Abbaszadegan, A., Rios, F. C., Grau, D., Assainar, R., Ganapathy, R., and Diosdado, C. (2022). Stabilizing Operations Workflow in Construction with Real-Time Monitoring of Craft Labor Crews. Lean Construction Journal 2022 pp 184-205
(Submitted 08Apr21; Accepted 29Dec22)
www.leanconstructionjournal.org

Stabilizing Operations Workflow in Construction with Real-Time Monitoring of Craft Labor Crews

Amin Abbaszadegan[1], Fernanda Cruz Rios[2],David Grau[3], Rizwan Assainar[4], Ram Ganapathy[5], and Cristobal Diosdado[6]

Abstract

Question: How does the variation of workflow occur, if it does, during the execution of operations? Can operations workflow be documented, assessed, and proactively stabilized? And if so, how?

Purpose: The purpose of this paper is to 1) explore the workflow during operations executed by individual production units, 2) investigate their documentation, monitoring, and stabilization, and 3) assess the effectiveness and limitations of a near real-time monitoring approach to stabilize the operations flow of individual production units such as crews.

Research Method: Pilot test during the renovation of a hospital facility. Information technologies were leveraged to enable the near real-time monitoring of field operations so that workflow variability during operations could be documented, and corrective actions could be timely triggered in response to workflow deviations. Data were collected and results analyzed.

Findings: Workflow variability during operations was demonstrated, quantified, and analyzed. Evidence of an opportunity to stabilize the flow of work during the execution of operations was provided. The feasibility of an instantaneous mechanism of control to stabilize workflow was demonstrated. Management responses to deviations in operations workflow from baseline values were proven

[1] Ph.D. candidate, School of Sustainable Engineering and the Built Environment, Arizona State University, 660 S College Avenue, Tempe, AZ 85281, USA, Phone +1 (416) 347-7547; email: aabbasz1@asu.edu
[2] Postdoctoral Associate, School of Sustainable Engineering and the Built Environment, Arizona State University, 660 S College Avenue, Tempe, AZ 85281, USA; Phone (480) 727-0665; email: fernanda.cr.ford@gmail.com
[3] Associate Professor, School of Sustainable Engineering and The Built Environment, Arizona State University, P.O. Box 873005, Tempe, AZ 85287-3005; Phone (480) 727-0665; email: david.grau@asu.edu
[4] DPR Construction, 222 N. 44th Street, Phoenix, AZ 85034; Phone +1 602-8080500; email: rizwana@dpr.com
[5] DPR Construction, 222 N. 44th Street, Phoenix, AZ 85034; Phone +1 (602) 333-1865; email: ramg@dpr.com
[6] DPR Construction, 222 N. 44th Street, Phoenix, AZ 85034; Phone +1 (602) 808-0500; FAX (602) 808-8843; email: josed@dpr.com

to partially mitigate such deviations and stabilize flow proactively.

Limitations: The pilot test was implemented in support of drywall activities for a specific project, and thus results were not externally validated.

Implications: Future studies should investigate the undocumented topic of operations flow in the construction domain and contribute knowledge to the corresponding literature, which is dominated by studies with a sole focus on process flow. Practitioners should focus on stabilizing operations flow as a novel approach to reduce work variability further.

Value for practitioners: V.1 Variability during the execution of operations should be controlled. V.2 Monitoring should be regarded as a novel and proactive approach that effectively contributes to workflow stabilization and enables reliable work promises, i.e., those made during planning. V.3 Meeting work promises should not only depend on the goodness of a plan but should be complemented with the ability to intervene during work operations when these deviate from baseline values. V.4 Practitioners should recognize that empowering workers to directly resolve a variability event is a strong management strategy to minimize the downstream impact of such an event.

Keywords: workflow, operations workflow, lean construction, production controls and planning, production design, stabilization, real-time, monitoring, controls, takt.

Paper Type: Full Paper

Introduction

Despite the notorious influence of craft labor productivity on project success (Koskela 1992; Ballard 2000), labor work has traditionally been poorly planned and executed. Deviations from plans are the norm and result in endemic cost and schedule deviations (Flyvbjerg 2006; Mulva and Dai 2012; Grau and Back 2015). That management has focused on transforming outputs from inputs obviating the production process (Howell and Ballard 1996, Koskela 2000) has resulted in planning and control mechanisms with a work completion focus that neglect the quality of work (Kim and Ballard 2000; Seppänen 2009). For example, the critical path method represents a project as a sequence of activities through finish-to-start or similar type of relationships. Such project management focus fails to acknowledge other constraints with a plausible impact on workflow (Koskela 2000). Indeed, the fluctuation or variability intrinsic to workflow is prevalent and negatively influences project performance (Thomas 2000; Hamzeh 2009; Brodetskaia 2013; Seppänen 2009; Liu et al. 2011; Arashpour and Arashpour 2015). On the contrary, a smooth and stable workflow is an intrinsic condition for a reliable plan and effective production management (Sacks et al. 2010). In reality, the ability to reliably foresee workflow holds the promise to align estimating, design, planning, and execution, so that work can be effectively delivered according to the original plan and budget expectations with minimal or null deviations.

The theoretical underpinning of lean construction maintains that an efficient and well-balanced production system satisfies three fundamental propositions: transformation, flow, and value (TFV) (Koskela 2000). The output-from-input transformation management view has historically shaped planning and control functions that focus on outputs and ignore the transformation of work (Olli Seppänen 2009). In addition to transformation, the value approach aims to deliver the maximum value from the customer's perspective, while the flow approach aims to eliminate waste, e.g., by minimizing non-value-adding tasks or simplifying the design of production. The variability of workflow is an example of waste. In construction practice, the Last Planner System (LPS) (Ballard 2000) has become a mainstream planning and control technique aiming to improve workflow and minimize variability and waste. LPS aims at increasing the chances of executing lookahead and weekly work plans with a steady or at least reliable flow of work *in-between activities or tasks*. At the end of the commitment plan period (e.g. one day, one week) (Ballard and Tommelein 2021), the metric percent plan complete (PPC) evaluates the goodness or reliability of the plan by measuring the percentage of completed activities over the total number of planned activities. Even though the plan period could be short (e.g. one shift or one day) and thus enable proactive interventions, weekly commitment plans are the norm and prevent proactive responses to deviations. Even though the tremendous contribution of LPS, opportunities for improvement exist:

- **Weekly work plans fail to facilitate continuous improvement.** Even though LPS was initially designed to support learning from success, Sacks et al. (2010) argue that "the pressures of day-to-day construction make recording of success for learning (both within and beyond the current project) impractical." Sacks et al. also argue that data collection and information technologies should be leveraged to enable continuous improvement and retrospective data analysis.
- **The transfer of workflow between activities is still inefficient.** Practitioners indicate a range of PPC accomplishment between 70% and 80% (LCI 2015). Thus, roughly 20% to 30% of the weekly planned activities are not completed or not even started. Such PPC values imply that the work transfer between activities fails to flow in similar percentages.
- **Control is reactive and fails to address deviations in a timely manner.** At the end of the week, the control has already failed to resolve unexpected constraints as these have already occurred. A frequent control or continuous monitoring (i.e., real-time or near real-time) could communicate deviations as these happen and thus support the implementation of proactive mitigation actions. Such frequent flow of information would also enable pull planning (Sacks et al. 2010) since such information would likely enable task prioritization "in relation to signals from downstream demand."
- **An opportunity to stabilize workflow within production units by means of the real-time monitoring of workers exists.** Currently, stabilization within production units has been proposed mostly through planning and design, thus, without workers' involvement. Thus, the stabilization of the pace of work by means of a real-time or near real-time feedback loop involving the workers represents a latent opportunity to improve planning reliability. In short, if the production unit maintains a steady pace of work, the activity is to be completed on time, and thus flow will be available for transfer to successor activities as planned.

In response to such shortcomings, the study presented in this article investigated the stabilization of workflow at the production unit level with the support of a technology-enabled monitoring approach and with the involvement of workers. The monitoring approach was instantiated and evaluated through a pilot test.

The rest of this article is structured as follows. The two sections below provide a review and critique of the literature. Then, the objectives and scope precede the description of the pilot test and near real-time monitoring and controls approach. The results and their implications are discussed. Finally, the conclusions summarize the contributions of this study and provide directions for additional research efforts.

Process vs. Operations Flow

Shingo and Dillon (1988) distinguished between process and operations workflow in the manufacturing domain. On the one hand, process flow captures the flow of work exerted on a product as it moves through workstations. Ideally, process workflow is stable across workstations and matches the customer's demand rate or takt time. On the other hand, operations flow captures the flow of work executed by a production unit, e.g., worker(s) or workstation. Shingo and Dillon noted that the optimization of individual production units does not necessarily result in the optimization of the production system. Within the manufacturing domain, Schonberger (1986) unambiguously claims that "variability is the universal enemy."

