USA*: 23-25.

Zhang, C. and Hammad, A. (2011). "Multiagent approach for real-time collision avoidance and path replanning for cranes." *Journal of Computing in Civil Engineering* 26(6): 782-794.

Zhang, C., Hammad, A. and Rodriguez, S. (2011). "Crane pose estimation using uwb real-time location system." *Journal of Computing in Civil Engineering* 26(5): 625-637.

Zhang, H., Li, H. and Tam, C. (2006a). "Particle swarm optimization for preemptive scheduling under break and resource-constraints." *Journal of Construction Engineering and Management* 132(3): 259-267.

Zhang, H., Li, H. and Tam, C. (2006b). "Permutation-based particle swarm optimization for resource-constrained project scheduling." *Journal of Computing in Civil Engineering* 20(2): 141-149.

Zhang, L., Zou, X. and Kan, Z. (2014). "Improved strategy for resource allocation in repetitive projects considering the learning effect." *Journal of Construction Engineering and Management* 140(11): 04014053.

Zhang, S. and Bogus, S. (2014). "Use of low-cost remote sensing for infrastructure management". Construction research congress 2014, American Society of Civil Engineers**:** 1299-1308.

Zhou, F., Abourizk, S. M. and Al-Battaineh, H. (2009). "Optimisation of construction site layout using a hybrid simulation-based system." *Simulation Modelling Practice and Theory* 17(2): 348-363.

Zhu, Z. and Donia, S. (2013). "Potentials of rgb-d cameras in as-built indoor environments modeling". Los Angeles, CA: 2013 ASCE International Workshop on Computing in Civil Engineering.

Zollmann, S., Hoppe, C., Kluckner, S., Poglitsch, C., Bischof, H. and Reitmayr, G. (2014). "Augmented reality for construction site monitoring and documentation." *Proceedings of the IEEE* 102(2): 137-154.

Zou, J. and Kim, H. (2007). "Using hue, saturation, and value color space for hydraulic excavator idle time analysis." *Journal of Computing in Civil Engineering* 21(4): 238-246.

Zouein, P. and Tommelein, I. (2001). "Improvement algorithm for limited space scheduling." *Journal of Construction Engineering and Management* 127(2): 116-124.