THE IMPACT OF VISUAL PRODUCTION MANAGEMENT ON CONSTRUCTION PROJECT CONTROLS: A CASE-BASED REASONING

BY

MANISH PATIDAR

THESIS

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Adviser:

Associate Professor Mani Golparvar-Fard
ABSTRACT

Over the past decade, production control theories such as the Last Planner System by Ballard, G., (2000) have emerged that stabilize workflows by shielding the direct work from upstream variation and uncertainty. Although theories have been well documented, yet their full-scale implementation is not realized, and the root-causes for this are not entirely understood. A large body of empirical observations suggest that successful implementation of control mechanisms requires dedicated facilitators and engages practitioners in a relatively deep learning process. Sustaining this level of commitment for the duration of a project is difficult, and in its absence, project teams revert to traditional project control practices. These barriers are in part attributed to the people and organizational processes involved in implementing lean principles, however there is a growing recognition among researchers that the functional aspects of production control techniques need close re-examination to understand better, predict, and analyze reliability in performance, and preserve effective and timely flow of information both to and from the workforce.

To address these knowledge gaps, Lin and Golparvar-Fard (2016) proposes a visual project control system that a) improves understanding of how construction performance can be captured, communicated, and analyzed in form of a production system; b) predicts the reliability of the weekly work plan and look-ahead schedule, supports root-cause assessment on plan failure at both project and task-levels; c) facilitates information flows; and d) decentralizes decision-making. The web-based system which is built on visual data analytics maps the current state of production on construction sites in 3D and exposes waste at both project and task-levels and it then forecasts reliability in the future state of production to highlight potential issues in a location-driven scheme.
The platform also supports collaborative decision making that eliminates root causes of waste and provides visual interfaces between people and information that enable effective pull flow, decentralize work tracking, and facilitate in-process quality control and hand-overs among contractors. To ensure their implementation does not take away from actual productivity, it extends the value of 4D Building Information Models (BIM) commonly used for constructability review as a benchmark for performance. It also leverages images and videos frequently collected by project participants or professional services via consumer-grade, time-lapse, smartphone cameras and Unmanned Aerial Vehicles (UAVs) to visually document actual performance.

To better understand, assess, and improve the performance of this visual production system, a case-based reasoning study is conducted in this thesis using case studies based on two real-world construction projects. The use of simple and effective visuals of work-in-progress and at risk locations on construction sites offered through visual production management is assessed to better understand if such systems can improve reliability of short-term planning, enhance situational awareness, enable easy and quick root-cause assessment of plan failures, and facilitate flow of information onsite and during coordination sessions. The lessons learned and areas for further development in theory and technology are discussed in detail.
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CHAPTER 1: INTRODUCTION

1.1 Introduction

Achieving smooth process in construction and avoiding waste require effective team planning (Aritua et al. 2009; Ballard 2000; Ballard and Howell 1994; Brodetskaia et al. 2013; Dave et al. 2014; Gurevich and Sacks 2014; Hamzeh et al. 2012; Lindhard and Wandahl 2013; Sacks et al. 2010a). Recently, theories such as the Last Planner System (Ballard 2000) have been developed that propose workflows that can protect the immediate work from upstream uncertainty. While the advantages of these methods are well known, implementation is rarely achieved for entire project duration, and the underlying shortcomings are not entirely understood. (Brodetskaia et al. 2013; Dave et al. 2014, 2015; Hamzeh et al. 2015; Yu et al. 2009). Extensive studies and many empirical observations have recommended effective usage of the Last Planner System requires committed facilitators (champions) and engages professionals in a generally profound learning process (Alarcón et al. 2008; Dave et al. 2015). It remains a challenge for a project team to remain committed during the entire duration of project, and in absence on the champion of workflow, team tend to return to conventional practices (Bortolazza et al. 2005; Dave et al. 2015; Gurevich and Sacks 2014; Leigard and Pesonen 2010; Sacks et al. 2010a, 2013). These obstructions tare mainly related to the organisational aspects of implementing lean principles. In research community, however there is growing believe that re-evaluation of functional aspects of production control systems is needed to analyse reliability in performance and transparency in flow of information to ensure benefits to the project. (Aritua et al. 2009; Brodetskaia et al. 2013; Dave et al. 2014, 2015; Gurevich and Sacks 2014; Hamzeh et al. 2012; Lindhard and Wandahl 2013).
To address these knowledge gaps, a new visual production management system has been developed by Lin and Golparvar-Fard (2016) that a) refines understanding of how construction performance can be captured, communicated and analyzed in the form of a production system; b) predicts the reliability of the weekly work plan and look-ahead schedule, supports root-cause assessment on plan failure at both project and task levels; c) facilitates information flows; and d) decentralizes decision-making. Specifically, the platforms leverage a model-driven visual sensing and analytics that map the current state of production in 3D and expose waste at both project and task levels; forecast reliability in the future state of production to highlight potential issues in a location-driven scheme; support collaborative decision making that eliminates root causes of waste; and provide visual interfaces between people and information that enable effective pull flow, decentralize work tracking, and facilitate in-process quality control and hand-over among contractors.

To ensure 4D Building Information models (BIM) is implemented preserving actual productivity, the method is used to perform constructability reviews prior to execution. Similarly, photos/videos, captured as frequently as possible by team members or third party photography agency using cell phone, cameras and Unmanned Aerial Vehicles (UAVs) are utilized to report actual executed work visually.