In contrast, Sacks (2016) observed a convoluted understanding of these two expressions of flow in the construction literature, even though several other researchers had introduced the concepts of process and operations flow with a construction lens, among others Koskela (2000) and Koskela et al. (2007). Sacks elaborated that such convoluted understanding likely results from the uniqueness of construction projects with a batch (as opposed to continuous) production mode, in which production units move through distinct locations within the product at batch or discrete intervals. Nonetheless, Sacks proposed maintaining the distinct concepts of process and operations workflow defined in the production systems domain. Thus, in this article, process workflow refers to the flow of work exerted on the building/facility product by multiple production units, while operations flow represents the pace of work delivered by individual production units, e.g., a crew.

Controlling Variability

In manufacturing, production monitoring highlights the importance of both process and operations flow during production design and control. Continuous and real-time monitoring of the production status exists to 1) identify and eliminate variability immediately and at the source and 2) prevent the impact of variability events from spreading to downstream operations. For example, a worker in a car assembly line is requested to stop the advancement of the car being assembled through the workstation when work cannot be completed in a predefined stretch of the assembly line. Marking tape on the floor indicates the physical boundary of production. Halting the flow of a product enables the immediate elimination of variability and minimizes the chances of jeopardizing the production system's steadiness. Empowering the worker to resolve the variability event without management supervision is a key production strategy that enables real-time response and prevents propagation into downstream operations. In another example, when the supply of a part is 15 minutes late, the late delivery event is immediately communicated, and a contingency plan automatically triggers. In the controlled manufacturing environment, managers observe the fluctuation of process flow due to fluctuations in the flow of operations. Thus, continuous production monitoring enables an instant flow of information that triggers immediate corrective actions against both process and operations flow deviations.

In comparison, stabilizing flow through the minimization of variability is a relatively new theme in construction research. During construction operations, the intrinsic variability of flow causes a negative influence on productivity (Brodetskaia 2013; Seppänen 2009; Liu et al. 2011) and, ultimately, project performance (Thomas 2000; Hamzeh 2009; Arashpour and Arashpour 2015). Simulation efforts have provided further evidence that fluctuations result in negative impacts (Tommelein et al. 1999; Bashford et al. 2005; Sacks and Golding 2007). The management of workflow has been explained through production and lean perspectives (Koskela 1992; Koskela 2000; Ballard 2000). Partially consistent with the manufacturing approach to managing workflow through production systems design, production controls, and kaizen or continuous improvement (Liker 2003), Brodetskaia et al. (2013) discussed a workflow management approach for construction operations. Such an approach proposes three mechanisms to manage and stabilize flow: design of a production system in consideration of the constraints that cause fluctuations; proactive planning based on work readiness and readiness of subsequent trades to accommodate work; and continuous reduction of variability during the production of individual activities. The continuous control and reduction of variability is of particular interest to this study. Indeed, the communication of accurate and timely production data is essential to flow stabilization (Formoso et al. 2002; Rusell et al. 2009; Gurevich and Sacks 2014; Matthews et al. 2015). Information flow is critical for a smooth flow of work (Dave et al. 2010; Sacks et al. 2010). The rest of this section reviews the body of knowledge in each of the three mechanisms proposed by Brodetskaia et al. (2013).

First, the design of construction operations aims at structuring the inputs of work for an uninterrupted and steady flow of work (Howell and Laufer 1993; Howell and Ballard 1999; Tsao et al. 2000; Chitla and Abdelhamid 2003; Abdelhamid et al. 2009; Abdelhamid et al. 2010; Nerwal and Abdelhamid 2012). Construction operations are dynamic, time-sensitive, involve multiple resources and actors, and thus their design seeks to enable flexibility against uncertainty. As such, the consideration of buffers and shared resources was proposed to isolate subcycle work units from their immediate interaction (Howell and Laufer 1993), e.g., so that the delay of a task did not impact downstream operations. Complementary, a two-step framework to design construction operations was investigated: work structuring and product design, and LPS (Howell and Ballard 1999). While work structuring and product design inform on design information, procurement, resource allocation, or work methods, LPS carries forward from detailed planning until completion. When selecting a crew, size, flexibility, and heterogeneity were deemed key variables against uncertainty (Nerwal and Abdelhamid (2012). While flexibility aims to increase workers' assignments' interchangeability, heterogeneity aims to balance crew members' skills, experience, or behaviors. Case studies have been produced to exemplify work structuring. Thus, approaches to flexible work alternatives against contractual and trade work method constraints were proposed (Tsao et al. 1999). In addition, the structuring of crews' work was analyzed through the installation of light fixtures (Nerwal and Abdelhamid 2010).

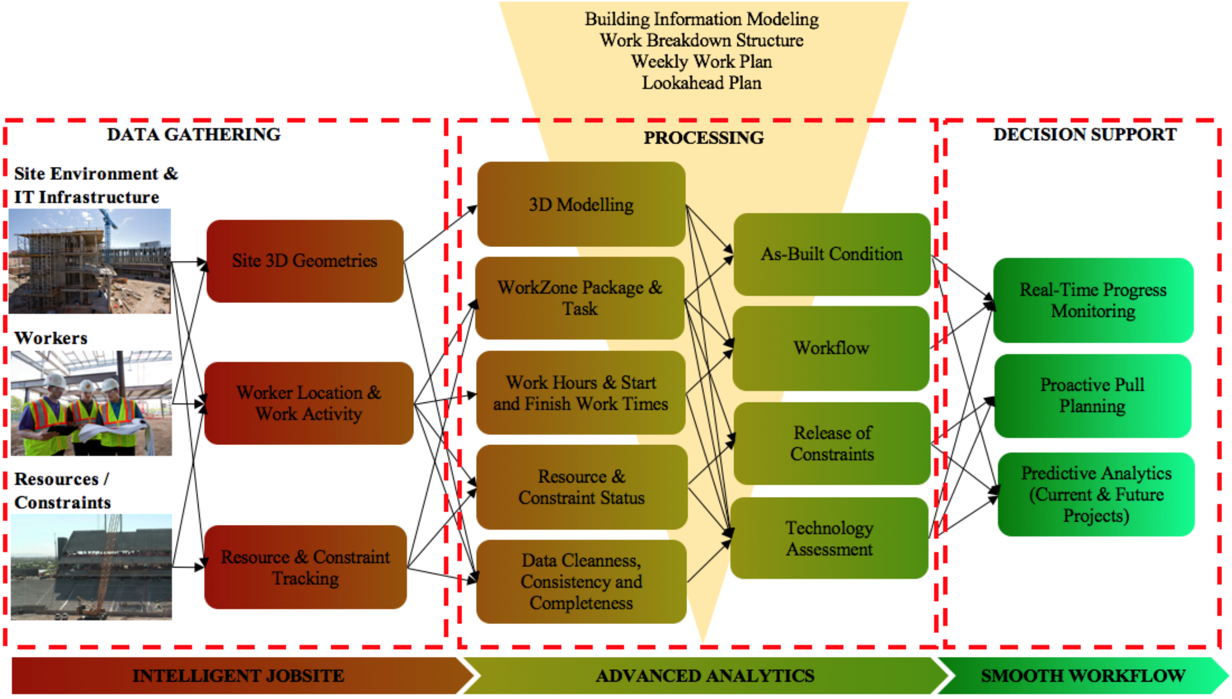
Second, as previously introduced, LPS has become a mainstream planning technique to stabilize and control flow. LPS aims to increase the reliability of lookahead and weekly work plans with a steady or at least reliable flow of work between activities. LPS is implemented as a collaborative planning technique in which those in charge of execution (i.e., the last planners) commit to the weekly work plan. During the collaborative planning effort, the last planners identify constraints (such as predecessors or availability of resources) and resolve them before committing to the execution of a task. At the end of the planned period (e.g., typically one week), PPC becomes an after-the-fact control metric that measures the goodness of the plan and, thus, workflow reliability. Introduced early in the XXI century, LPS represented a leap in understanding construction from a production systems lens despite its use as a retroactive mechanism of control.