To better understand, assess, and improve the performance of this visual production system, a case-based reasoning study is conducted in this thesis using case studies based on two real-world construction projects. The use of simple and effective visuals of work-in-progress and
at risk locations on construction sites offered through visual production management is assessed to better understand if such systems can improve reliability of short-term planning, enhance situational awareness, enable easy and quick root-cause assessment of plan failures, and facilitate flow of information on-site and during coordination sessions.

In the following, an overview of the state of the industry together with a discussion on the specific practical problems and the opportunity of using visual data as a source for capture, analytics and representation of Plan and As-built status of a construction project is provided. In the next Chapter, state of the art in the literature is discussed in detail. Next, the capabilities of the visual production management system in used is discussed followed by details about the case studies conducted.

1.2 The State of Productivity in the Construction Industry
The construction industry is plagued with inefficiencies, including cost overruns and delays. According to a recent analysis by McKinsey & Company (2015), 98% of large construction projects incur delays averaging 20 months with cost overruns of 80% on average. Additionally, productivity levels in the industry have been flat for decades, particularly in comparison to other industries such as manufacturing, in which productivity doubled in the same period (Fig. 1).

![Productivity Graph](image.jpg)

Figure 1. Productivity in construction has remained flat over the past twenty years, while productivity in manufacturing has nearly doubled. Graphic from McKinsey report on construction productivity (2015).
Key factors which resulted in lack of improvement in productivity are inconsistent reporting which makes it difficult for construction executives to understand actual status of work progress. Besides, daily planning tends to fall short in execution due to poor reporting of work progress. Lower productivity also reflects flawed production controls in practice, poor short term planning to access risk of delays. “These problems (see Fig. 2) are serious, systemic, and all too common” in the construction industry McKinsey & Company (2015).

Figure 2. Most typical projects complete behind schedule, over budget. Cost is improved more than schedule on best performing projects. Data from Mckinsey and Company (2015) and Dodge Data and Analytics (2016).

Impact of cost and schedule due to lack of information can be mitigated using effective, fast and easy update to project information and status. Monitoring actual progress is key to curb cost and schedule overrun because it ensures plans are followed and resources have been effectively utilized. Current monitoring tools can be subjective, time-consuming and sometime expensive. More often than sometimes, progress data reported is either incomplete or less frequent to be used for accurate analysis for future. (see Fig. 3). Also, subcontractors, contractors, and owners do not have a common understanding of how the project is faring at any given time. Such inconsistencies in reporting result in flawed performance management which leads to unresolved issues stacking up because of lack of communication and accountability (see Fig. 3).
Construction firms are good at understanding and planning progress to be achieved in two to three month but rarely have an insight for next week or two. There are different levels of planning, from high-end preparation to day-by-day programs. If daily work does not go as planned, the scheduler should know about it but more often do not—so that they cannot update priorities in real time.

Long-term risks get important consideration but the kinds that crop up on the job not nearly as much. Addressing these issues through timely and accurate information on project progress and performance can enable better communication and decision-making. The visual production management system presented in the following sections has potential to provide construction practitioners with easy and quick access to visual performance analytics, providing them with the data they need to make informed decisions at the moment.

If successfully executed, this research will contribute to the goals of the national academies. In a recent report, investment is encouraged by the National Academy of Engineering (NAE 2012)
on five interrelated research activities that will lead to breakthrough improvements in efficiency and competitiveness of the construction industry: performance measurement at project and task-levels; wider deployment of BIM; effective interfacing of people, processes, materials, equipment, and information; greater use of pre-fabrication; and wider use of demonstration installation. The application of the presented visual production management system by (Lin and Golparvar-Fard 2016) is well-aligned with the first three goals and supports the other two via visual production state mapping.

The model-driven analytics also support research on enhanced visualization which is listed as a grand challenge by the National Academy of Energy (NAE 2012). Any effort towards enhancing the $1.1 trillion construction industry (Bureau 2016) – which from 1964 to 2012 exhibits -0.32% per year decline in productivity compared to +3.06% in all non-farm industries (Teicholz 2013) – even by 0.1% increase in efficiency can minimize delays, cost overruns, and lead up to $1.1 billion in annual savings.

1.3. The Unprecedented Growth of Visual Data

The recent developments are the diffusion of consumer commodity devices with built-in cameras, such as smart phones, tablets, wearables, and camera-equipped unmanned ground/aerial vehicles (denoted as UAV). These camera-equipped platforms have led to an exponential growth in the volume of images and videos that are being recorded on construction sites on a daily basis (Han and Golparvar-Fard 2017). To streamline the process of collecting images and videos, professional photography has also received significant attention. According to one of the popular construction documentation service providers, about 325,000 images are taken by professional photographers, 95,400 images by webcams, and 2000 images by construction project team
members at a typical commercial building project (∼750,000 sf). These are more than 400,000 images in total. The number can be much higher with the use of UAV for capturing images. The ever increasing volume of digital images (see Fig. 5) provides an unprecedented opportunity to visually capture actual status of construction sites at a fraction of cost compared to other alternatives such as laser scanning.