Finally, in response to such a shortcoming, recent efforts have investigated advanced computing and information technologies to advance flow planning and control capabilities. Jongeling and Olofsson (2007) investigated a 4D CAD planning method combining location-based scheduling and 3D CAD. The line-of-balance schedule provided a visual representation of the synchronization between planned and actual workflow. Sacks et al. (2010) proposed Building Information Modeling (BIM) to support LPS and enable pull planning and collaboration among team members. The logic was embedded through a user interface that enabled the visualization of the planned work sequence in the 3D model and automatically propagated plan alterations through the schedule to ensure consistency. The interface facilitated the introduction of field production data through mobile devices. Gurevich and Sacks (2014) evaluated the influence of the same BIM-enabled approach in work sequence decisions by trade crews. With a similar approach, Heigermoer et al. (2019) recently investigated the implementation of lean principles with BIM. The research prototype enables the division of a project in construction zones, automates the quantity take-off, and offers color-coded 4D visualization of progress. Matthews et al. (2015) theoretically proposed real-time progress monitoring using commercially available software tools. Such a study qualitatively evaluated the monitoring approach with unstructured interviews and highlighted the integration of project information as a major enabler. Dave et al. (2016) proposed a theoretical platform to integrate and visualize product and process information and extend it through the project life-cycle. Finally, Lin and Golparvar-Fard (2021) proposed a vision-based controls and collaborative planning approach capable of mapping the production state in 3D. A visual 4D interface supported collaborative decisions during big room meetings even though the approach required dedicated data collection efforts and thus lacked real-time communication of field information. When implemented on a project with weekly images and video captures, a 30% PPC increase was observed. Despite these and other successful efforts, the implementation of LPS has failed to embrace the benefits of integrating information technologies (Heigermoser 2019; Lin 2021).

Indeed, concerning the specific aims of this study, an opportunity exists to explore and stabilize operations workflow with real-time communication of information or monitoring by leveraging advanced technologies and the proactive involvement of the workers. Within a production unit, fluctuations in its workflow imply that resources are either underused, overused, or alternated between both conditions. In a production system, such fluctuations will eventually disrupt the smooth transfer of work between activities and unbalance production. The opportunity to stabilize operations flow is latent for finishing activities due to their short durations, varying dependencies on information, preceding tasks, and equipment (Brodetskaia et al. 2011).

Objectives and Scope

Figure 1 illustrates the framework pursued through this study and the corresponding line of research. The framework introduces a comprehensive perspective on the attributes and functions necessary for an automated and real-time monitoring and control of workflow in construction. In the framework, advanced sensing, data communications, and mobile technologies can automate the collection or, at a minimum, the communication of spatiotemporal site events as these happen (see the left box in Figure 1). The corresponding architecture integrates cloud computing and the internet of things (IoT) technologies to enable real-time monitoring and information communication. The real-time monitoring of workers' status, resources, and constraints can also enable an immediate response to pull signals from downstream tasks. The fusion of real-time progress data in combination with planning and design information and quantities from BIM models offers the potential to advance the understanding of construction with novel knowledge in production systems (see the middlebox in Figure 1). Fine-grained data collection offers multiple avenues for supporting informed decisions (see the right box in Figure 1). First, real-time monitoring enables stabilization. Thus, real-time access to fine-grained production data should become a fundamental step toward empowering crews in self-stabilizing their work pace. Indeed, anecdotal evidence indicates that empowering construction workers with the ability to resolve unexpected events minimizes the negative impact of such events (Desai and Abdelhamid 2012). Second, that downstream changes in the status of constraints (e.g., release) or tasks (e.g., completion) are immediately communicated facilitates the update of the work plan so that it mirrors actual site conditions and facilitates a smooth workflow. Finally, the accumulation of fine-grained production records opens the door to predictive analytics and artificial intelligence to discover hidden patterns and correlations. Such fine-grained information is often not available in current practice and precludes learning from completed projects.



(*graphic design adapted from Teizer and Cheng 2015)*

Figure 1. Real-Time Monitoring and Controls

Within such a framework, this article hypothesizes that operations workflow can be documented, assessed, and proactively stabilized with instantaneous monitoring approaches. The objectives of this study are: 1) investigate a technology architecture that can satisfy the collection, communication, and analysis of operations workflow data in near real-time, and; 2) document and analyze the operations flow of crew production units during finishing activities; and 3) assess the impact on the stabilization of operations flow from such technology-enabled monitoring. In terms of scope, the study is limited to the stabilization of operations workflow.

Pilot Test

A three-week pilot test focused on stabilizing drywall-finishing tasks during the renovation of a 7-floor and 3,582 square feet footprint hospital facility in Phoenix, Arizona. The scope of the multidisciplinary health care facility included medical, radiation, surgical oncology, pathology, laboratory, and diagnostic imaging services, in addition to other supportive clinical services. An integrated project delivery (IPD) agreement aimed at maximizing alignment and collaboration among project stakeholders.

The general contractor completed the installation of drywall through 12 sequential tasks. In order of installation, these tasks were: (1) layout of walls; (2) installation of top track; (3) framing of walls; (4) installation of hollow metal frames; (5) hanging of drywall above the ceiling; (6) installation of shaft wall; (7) installation of wall insulation; (8) installation of strap backing; (9) hanging of drywall below the ceiling; (10) framing of ceilings; (11) framing of soffits, and; (12) hanging of drywall at ceiling level. The estimated completion time was 12 weeks. The general contractor directly performed the installation of drywall with in-house crews, a condition sought in this study to guarantee the alignment of the crews with the pilot test.

Technology-Enabled Planning and Monitoring of Operations Workflow

A planning and monitoring approach was designed and actualized. The near real-time monitoring approach was divided into four functions: 1) collection of labor flow; 2) instant communication of flow information; 3) advanced controls; and 4) flow stabilization through corrective actions and updated work plan. The approach was evaluated and refined previous to its actualization through three workshops with project team members -management, superintendent, and supervisors. Corporate management actively supported and communicated the need for the pilot test. Figure 2 illustrates the planning and monitoring approach, its four functions, and their relation with pre-construction planning efforts. The rest of this section explains these functions. First, the collection of field production data was facilitated by a touch-based user interface on mobile tablet devices. Figure 3 illustrates a data collection window of the user interface. During drywall installation, supervisors were instructed to submit crew production data twice a day, before lunch and at the end of the day. Data included start and finish times, crew identification, number of workers, total work hours, work task, package identification, and installed quantities. Supervisors could also report the stop or completion of a task. As such, insights and lessons learned were asked to be reported at any moment. The completed work was also reported and captured in the BIM model through a dynamic interface that enabled identifying and reporting installed drywall objects, i.e., parts. In addition to submitting field data, the user interface enabled supervisors and crew leaders to access the latest work plan, BIM information, seek a resolution to constraints, or coordinate efforts with other crews.

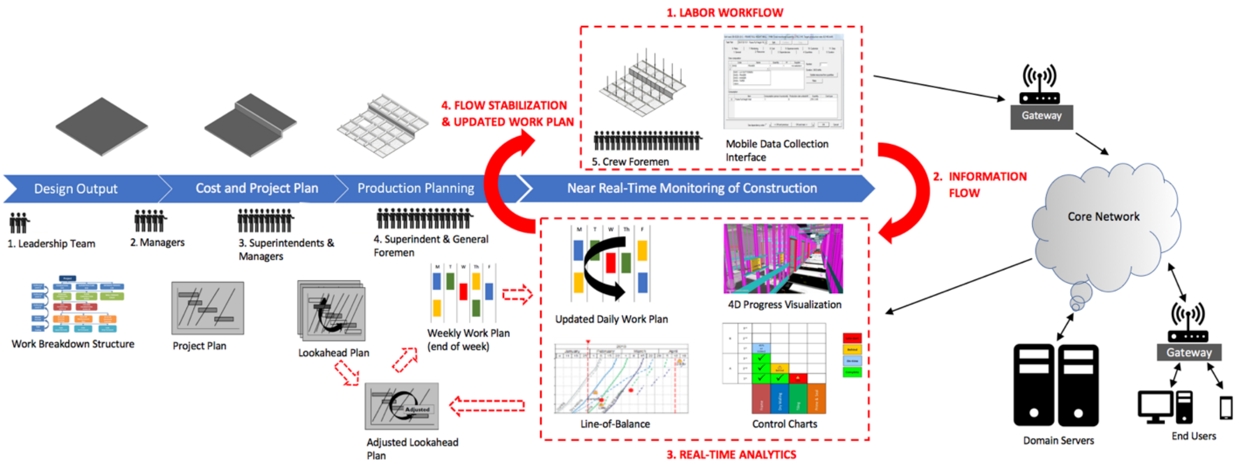


Figure 2. Technology Architecture

Second, wireless communications enabled the timeless feed of crew production data into a commercial cloud-based and integrated services package. Standard IEEE 802.11 wireless data communication protocols were leveraged to transfer the collected data through an existing wired network of access point (WAP) hardware devices in the hospital facility. BIM and project management services were integrated through the commercial cloud platform and instantiated with estimating, scheduling, design, work planning, and management applications. Such integration enabled the generation of 4D (3D object-oriented design + schedule) and 5D (+cost) simulations. Cloud service providers handled maintenance, software upgrades, or security patching on the back end.