![Various forms of visual data and their frequency of capture (data and figure from Golparvar-Fard et al. 2016).](image)

In the meantime, nth -dimensional (nD) Building Information Modeling (BIM) (i.e. 3D models enriched with performance information such as time, cost, safety, and productivity) has received a certain level of maturity. As BIM has advanced, enhanced 3D visualization with semantic building information at job sites has shown its value in improving communication and coordination. The applications include design development, construction coordination, and planning and the value-added by BIM are well documented. For example, Lu et al. (2014) report 6.92% cost saving by using BIM even after accounting for the added efforts during the design phase. Similarly, Staub-French and Khanzode (2007) report 25–30 % productivity improvement
through BIM-driven coordination and constructability reviews that identified most design conflicts before construction.

These emerging sources of visual data provide a unique opportunity to continuously reconstructs and visualizes Reality directly within 4D BIM, measures progress and productivity, and analyzes risk for delay. By putting schedule tasks and project performance data in a visual context for the entire team and mapping Reality to Plan, a visual production management platform (see Fig. 6) provides transparency in project execution and helps project teams better plan, coordinate, and communicate.

![Visual Production Management Model](image)

Figure 6. Visual Production Management workflow proposed by Lin and Golparvar-Fard (2016).

The following chapter summarized the key literature on which the foundation of Lin and Golparvar-Fard (2016)’s Visual Production Management is built upon. Chapter 3 introduces this visual production management platform and offers insight on the workflows that are enabled by it. Next, the case studies and the lessons learned are introduced and discussed in detail.
CHAPTER 2: LITERATURE REVIEW

2.1 Techniques for understanding and analyzing the state of production are not well established

Stabilizing workflow requires tasks to be pulled only when they are ready (Ballard and Howell 1994; Brodetskaia et al. 2013) (see Fig. 7). In lean manufacturing plants, pull flow is controlled using Kanban Cards (a visual system) which signals from downstream to upstream to produce something. However, the physical configurations and contractual relationships of construction make the direct application of lean techniques which function well in manufacturing, inappropriate (Brodetskaia et al. 2013; Dave 2013; Dave et al. 2015; Yu et al. 2009). The key problem is that capturing, synthesizing and visually communicating work status– necessary for establishing effective pull flows– is very difficult to achieve in construction (Dave et al. 2014, 2015; Gurevich and Sacks 2014; Sacks 2013).

Figure 7 Last planner system used during a compression workshop.

Despite a) the benefits of BIM (Eastman et al. 2011; Young et al. 2009) and its synergy with lean construction principles (Dave et al. 2010; Hamdi and Leite 2012; Oskouie et al. 2012; De Pablo et al. 2010; Sacks et al. 2010a); b) the unprecedented potential of using massive collections of today’s site images (El-Omari and Moselhi 2008; Golparvar-Fard et al. 2009b, 2011, 2012a; Karsch et al. 2014; Son et al. 2015a; Yang et al. 2015) and their role for effective implementation
of the lean construction techniques (Alarcón et al. 2008; Dave et al. 2014; Mossman 2014a); c) the pervasiveness of smart devices on jobsites—80%+ among U.S. contractors (Constructech 2014); and most importantly d) the empirical observations (Salem et al. 2005) that show the probability to reach 80% Percent Plan Complete (PPC) in projects can improve from 21% to 39% by effective information communication techniques, yet several knowledge gaps still require close examination to enable procedures that capture, synthesize, and visually communicate work status:

*Systematic work tracking at the project-level is not too common—* Situational awareness (“who is working on what task in what location” and “capture/communicate state of work-in-progress, expose waste, make tasks ready, and initiate re-planning as required”) is key in lean thinking (Dave et al. 2015; Koskela and Howell 2008), but not much is said in the literature on how to effectively achieve it during construction. Current methods require significant upfront efforts to assemble the Work Breakdown Structure for work tracking (Garcia-Lopez, Nelly P and Fischer 2014). The documentation of what is DONE (Mossman 2014b) and the knowledge of what SHOULD and CAN be done (Ballard and Howell 1994) also relies on traveling between the site and trailers to access paper-based documents (Bae et al. 2013; Kamat, Vineet R. and Akula n.d.; Kamat et al. 2010), or at best searching on smartphones which requires 3D as-planned views to be manually generated for each task (Bae et al. n.d.; VPlanner n.d.). Sustaining these efforts for “feedback and learning” is key to improvement but is difficult to achieve.

*Automated progress monitoring is still in its early stages and existing methods are based on Earned Value Analysis (EVA) concepts—* To empower systematic work tracking, research has concentrated on automated comparison of 4D BIM with time-lapse videos (Abeid et al. 2003; Abeid and Arditi 2002; Golparvar-Fard et al. 2009a; Yang et al. 2015), or 3D image-based and laser scanning point clouds (Bosche et al. 2014; Bosche and Haas 2008; Golparvar-Fard et al.
2009b, 2011, 2012b; Han and Golparvar-Fard 2014; Son et al. 2015b; Turkan et al. n.d., 2012). These investigations focus on how physical presence or appearance of building elements can be detected. However, their successful execution requires high geometrical accuracy (Bosche et al. 2014), formalized knowledge of sequencing (Han and Golparvar-Fard 2014), and reasoning mechanisms via appearance-based recognition (Han K. and Golparvar-Fard 2015). Also these methods only tie performance deviations with retrospective Earned Value metrics (Golparvar-Fard et al. 2009a; Turkan et al. 2013) and do not communicate who is working on what task in what location on daily/hourly basis. Hence, a time lag exists between facing an issue on site once a work is underway and when managers and trades are informed to mobilize their teams into unoccupied locations, streamline workflows, and minimize waste (Garcia-Lopez, Nelly P and Fischer 2014; Sacks et al. 2009, 2010b, 2013; Wang 2008). The inability to have two-way communication on task scope, methods, resources delays work approvals, quality inspections, contractor hand-overs, and leads to waste (Dave et al. 2015; Garcia-Lopez, Nelly P and Fischer 2014; Gurevich and Sacks 2014). Much work is still needed to bring these methods into application (Son et al. 2015b; Yang et al. 2015).