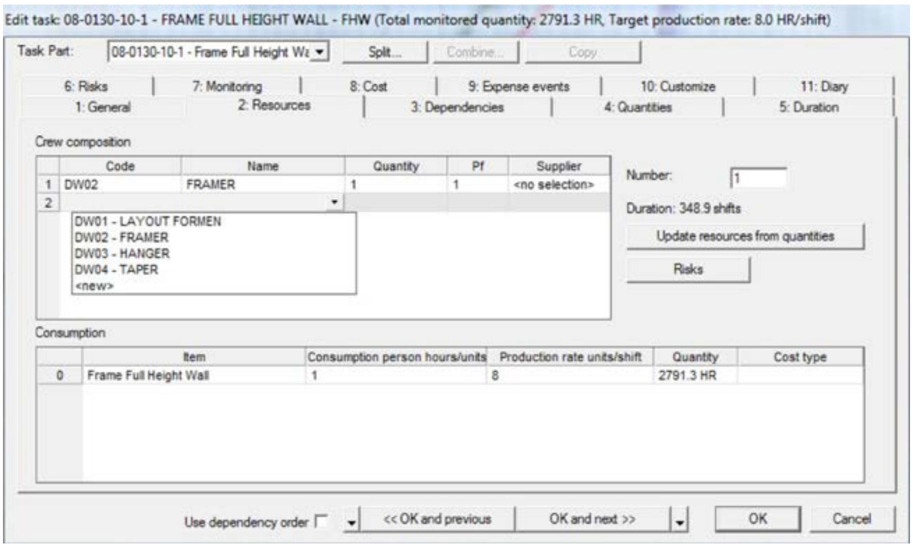


Figure 3. User Interface (courtesy DPR, Inc.)

Third, end-users customized advanced control analytics from cloud services. To understand the control aspect of the pilot test, the reader needs to understand the planning of drywall activities. Thus, the text herein discusses both planning and controls. In terms of planning, since interference with other trades would represent a disruption of the pilot, the work package of each floor had been previously divided into small work-located packages. In reality, installing mechanical, electrical, and piping (MEP) ducts through the wall preceded the task of drywall hanging above the ceiling. Also, the MEP trades preceded the tasks of framing ceilings and framing of soffits. Thus, to maintain work-ready locations ahead of the drywall crews, the work within each floor had been divided into small location-based packages. Figure 4 illustrates the distribution of drywall packages through the first floor of the hospital facility. Each location-based package accounted for less than 200 hours of drywall work. In addition to location-based packages, the team collaboratively planned the weekly work with the LPS approach. In terms of controls, customized analytics combined planning, BIM model information, and field actuals to assess the progress of each drywall task and identify deviations in the crews' operations workflow from the baseline flow value of each task. For example, the line-of-balance representation enabled the visual comparison of synchronicity between baseline and actual flows to rapidly identify deviations. See Figure 5. The illustration of drywall installation progress in the BIM model also enabled the visual tracking of progress by color-coding the installation status of each drywall object in the model. See Figure 6. Execution quantities were extracted from the BIM model.

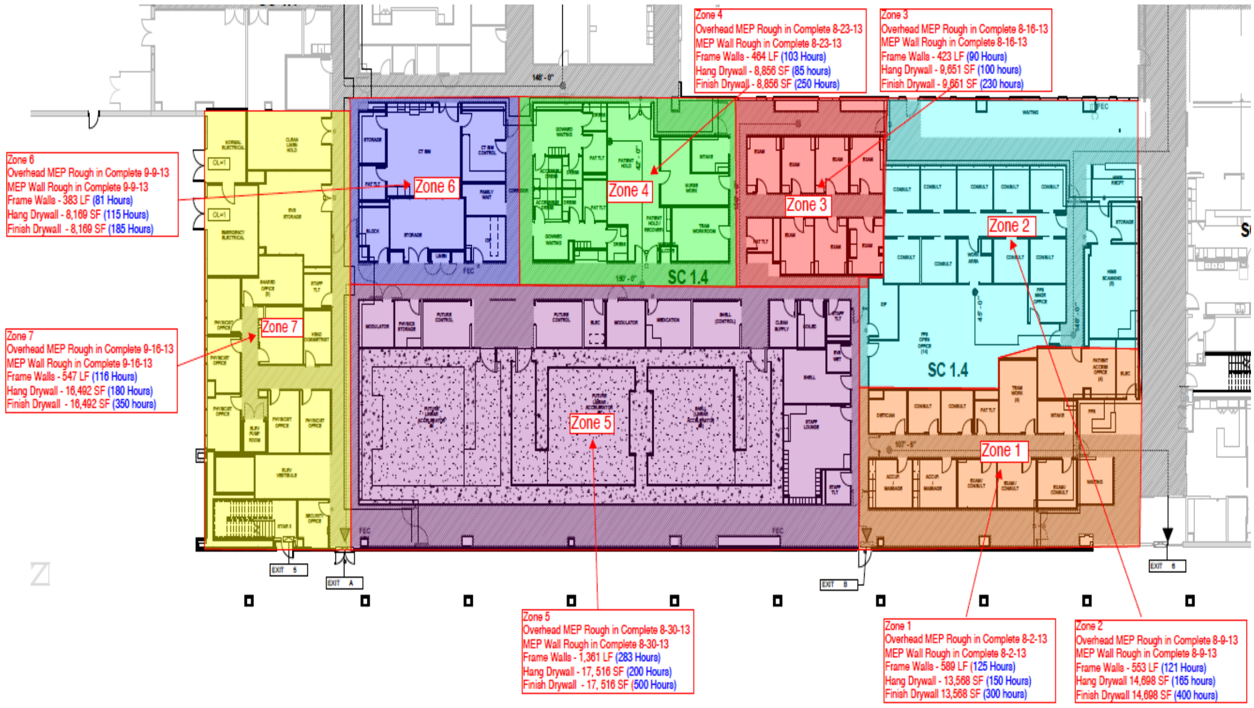


Figure 4. Location-Based Planning (courtesy DPR, Inc.)

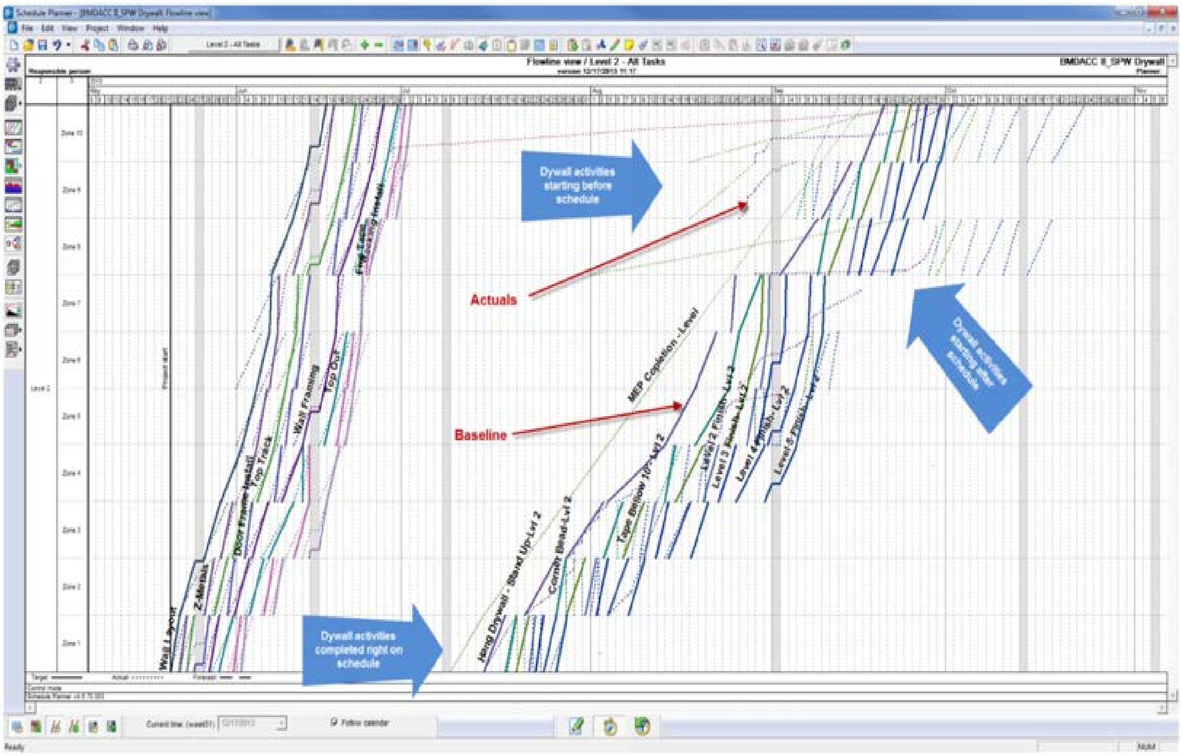


Figure 5. Line-of-Balance Analysis (courtesy DPR, Inc.)