Decentralizing pull planning and work tracking via BIM-driven methods are not well studied and evaluated— In the absence of automated solutions, model-driven methods (Dave and Buddy 2015; Garcia-Lopez, Nelly P and Fischer 2014; Gurevich and Sacks 2014; Sacks et al. 2010b, 2013) built on 4D BIM for pull planning and work tracking (see Fig. 8). However, these methods rely on time-consuming and often manual updates to reflect as-built 3D conditions in 4D BIM. Moreover, they cannot accurately document many field issues since their Model Breakdown Structure typically does not match operational details or require creating complicated namespaces (Garcia-Lopez and Fischer 2014) which without visual representations are difficult to
communicate. Hosting, querying, visualizing 4D BIM, and BIM-driven information sharing on commodity smartphones is also challenging. Thus, users still need to travel to jobsite offices (Garcia-Lopez, Nelly P and Fischer 2014) or access onsite kiosks for work tracking and pull planning (Gurevich and Sacks 2014; Hewage and Ruwanpura 2009; Sacks et al. 2010b) which challenges scalability in current solutions. Consequently, information is not communicated in a publish and subscribe method as stated in “Power to the Edge” principles (Alberts and Hayes 2003), work tracking is not decentralized, and command and control reverts back to traditional push mechanisms (Dave et al. 2014, 2015; Garcia-Lopez, Nelly P and Fischer 2014).

![KanBIM System architecture chart](image)

**Figure 8** From left, (a) KanBIM system architecture chart, (b) Primary Interface.

*Not much has been investigated on how effective people-information interfaces can be established/persevered in real-time*— Despite the benefits of face-to-face discussions in toolbox meetings, anecdotal observations show alarming status in receiving and remembering project information among practitioners: Only 73% of the time, the Last Planers receive such information during meetings. Among workers, the rate is barely 60% (Dave et al. 2015; Salem et al. 2005). The troubling situation is remembering information from meetings during onsite operations. Alarcon et al.’s observations (Alarcón et al. 2008) reveal that only 69% of planners remember information from meetings, while this rate among workers is about 51%. Recent systems support
production management at the site, yet the problems of easy and quick communication of discreet information sources remains to be tackled. (Choo and Tommelein 2001; Sacks 2013; Sacks et al. 2010a).

2.2 Measurement methods to benchmark reliability in look-ahead planning are not well studied.

The PPC and Earned Value SPI/CPI are retrospective metrics and only enable learning from past mistakes (Gurevich and Sacks 2014; Koskela and Howell 2008). To improve planning reliability and stabilize workflows, new metrics are needed to detect and characterize reliability in the flow of tasks in the future and prevent performance issues in a timely fashion. Apart from Sack’s time-dependent maturity index (Sacks et al. 2010a) and Ballard/Tommelein task anticipated and task made ready metrics (Hamzeh and Bergstrom 2010; Hamzeh et al. 2015), very little is investigated on how flow reliability in upcoming tasks can be estimated based on current state of operations (Kenley and Seppänen 2009). Also, location-driven metrics for measuring reliability in the flow of ongoing and upcoming tasks have not been investigated before. If measured and communicated successfully, such metrics can guide crews to pursue work according to pull flow strategies (Brodetskaia 2012).

2.3 Root-cause analysis at the task-level is key to continuous improvements, yet little is done to make workface assessment scalable.

Managing variations in labor productivity on jobsites is an important aspect of lean construction (Caldas et al. 2015; Gouett et al. 2011; Idiake and Ikemefuna 2014; Song et al. 2006). The Deming’s wheel of Plan-Do-Check-Adjust involves First Run Studies or Activity Analysis to benchmark efficiency of the workers, conduct root cause analysis on performance issues, devise new plans, and then test performance against plan criteria (Mossman 2014a). Yet teams, tasks, and locations frequently change on a jobsite and thus workface assessment needs to be repeated
frequently to provide actionable activity analysis data for performance improvements. To facilitate workface assessment, since Oglesby et al. (Oglesby et al. 1989), the literature has suggested videotaping operations (see Ballard’s talk on how 15 foremen were required to videotape their daily operations on a single project (Ballard 2014)). However, manual video assessments are still time-consuming, undesirably affect quality (Cheng et al. 2013; Gong and Caldas 2011; Goodrum et al. 2011; Memarzadeh et al. 2012, 2013; Park et al. 2012; Shan et al. 2012; Su and Liu 2007; Yang et al. 2012; Zhai et al. 2009), and often take away time from the more important tasks of root-cause analysis and planning for productivity improvements (Academies 2009; CII 2010).

To automate workface assessment, a large body of research has focused on using UWB (Cheng et al. 2011; Shahi et al. 2012; Teizer et al. 2007; Yang et al. 2011), RFID tags (Costin et al. 2012; Zhai et al. 2009), GPS (Hildreth et al. 2005; Pradhananga and Teizer 2013) to vision methods using video and RGB-D data (Khosrowpour et al. 2014; Peddi et al. 2009; Rezazadeh Azar et al. 2013; Rezazadeh Azar and McCabe 2011, 2012; Teizer and Vela 2009). The majority of these works only track the location of the workers. However, without interpreting activities and purely based on location information, deriving meaningful workface data is challenging (Khosrowpour et al. 2014; Yang et al. 2015); e.g. for drywall activities, distinguishing between idling, picking up gypsum boards, and cutting purely based on location is difficult, as the location of a worker would not necessarily change during these tasks. Computer vision methods are also not advanced enough to conduct detailed assessments from videos or RGB-D data because methods for fully automated detection and tracking (Brilakis et al. 2011; Escorcia et al. 2012; Memarzadeh et al. 2013), and deriving activities from long sequences automatically (especially when workers interact with tools) are not mature (Golparvar-Fard et al. 2013; Gong et al. 2011; Khosrowpour et al. 2014; Kim and Caldas 2013). The current taxonomy of construction activities also does not enable “visual activity
recognition” at a task level to be meaningful for workface assessment (Liu and Golparvar-Fard 2015). While full automation is appealing, training machine learning methods requires very large amount of empirical data which is not yet available to the construction informatics community (Liu and Golparvar-Fard 2015). A reliable method that provides visual workface data and assists with root-cause assessment at the task-level is needed.

2.4 Gaps in Literature
A model-driven workflow information system is needed to help implement lean pull flow strategies by decentralizing documentation of what SHOULD and CAN be done (pull planning) and what is DONE and WILL be done (work tracking) onsite (Dave et al. 2015; Mossman 2014a) among last planners. Status visualization can display information defining the locations of other crews, the state of completion of prior work, and the availability of materials, all of which are preconditions for stable work assignments (Dave et al. 2015; Gurevich and Sacks 2014; Yu et al. 2009). Through visualization, project information can be shared with last planners and workers such that is readily understood by all, irrespective of their technical knowledge, language, or the time they have spent on a site (Alarcón et al. 2008; Yu et al. 2009). Hence, new methods are needed to create visual production state maps by encapsulating 4D BIM and as-built 3D such that the problems associated with manual adjustments to model/work breakdown structure and namespaces, common in current model-driven methods, are minimized. New location-driven measurement metrics are also required to understand, predict, and analyze performance reliability in weekly plans and look-ahead schedules and transform task-driven to location-driven controls. Without such metrics, it is difficult to proactively and collaboratively address issues in upcoming tasks and constraints which is a tenant of lean thinking. Finally, without systematic workface assessment, eliminating the root-causes of waste at the task level will be difficult. A careful
examination of the gaps in knowledge and development of theoretical concepts, methods, and metrics is essential to achieve smooth flow of production in construction. The following section introduces the visual production management system of Lin and Golparvar-Fard (2016) that addresses these gaps in knowledge. An overview of the system is first provided followed by specifics of the case studies conducted to validate the system.
CHAPTER 3: VISUAL PRODUCTION MANAGEMENT SYSTEM

To streamline current workflows for progress tracking and information communication, Lin and Golparvar (2016) presents a web-based work tracking system which builds on 4D visual production models assembled via superimposition of 4D BIM and 3D point cloud data. These models allow tasks in weekly work plan and look-ahead schedule and their procurement/logistical constraints to be mapped in 3D, at any desired spatial and temporal resolution, and to any location. By allowing the last planners to visually commit tasks to locations – consisting of 4D BIM elements or areas directly marked on the point cloud, documentation of what SHOULD, CAN, and is done can be decentralized and monitoring transforms from task or organization-based tracking to location-driven monitoring. Figure 8 shows the cycle of planning, execution and monitoring of weekly work plans with visual production models (builts on Sacks et al., 2010). Figure 9 shows how a visual production management system (marked as Integrated Information Model) can empower a Last Planner System based cycle (see Lin and Golparvar-Fard 2016) for more details. The following describes the specific elements of this web-based work tracking system.

Figure 9. The show the cycle of planning, execution and monitoring of weekly work plans with visual production models (builts on Sacks et al., 2010).
3.1. Generating and Visualizing As-planned and As-built Progress Models

Effective visual mapping of the state of construction requires generating as-built 3D models, integrating them with as-planned 4D BIM, and forming integrated information models. The state-of-the-art is first to reconstruct 3D point clouds from a collection of images taken on the site (via commodity smartphones, digital camera, or camera-equipped UAVs) and then register them with BIM to in turn bring all image and the resulting point cloud model into alignment with the BIM.