Finally, the previous analysis led to management's remediation actions with the aim of stabilizing the crews' flow of work. When a meaningful deviation was identified, its root causes were sought, and corrective measures were immediately adopted. Whenever variability prevented the completion of the weekly plan, such a plan was revised. Incoming field data also enabled pull planning based on the availability of resources from downstream tasks, e.g., location.

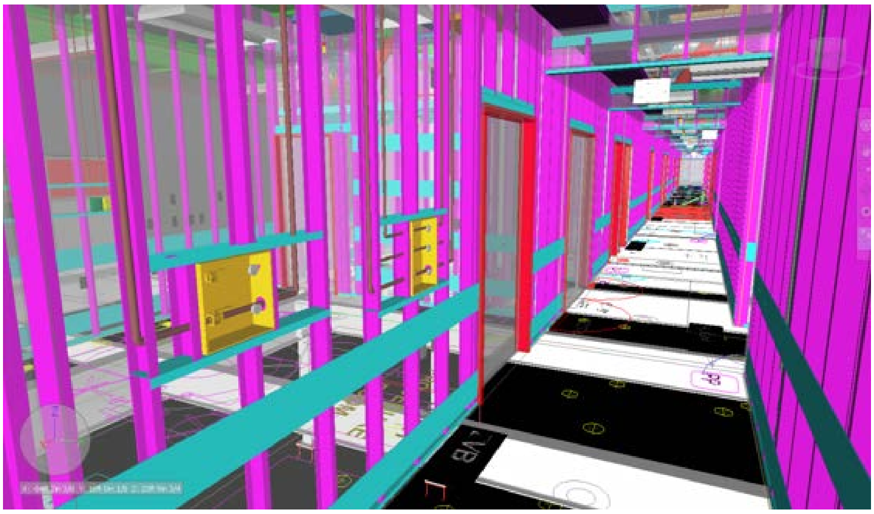


Figure 6. Object-Oriented Controls (courtesy DPR, Inc.)

Workflow Stabilization Analysis

The analysis of results indicates that the immediate communication and analysis of operations workflow triggered proactive actions that resulted in the partial and/or nearly complete stabilization of deviations. When meaningful differences existed between actual and planned flows, managers' interventions were observed to revert the actual flow to the planned flow rate or close to it. This section presents the stabilization of operations workflow for six drywall tasks. Such tasks are represented with eight or more consecutive data records (each record corresponding to a half-day of work) by the same crew. Such a condition of continuity by a single crew enables the observation of the near real-time monitoring influence on operations workflow variability. Such continuity condition also contributes to mitigating the influence of factors extraneous to the task execution -other than management interventions.

For each task, a chart represents the time series of consecutive crew performance records. While the horizontal axis in each chart represents the baseline operations flow value, the vertical axis represents the difference (either positive or negative) from each production record to such a baseline. In doing so, the sequence of consecutive production rates illustrates the fluctuation of workflow through time against the planned measure for the tasks of layout of walls, installation of top tracks, framing of walls, hanging of drywall below the ceiling, framing of ceilings, and framing of soffits. The red circles indicate the intervention of management to correct workflow deviations. Most often, interventions immediately improved the operations workflow, and such improvements were captured in subsequent data records. The reader should notice that such interventions were only implemented at the start of the following half-day work period. However, in the figures below, such interventions are condensed in a single moment coincident with the data record that originated the intervention. For each task, the rest of this section discusses the time series of workflow values and interventions.

Indeed, Figure 7 illustrates the operations workflow for the layout of the walls. Two interventions eventually triggered an immediate improvement in workflow production ratios. Production ratios fluctuated above and below the estimated workflow value during the test. The two interventions preceded the two above-the-average workflow performances.

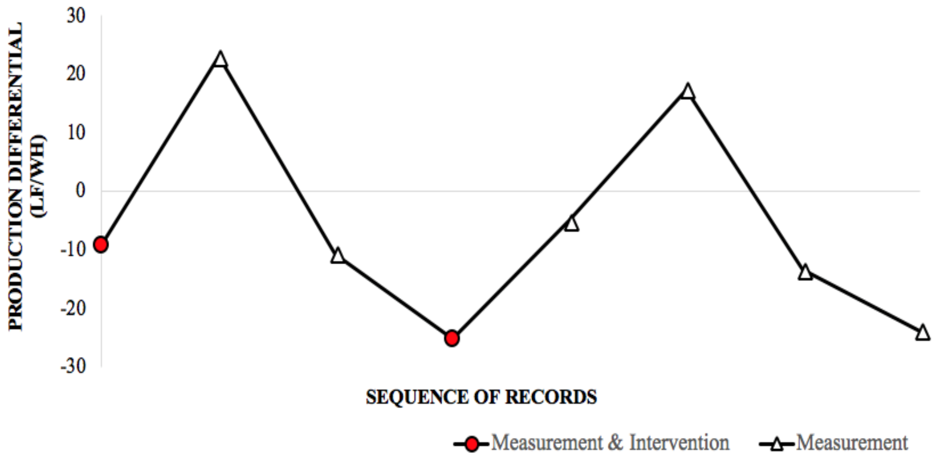


Figure 7. Operations Workflow - Layout of Walls

Figure 8 illustrates a fluctuation pattern above the estimated flow of work supported by minimum flow values immediately below the baseline for the installation of the top tracks. Monitoring was continuous. However, an intervention was not deemed necessary to correct the fluctuation of operations workflow around the baseline value.

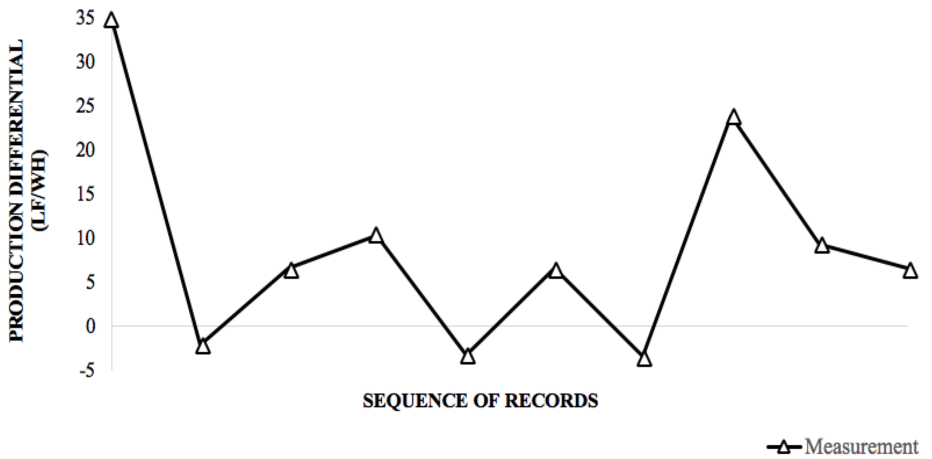


Figure 8. Operations Workflow - Installation of Top Track

Similarly, Figure 9 and Figure 10 illustrate time series data with a pattern of alignment between consecutive performance records and the estimated flow for the framing of walls and hanging of drywall below ceiling tasks, respectively. Management decided not to intervene since the actual performance of the crew self-adjusted to the estimated value –a likely indication of a constraint-free and ideal work environment. In Figure 10, the peak workflow value indicates an overproduction rate that workers justified through a rapid setup and highly repetitive conditions.