In this work, the method introduced in (Lin et al. 2015) is used to generate these models. The goal forms a data capture perspective is to capture changes from last week to observe changes on site as coordinate with upcoming look ahead schedule, Figure 10 represents zoning of the project site (in case study 2) for planning flight path to capture images and videos. Based on the site condition, the height of the structure, obstruction present (e.g. cranes), the suitable flight path is selected which covers maximum active workspaces in the project. Figure 11 shows the UAV operator in action.
Figure 1. A thorough flight planning session was conducted with UAV operator to make sure the images can produce point cloud models.

Figure 12. a UAV in operation on a case study project site.
The process is repeated on a weekly basis to generate As-built documentation, and the interface is used in daily site coordination meeting, quality control, and safety monitoring. Figures 13, 14 and 15 show an example of such 3D and 4D point cloud models.

Figure 13, 14, 15 From Top to Bottom: (a) Snapshot of web viewer showing camera location over point cloud, (b) & (c) Point cloud view from camera’s field of view, photos captured can be turned on/off for detailed assessment.
Figure 16, 17: From Top to bottom, (a) Snapshot of web-based viewer used for interactive measurements of concrete, (b) Creating section planes with point cloud in background.
Figure 18, 19: Top to bottom, Web-based platform of Lin and Golparvar (2016), creates timeline for 3D point cloud which can be retrieved, figures shows comparison at different times.

We use these 3D point cloud models as a mechanism for documenting as-built performance, and we integrate them with BIM, fuse with the weekly work plans as a source of 4D (3D+time) as-planned performance- to identify, characterize, and communicate actual and potential performance problems. By integrating work commitments into BIM in the form of weekly work plans, and holding project participants
accountable for their workflows, we can detect, visualize and communicate actual and potential performance deviations by analyzing current work commitments and predicting the reliability of weekly work plans with respect to the look-ahead schedule.

While coordinating with various BIM models, i.e., Architectural, Structural, Mechanical, Electrical, Fire-protection, etc., typically, BIM model does not reflect follow work breakdown structure (WBS). This can cause problems for the development of 4D BIM since elements, and WBS locations can not be easily matched. Figure 12 shows snapshots (a) of project schedule, created based on area and level divisions of the building (e.g., Level 2, Area 3). While snapshot (b) shows model breakdown based on the type of material (concrete and steel). This create inevitable hurdle of rework to create an accurate 4D model.

![Figure 20](image)

**Figure 20** Top (a) Project schedule broken down into location and levels, (b) Project model for CFE showing model breakdown based on type of material.

Figure 21 shows how BIM, integrated with the weekly work plan, is jointly visualized with the 3D point cloud in our web-based work tracking system. In the resulting integrated information models, only elements that were expected to be completed by the construction teams are visualized with respect to the 3D point cloud model.
Using the web-based platform, the 4D model is aligned with point cloud processed with images captured, with activities lined with schedule and trades; it is ready for use in daily coordination. Figures 22 show example of such model.
To account for issues associated with limited memory and bandwidth for (1) interaction, manipulation and presentation for large-scale pointclouds and (2) displaying BIM model with pointclouds and images, on commodity smartphones and tablets, several new methods are considered. First, to visualize large-scale point cloud models in a relatively small amount of time, similar to (Scheiblauer et al. 2015) a nested octree structure is generated for store the point cloud data. The octree structure stores the pointcloud in different hierarchical levels of detail which in turn enhances the efficiency of point cloud rendering. Specifically, this structure allows only those details that are within the field of view to be shown to the user. This strategy allows the system to effectively deal with limited memory and bandwidth of a commodity platform, yet provide opportunities for point cloud interactions. A set of control tools are also developed to enhance the user experience with exploring the point cloud. For example, the user can pan, rotate, move and fly through the point cloud to explore the scene in detail. As the user moves closer the system, the system automatically loads the points inside the view within a lazy scheme to reduce the loading speed. The images used to generate the point clouds are superimposed, this can let the user have a detail look on the pointcloud and do accurate measurement either on images or pointcloud (See https://youtu.be/8k4ojAF_lpU).

The interaction with BIM model is built on top of the BIMServer (Beetz et al. 2010). Geometric information or other element properties can be queried or pushed in through the platform and visualized via the web-based work tracking system. The initial model breakdown structure can follow the structure embedded in the IFC (Industry Foundation Class) model and be presented as a selection tree view to easily choose appropriate work breakdown structure for pull planning and work tracking.
Using this system and during the weekly work planning and coordination session, on or offsite, project engineers or last planners can highlight an area within BIM or from the point cloud and assign weekly work planning tasks and relevant project information. This strategy eliminates the need for revising model breakdown structure in 4D BIM, and instead allows direct documentation via the point cloud data. On the construction site, the last planners can commit to a location to highlight who does what work and in what location, report on task completion of problems, and automatically notify inspectors to perform inspection and quality control tasks as soon as a task is completed. Figure 24 shows how the visual production models are associated with construction workflows.

![Image](image_url)

Figure 23. Directly assigning a task on location instead of models to indicate “who does what task at what location.”

### 3.2. Transforming retroactive progress tracking into proactive monitoring of plan

Inspired by (Sacks et al. 2010a) and instead of simply measuring and tracking PPC, Lin and Golparvar-Fard (2016) introduce metrics for measuring reliability of current weekly work plans and two-week look ahead schedules. The key idea was that PPC is a retroactive performance metric and only allows learning from past performances. Nevertheless in construction projects, tasks do not repeat to enable learning from the past. Here we use Percent Complete (PC) for tasks
and task constraints. If the readiness level associated with upcoming tasks are measured, teams will have a better understanding of which tasks can start on time and which ones require revision in upcoming coordination meetings. The metrics, Readiness Index \((RI)\) and Readiness Reliability \((RR)\) for each ongoing and/or upcoming task \(i\) simply measures the status of all task predecessors and their procurement and logistical constraints \(j\) to provide construction teams with a better understanding of when each team can mobilize their crews to initiate certain tasks. When these tasks are not ready for a scheduled start time, the teams will be able to pull those tasks that are ready and inturn stabilize workflows.

3.3. Transforming task-driven monitoring to location-driven monitoring

Directly communicating progress deviations per schedule task among construction teams may negatively impact the spirit of collaborative partnerships among construction teams. To improve control opportunities, Lin and Golparvar-Fard (2016) explored measuring the stability of workflow at a given location (location stability index) based on task readiness reliability. Their work is specifically defined Location Work Flow Stability Index \((SI)\) as a metric to measure the reliability based on locations assuming all tasks and constraints are not independent but are mutually exclusive.

Based on the calculated indexes, we highlight top at-risk locations to communicate not only the most important tasks that need attention in coordination meetings but also support collaborative planning which is one of the pillars of lean construction. By providing these visual 3D production maps color-coded with top at-risk locations, the project management team can prioritize problems based on their impact on the construction plan and bring transparency to the ongoing workflows.
CHAPTER 4: CASE STUDIES

To validate the impact of the visual production management system and performance metrics, we partnered with several industrial partners to implement Lin and Golparvar-Fard (2016)’s web-based work tracking system. Over a span of a year, we specifically focused on a workflow that identifies, characterizes, and communicates actual and potential performance problems. By integrating work commitments into BIM in the form of weekly work plans, and holding project participants accountable for their workflows, we were able to detect, visualize and communicate actual and potential performance deviations by analyzing current work commitments and predict the reliability of weekly work plans with respect to the look-ahead schedule. Every week the project teams were provided with visual production reports which highlighted the top at-risk locations (locations where tasks will likely suffer from potential performance problems), together with all ongoing tasks and their percent complete rates, a list of upcoming tasks with respect to the schedule in that location, their readiness levels (as well as their logistical and contractual constraints) and the location’s stability index. The following provides more details about the conducted case studies:

4.1. Case Study #1

Following various previous research which focuses on creating tools to model the temporary structures such as scaffolding and formwork using computer aided designs and advanced algorithms which can detect various surface types and assign a correct component to it. The pilot project was intended to provide a practical approach towards understanding the complexity of formwork with a 3D model and then have site condition lay over on it to understand the potential problem in future during construction. The idea was to gain knowledge from the formwork design
companies expertise and use tools developed by them and find the best way to model and verify the safety of temporary structures.

For the use of designing temporary structure and monitoring progress with web based viewer which enables BIM model layover with point-cloud created using site images collected using UAV. This method involves creating models of temporary structures moving along with their pour sequence and exactly identify the component which is not in their correct position as planned by imposing it on the point cloud. This method will greatly help in identifying potentially risky scaffolding on site and any variation in system formwork such as jump forms which require great precision.

Figure 24: Render of pylon for bridge project.

Figure 25: Snapshot of Web-viewer with interactive measurement of length, areas and angles for bridge project.
Figure 26: Camera is texture-mapped with the image and is overlaid on point cloud model.

Figure 27: Camera locations are automatically registered w.r.t. point cloud model.

Figure 28: The point cloud model is generated from regular images from the site. Reconstructed model is visualized in a web based viewer.
The formwork solution providing company provided with images and videos of the project to help create point cloud and reconstruct the site in the web-based viewer. A combination of overlaid 3D model and point cloud helped in understanding successive pour to be carried out in this project which is located in the middle of Ohio River.

4.2. Case Study #2

We have conducted a three-month pilot project with one of the top CM firm. The project consists of an extension of existing Building called and two new facilitates, an Athletic Performance Center and Indoor Athletic Practice Facility for a university campus. The project consists of high-end finishes and specialty equipment requiring coordination among the owner, architects, designers, and various subcontractors. Since the project is setup as Fast track as well as Integrated Project Delivery process the on-site coordination became critical, visual production management tool was critical in identifying, coordinating and resolving the issues. Various steps discussed in methodology were followed to create site reconstruction and integration with 4D BIM. The following provides additional details:

![Figure 29: 3D rendering of the athletic practice facility and nutritional center for students.](image-url)
a. Overlaying as built condition and 4D model

During daily coordination meeting with a subcontractor, the Superintendent was able to relate activities around the site on the smartboard screen with a 4D model in the background; this proved to be critical for coordinating activities like excavation and concreting.