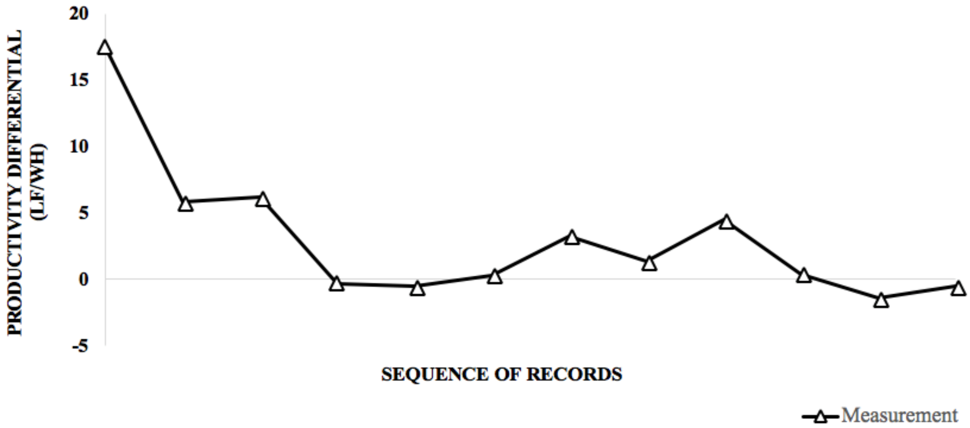


Figure 9. Operations Workflow - Framing of Walls

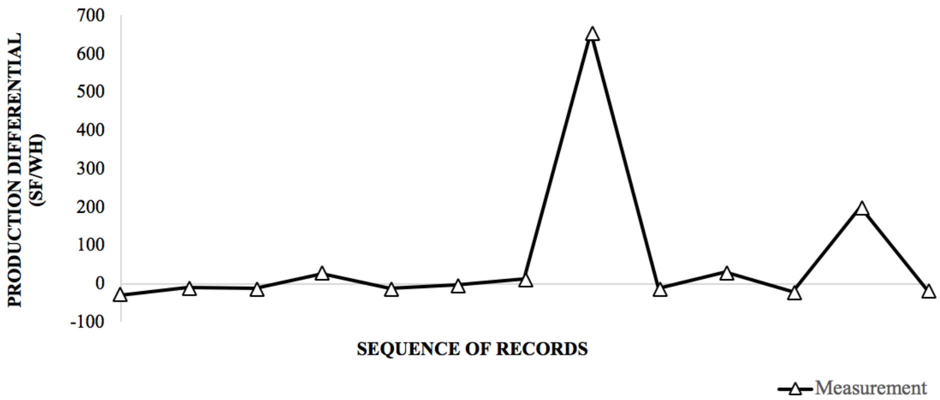


Figure 10. Operations Workflow - Hanging of Drywall below Ceiling

On the contrary, Figure 11 and Figure 12 illustrate the time series of workflow variation for the tasks of framing of ceilings and framing of soffits, respectively. Both time series of performances indicate a struggle to keep up with the baseline value. It is important to notice that all the interventions triggered immediate performance improvements and that, as a result, the production of each task was more stable or closer to its baseline. In most cases, though, the results of such interventions were relatively short-lived.

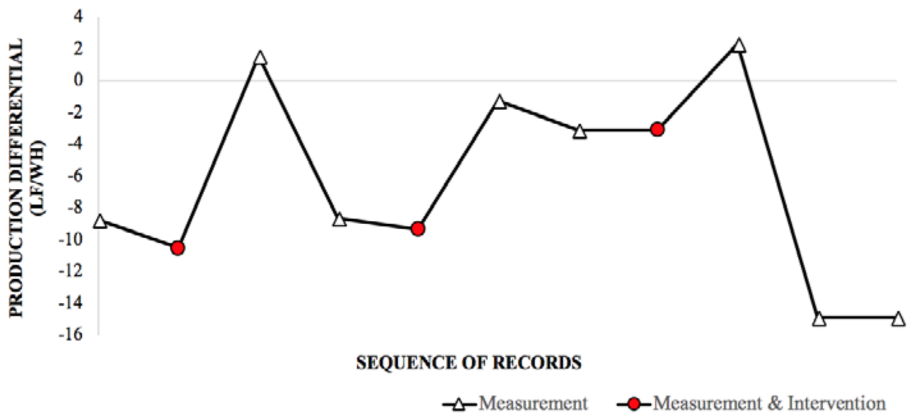


Figure 11. Operations Workflow - Framing of Ceilings

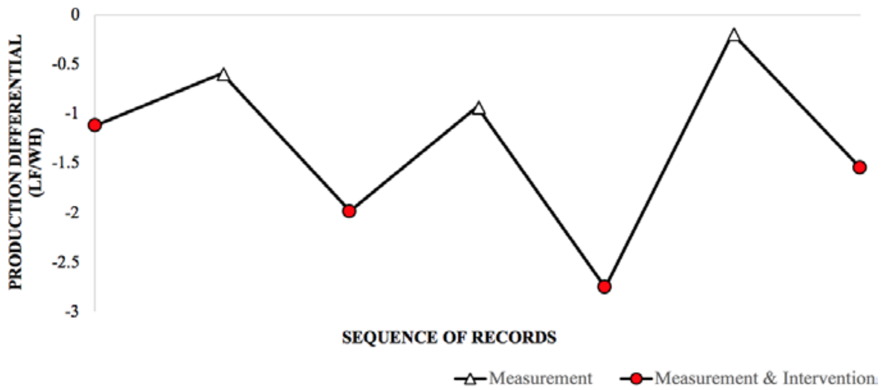


Figure 12. Operations Workflow - Framing of Soffits

Statistical Measures of Variation

Table 1 contains the summary of production results for each of the 12 drywall tasks. The expected or baseline production value for each task resulted from dividing the planned total quantity by the planned work hours. Similarly, each instance of actual production record resulted from dividing the actual quantity of work produced during the half-day work period over the total number of worker-hours consumed.

Table 1- Descriptive Statistics

Records	Task	Units (/work-hour)	Baseline	Mean	Difference	Median	Standard Deviation
9	Layout of walls	lf	27.46	21.58	-5.88	17.52	17.54
10	Installation of top track	lf	15.83	24.77	8.94	22.40	12.16
12	Framing of Walls	lf	4.25	7.28	3.03	5.13	5.22
4	Installation of hollow metal frames	ea	0.50	1.06	0.56	1.125	0.411
4	Hanging of drywalls above the ceiling	SF	26.81	7.18	-19.63	7.19	1.68
3	Installation of shaft wall	lf	1.10	0.45	-0.65	0.50	0.13
4	Installation of wall insulation	SF	300.00	70.80	-229.20	71.9	8.27
2	Installation of strap backing	lf	22.96	38.90	15.94	38.9	0
13	Hanging drywall below the ceiling	SF	70.45	132.65	62.20	61.57	187.89
12	Framing of ceilings	lf	19.78	13.33	-6.45	11.10	6.06
8	Framing of soffits	lf	2.99	1.69	-1.30	1.86	0.87
4	Hanging drywall at ceiling level	SF	25.24	37.88	12.64	36.40	11.41

The reader can observe in Table 1 that standard deviations are of the same order of magnitude as the median or mean values for several tasks. In those tasks, such large deviations result from substantial variation in the collected samples. Since such samples were small, aggregate analyses were used to explain such distribution of variation.

Thus, aggregate analyses informed the overall distribution of workflow dispersion. Specifically, two analyses separately investigated the tasks grouped by an equal unit of measurement. Indeed, the order of magnitude of workflow deviation values was similar among tasks with the same unit, either square feet or linear feet. Thus, Figure 13 illustrates a histogram representing the dispersion of workflow for the four tasks of installation of drywall or insulation. Similarly, Figure 14 illustrates a histogram representing the dispersion of workflow with tasks with a linear feet measurement. Both distributions of variation gravitate around the baseline production (equal to zero on the horizontal axis) with their two tallest bins on each side. In both histograms, the bin to the left of the baseline production (indicative of underproduction) represents nearly 50% of the data records in both samples. Thus, the most common workflow condition captured during the test was a production immediately below the baseline. Complementary, the bin to the right captured 28% (Figure 13) and 21.1% (Figure 14) of the respective sample records. Such percentages indicate that the second most common workflow condition is that of production immediately above the baseline. Together, these production conditions around the baseline explain 76% (Figure 13) and 69.2% (Figure 14) of the total production. Such small negative and positive fluctuations in work might appear to compensate for each other. However, in reality, management should initially concentrate on leveling and identifying the causes of peak variations before attempting to continuously stabilize work around the baseline or expected value of flow. If deviations, even small, had been maintained over time, substantial workflow deviations could destabilize a task, alter progress workflow, and eventually propagate instability through the production system.

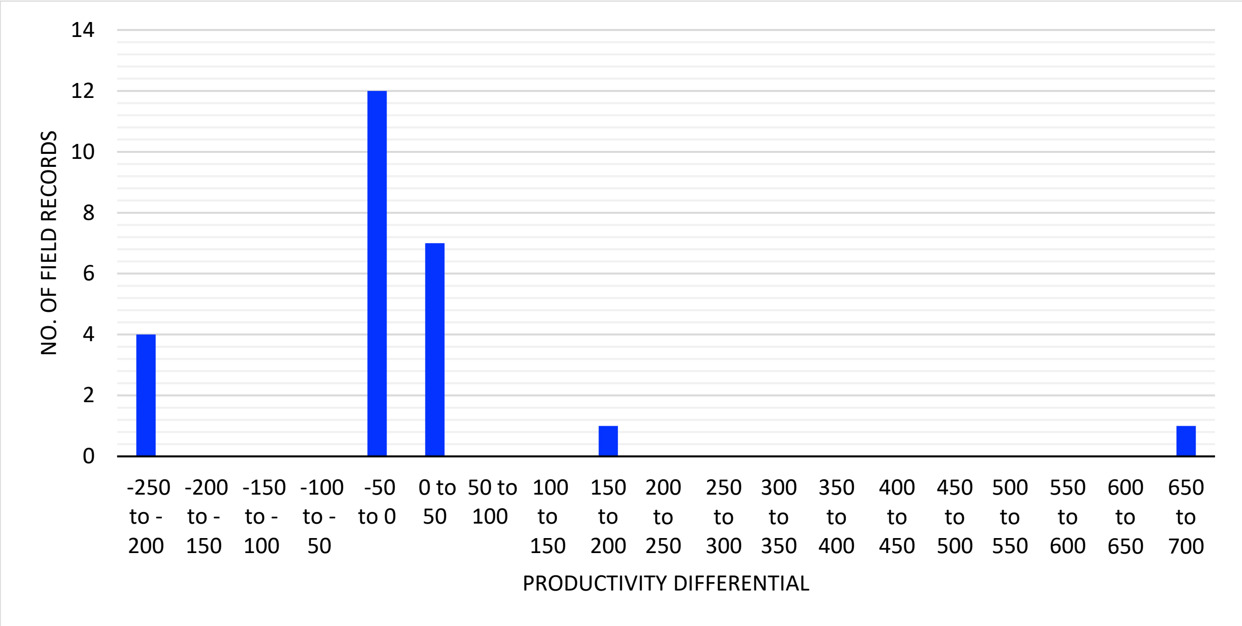


Figure 13. Distribution of Deviations from Baseline Production (S.F./wh)

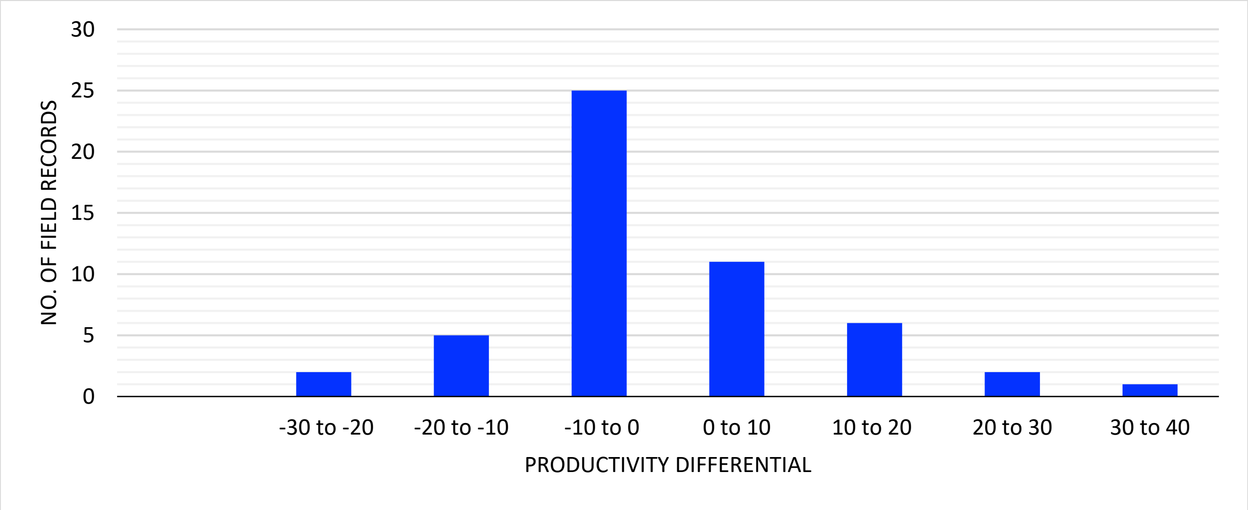


Figure 14. Distribution of Deviations from Baseline Production (L.F./wh)

Significance of Results

The implications of the results are four-fold. First, an opportunity to stabilize flow-through the monitoring and involvement of field workers exist. This study provides quantitative evidence of an uneven flow during the execution of operations by crew units of production. The study also provides evidence that the stabilization of flow through the analysis of fine-grained operations data is necessary and that such stabilization would eventually smooth the process flow between activities or trades.

Second, controls can effectively contribute to stabilizing workflow. All previous techniques planning and design (i.e. work structuring and product design) to smooth the flow of work. While such planning techniques aim to proactively enable flow, the associated mechanisms of control reactively assess planning success, i.e., once tasks have been completed, and thus cannot be leveraged to stabilize flow. This study provides tangible evidence that a proactive control mechanism can provide timely information on deviations as these happen so that corrective actions can be implemented. Thus, meeting work promises should not only depend on the goodness of a plan but should be complemented with the ability to intervene in work operations, with the involvement of the workers, when these deviate from the plan.

Third, empowering crews in self-stabilizing their work pace can further enhance operations workflow. Indeed, the provision of information, warning signs, or alerts directly to crew members without management intervention promises to expedite the correction of variability. Such empowerment of workers could be achieved through the refinement of real-time monitoring approaches such as the control mechanism discussed in this study. If properly implemented, empowering crew workers to directly resolve a variability event will minimize the impact of such an event.

Finally, advanced data collection, information, and computing technologies are vital in realizing continuous fine-grained monitoring in construction. Such technologies can enable the rapid transformation of massive amounts of data into intelligence that can be seamlessly shared among key parties in support of timely and informed decisions.

Observations and Limitations

This section compiles qualitative observations collected as a result of the pilot experience. The discussion includes feedback and experiences provided by field workers and managers who participated in the test. Also, the perceptions of corporate managers at the contractor organization were incorporated. The observations follow:

- **Automated data collection.** An automated data collection can ensure a consistent and continued gathering of error-free data. During the pilot, manual data collection was regarded as tedious and potentially error-prone. The consistency of the data that could be collected over a long period of time emerged as a potential concern.
- **Supervisors' reluctance to gather data.** The supervisors were reluctant to assess and introduce data through the user interface. Due to the lack of supervisors' support, the contractor decided to dedicate an engineer to collect field data.
- **Automated extraction of information.** In the future, managers expressed the need to enable automated analytics with warning messages or similar alert mechanisms that could alleviate the data analysis. For example, intelligence could automatically alert managers when workflow fluctuations or patterns that can threaten stability emerge.
- **Scalability.** Indeed, the team's opinion was that the proposed monitoring approach, as implemented in this pilot test, was sufficient for the study but could not be escalated to an entire project without automated data collection mechanisms and intelligent information extraction.
- **Fine-grained production records.** The contractor's vision was to generate a database of historical production records that could be leveraged in support of future projects. Figure 15 illustrates such a vision. The fundamental idea is that fine-grained production records hold value and that such value can be leveraged to support estimating, planning, and execution based on the analysis of records from previously completed and similar projects. For example, precise execution work hours could be populated by dividing the work quantities extracted from the BIM model by previously recorded production rates in similar projects. Fine-grained production records could be leveraged to support additional project functions, such as pre-qualifying subcontractors based on past performance. Besides, such a dataset could be mined in search of hidden patterns and correlations or prediction logic.

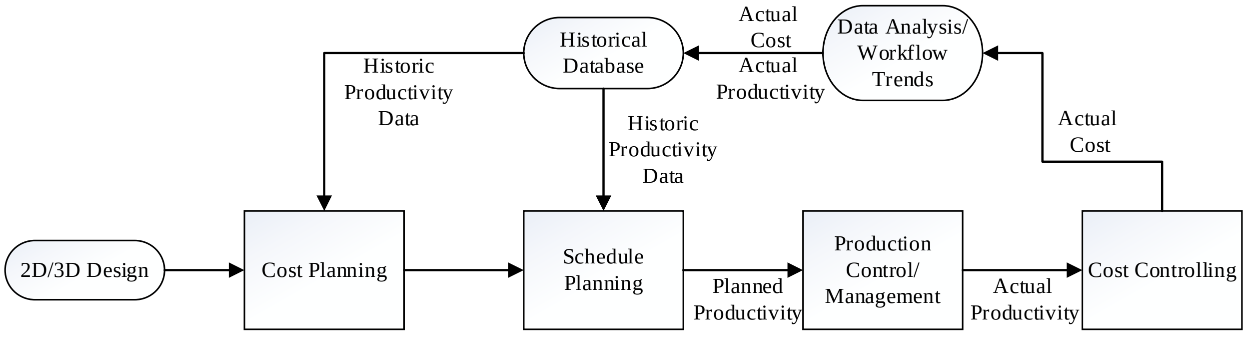


Figure 15. Leveraging Operations Workflow Records

Conclusions and Future Research

As a departure from past efforts that investigated the stabilization of operations workflow through planning and design, this study explored stabilization through real-time controls of field operations and with the involvement of the workers. The results provide quantitative evidence that an uneven workflow during the execution of individual tasks exists and support the notion that a proactive control mechanism can enable corrective actions and stabilize operations flow. Practitioners regarded the continuous monitoring of operations as a valuable and timely source of information that alleviated workflow variability and supported responsible decisions on behalf of the project, and, eventually, on behalf of the portfolio of projects and the contractor organization. Indeed, advanced data collection technologies and analytical approaches can enable the rapid transformation of massive amounts of data collected during operations into intelligence that can be seamlessly shared among key parties in support of timely and informed decisions. Finally, this study also provides empirical evidence that location-based scheduling combined with small work packages facilitates the instantiation of mechanisms to reduce variability.