![Figure 30: Snapshot of Web-Viewer, From Left: (a) Picture of point cloud reconstruction of jobsite. (b) point cloud with 4D model overlaid.](image)

The Concrete contractor planned a route around the site was clashing with the hauling route of excavation subcontractor. The potential delay for was saved and the operation was more coordinated.

b. Monitoring underground utility work

One of the suggestions from site team was to overlay site utility model with a point cloud. It helped sub-contractor to get a permit for shutting down utilities for new work. Communicating new location every day also helped in understanding complex underground utilities since it is easier to view them in 3D.
c. Monitoring work progress with complete and under construction areas

To accurately monitor project progress, the construction schedule was linked with production management platform. With updated weekly work plan, progress made in various location can be seen. With activities currently performed on the site being viewed in red and those complete in green.
d. Updating activity durations on the go

One of the challenges typically faced is the accuracy of activity durations between what was considered during the estimation vs. the pre-construction phase of a project. The difference is always a conflict and a challenge for project managers and superintendents to overcome. The visual representation of dates and 4D practically define the accuracy of it and at the same it the duration can be changed in the viewer to assign feasible durations and evaluate the impact on scheduled completion.

![Image](image.png)

Figure 33: Snapshot of Web-Viewer: Project Schedule and duration linked with 3D model.

e. Identifying who is working what work at what location

It becomes critical to understand the sequence of activities, especially at confined locations such as interior spaces, mechanical and electrical trades, as well as finishes.
Figure 34 & 35: Snapshot of Web-Viewer: From Top to Bottom, (a) Jobsite site reconstruction, (b) Foundation (purple) and structural (brown) steel overlaid showing the sequence of activities.

When 4D was overlaid with a point cloud, it becomes clear who works at what location at what time and avoid any clash or potential rework.
f. On-site coordination

Understanding requirements from sub-contractors to ease work on site is an effective feedback to refine and improve VPM since no two projects have similar challenges in execution.

![Figure 36: “Plan of the day” meeting in job trailer](image)

4.3. Discussion on the case studies

a. Using Web viewer for temporary structure design and monitoring

Monitoring of temporary structures with overlaid BIM model for a project is a newer approach which require future research to understand the benefits of it. The team in case study #1 observed interest from formwork industry leaders in using point cloud for project monitoring when we discussed with them the possibilities of implementing it on a large scale. Future work which we will continue to pursue will involve testing this method on a live project and get feedback from the site teams about the advantages and shortcomings of this method another area of research will be in developing these tools for inventory management and site logistics planning as advancement in automated formwork design greatly helps in accurate models to track concrete pouring sequencing and material rotation.
b. Realistic short-term planning

While projects have a baseline schedule, it was observed from several project experience that short-term plan (three weeks / four weeks look ahead) were found to have a significant deviation from initial plan. Using VPM, activities are associated with trades and de-centralized planning, visual bring craft foreman into short-term planning, this increases the reliability of duration and provides a more realistic plan.

c. Constraint-based look ahead schedules with improved reliability

Weekly work plan and look-ahead schedule and their procurement/logistical constraints can be mapped to integrated information models of 4D point cloud and BIM, at any desired spatial and temporal resolution, and to any location. By adopting last planners to visually commit tasks to locations –consisting of 4D BIM elements or locations directly marked on the point cloud documentation of what SHOULD, CAN, and is done can be decentralized and monitoring transforms from task or organization-based tracking to location-driven monitoring. Specifically, mapping and tracking work tasks based on locations, can lift barriers in the application of 4D BIM for production control, which are the need for continuous updates in model/work breakdown structure to maintain a realistic view of the work status, and creating namespaces. This is a great departure from current BIM-driven methods(Dave and Buddy 2015; Garcia-Lopez, Nelly P and Fischer 2014; Gurevich and Sacks 2014; Sacks et al. 2013). The same procedure can be used for mapping future state of operations wherein commitments to tasks in the look-ahead schedule can be visualized via locations. Augmenting visual production maps with performance reliability metrics can provide a deeper understanding of the current production issues.
CHAPTER 5: CONCLUSION

In this thesis, a Visual Production Management system was validated and its impact on the performance of a project was observed via several case studies. The system offers three modules which can be adopted and adapted based on the needs of various projects. The visual asset management continuously reconstructs reality on a construction site in 4d and contextualizes site images with/without reference to construction plans. The 4D visual production models integrate 4d reality and plan (4D BIM) and conduct progress monitoring, field reporting; quantity take-off. The predictive data analytics and risk management offer progress monitoring, productivity tracking, and predicting risk in project execution (short-term plans; long-term plans; short-term vs. Long-term).

The case studies conducted show the potential of the system to provide a transparent (visual) process view to eliminate problems for all trades as soon as possible. It also offers an opportunity to test the predictability of the planned execution while maintaining high flexibility for changes.

The project controls workflow enabled by visual production management system can contribute to the decrease in costs due to more reliable processes and prevention of interferences and can provide high stability of personnel planning and logistics. The underlying visuals and the contrast between Plan and Reality enhance quality control by comparing as-built models to specifications and provides for safer operations through knowledge of resource locations and safety hazards.

Visual production management tool maps reality to plan by linking project performance in visual context to scheduled tasks for the entire team. The platform also provides
transparency in project execution and helps project teams better plan, coordinate, and communicate and leads to a realistic view of total costs and project duration. Such systems and the collaborative workflows they enable offer a Win-Win situation for all involved parties. It allows project teams to work together to tap off delays between issues are surfaced on jobsites. Onsite construction teams and engineering teams can also collaborate in real-time and inform the owners of any actual or potential performance problems.

Future work will focus on further of validation of the underlying work tracking system in the Visual Production management platform, the applicability of the performance metrics, and the quantitative impacts of the visual production reports on work tracking and information flow on construction sites.
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