Further research efforts should investigate the impact of stabilizing operations workflow on the stabilization of process workflow. Also, additional research is required to investigate the impact of flow stabilization on project performance. Finally, the benefits and use of fine-grained operations data from previously completed projects should be explored.

Acknowledgments

The authors want to acknowledge and thank DPR Construction for the support in implementing the pilot test and collecting the data. The authors also want to thank all the subject matter experts that supported this research effort.

References

A.D. Russell, A.D., Chiu, C.Y., and Korde, T. (2009). "Visual representation of construction management data." *Automation in Construction*, 18 (8), 1045–1062.

Abdelhamid, T.S., Jain, S., Mrozowski, T. (2010). “Analyzing the Relationship Between Production Constraints and Construction Work Flow Reliability: an SEM Approach.” Proceedings of the 18th Annual Conference of the International Group for Lean Construction, July 2010, Technion, Haifa, Israel, pp. 525-537.

Abdelhamid, T.S., Schafer, D., Mrozowski, T., Jayaraman, V., Howell, G. and Mohamed A. El-Gafy (2009). “Working through unforeseen uncertainties using the OODA loop: an approach for self-managed construction teams.” Proceedings of the 17th Annual Conference of the International Group for Lean Construction, 15-17 July 2009, Taipei, Taiwan.

Arashpour, M., & Arashpour, M. (2015). “Analysis of Workflow Variability and Its Impacts on Productivity and Performance in Construction of Multistory Buildings.” *Journal of Management in Engineering*, 31(6), 04015006.

Ballard, G. (2000). The Last Planner System of Production Control. Ph.D. Thesis, The University of Birmingham, Birmingham, UK.

Ballard, G., and Tommelein, I.D. (2021). "2020 Current Process Benchmark for the Last Planner System of Project Planning and Control." Lean Construction Journal 2021, pp 53-155.

Bashford, H.H., Walsh, K., and Sawhney, A. (2005). "Production system loading–cycle time relationship in residential construction." *ASCE, Journal of Construction Engineering and Management*, 131 (1), 15–22.

Brodetskaia, I., Sacks, R., & Shapira, A. (2013). "Stabilizing Production Flow of Interior and Finishing Works with Reentrant Flow in Building Construction." *ASCE, Journal of Construction Engineering and Management*, 139(6), 665-674.

Brodetskaia, I., Sacks, R., and Shapira, A. (2011). "A workflow model for finishing works in building construction." *Constr. Manage. Econ.*, 29(12), 1209–1227

Chitla, V.R., and Abdelhamid, T.S. (2003). ""Comparing Process Improvement Initiatives Based on Percent Plan Complete and Labor Utilization Factors". Proceedings of the 11th Annual Conference for Lean Construction, 22-24 July 2003, Blacksburg, Virginia, 118-131.

Dave, B., Kubler, S., Främling, K. & Koskela, L. (2016). "Opportunities for enhanced lean construction management using Internet of Things standards." *Automation in Construction,* 61(C), 86-97.

Desai, A. P. & Abdelhamid, T. S. (2012). "Exploring Crew Behavior During Uncertain Jobsite Conditions." In:, Tommelein, I. D. & Pasquire, C. L., 20th Annual Conference of the International Group for Lean Construction. San Diego, California, USA, 18-20 Jul 2012.

Flyvbjerg, B. (2006). "From Nobel Prize to Project Management: Getting Risks Right." *Project Management Journal*, 37 (3), pp. 5-15.

Formoso, C.T, Santos, A.D., and Powell, J.A. (2002). "An Exploratory Study On The Applicability Of Process Transparency In Construction Sites." *Journal of Construction Research*, 3 (1), 35–54.

Grau, D., and Back, W.E. (2015). "Predictability Index – A Novel Metric to Assess Cost and Schedule Performance." *ASCE, Journal of Construction Engineering and Management*, 04015043-1 to -8.

Gurevich, U., & Sacks, R. (2014). "Examination of the effects of a KanBIM production control system on subcontractors' task selections in interior works." *Automation in Construction*,37, 81-87.

Hamzeh, F. (2009). "Improving Construction Workflow - The Role of Production Planning and Control." Civil Engineering, UC, Berkeley, CA.

Heigermoser, D., García de Soto, B., Abbott, E.L.S., Chua, D.K.H. (2019). "BIM-based Last Planner System tool for improving construction project management." Elsevier, Automation in construction, 2019, Vol.104, p.246-254

Howell, G., and Ballard, G. (1996). "Can project controls do its job?." *Proceedings of the 4th Annual Conference of the International Group for Lean Construction*, 1996.

Howell, G., and Ballard, G. (1999). "Design of Construction Operations." Lean Construction Institute, White Paper-4. Accessed December 28, 2022. http://lean-construction-gcs.storage.googleapis.com/wp-content/uploads/2022/08/08153223/Design_of_Construction_Operations.pdf

Howell, G., and Laufer, A. (1993). "Interaction between Subcycles: One Key to Improved Methods."ASCE, Journal of Construction Engineering and Management, 119 (4), p.714-728.

Jongeling, R., and Olofsson, T. (2007). “A method for planning of workflow by combined use of location-based scheduling and 4D CAD.” *Automation in Construction*, 16(2), 189-198.

Kim, Y.W., and Ballard, G. (2000) “Is the earned-value method an enemy of workflow?.” *In Ballard, G., and Chua, D. (eds.), Proceedings of the 9th Annual Conference of the International Group for Lean Construction*, Singapore. Koskela,

Koskela, L. (1992). “Application of the new production philosophy to construction.” Technical. Rep. No. 72, Center for Integrated Facility Eng., Dept. of Civil Eng., Stanford Univ., Stanford, CA.

Koskela, L. (2000). “An exploration towards a production theory and its application to construction.” D. Tech, Helsinki University of Technology, Espoo.

Lean Construction Institute (2015). “The Last Planner System.” Lean Construction Institute, Revision 6, June of 2015,

Liker, J.E. (2003). “The Toyota Way.” McGraw-Hill, New York, 2003.

Lin, J.J., Goparvar-Fard, M. (2021). “Visual and Virtual Production Management System for Proactive Project Controls.” ASCE, Journal of Construction Management and Engineering, 147(7):04021058.

Liu, M., Ballard, G., Ibbs, W. (2011). “Work Flow Variation and Labor Productivity: Case Study.” *Journal of Management in Engineering*, 27(4), 236-242.

Matthews, J., Love, P.E.D., Heinemann, S., Chandler, R., Rumsey, C., and Olatunj, O. (2015). “Real-time progress management: Re-engineering processes for cloud-based BIM in construction.” *Automation in Construction*, 58(C), 38-47.

Mulva, S.P., and Dai, J. (2012). “Performance assessment.” Construction Industry Institute and The University of Texas at Austin, Austin, TX.

Nerwal, N., Abdelhamid, T.S. (2010). “Work Structuring Of Construction Crews: Installation Of Light Fixtures Case Study.” Proceedings of the 18th Annual Conference of the International Group for Lean Construction, July 2010, Technion, Haifa, Israel, pp. 316-325.

Nerwal, N., Abdelhamid, TS (2012). “Construction Crew Design Guidelines: A Lean Approach.” Proceedings of the 20th Annual Conference of the International Group for Lean Construction, July 2012, San Diego, CA, USA.

Sacks, R. (2016). “What constitutes good production flow in construction?” *Construction Management and Economics*, 34(9), 641-656.

Sacks, R., & Goldin, M. (2007). “Lean Management Model for Construction of High-Rise Apartment Buildings.” *Journal of Construction Engineering and Management*, 133(5), 374-384.

Sacks, R., Radosavljevic, M., and Barak, R. (2010). "Requirements for building information modeling based lean production management systems for construction." *Automation in Construction*, 19, 641–55. Schmenner,

Seppänen, O. (2009). “Empirical research on the success of production control in building construction projects.” Ph.D., Helsinki University of Technology, Espoo, Finland.

Shingo, S., and Dillon, A.P. (1989). "A study of the Toyota production system: from an industrial engineering viewpoint. Produce what is needed, when it's needed." Taylor & Francis, New York, NY.

Thomas, H. (2000). “Schedule Acceleration, Work Flow, and Labor Productivity.” *Journal of Construction Engineering and Management*, 126(4), 261-267.

Tommelein, I.D., Riley, D.R., Howell, G.A. (1999). "Parade game: impact of workflow variability on trade performance." *Journal of Construction Engineering and Management*, 125 (5), 304–310.

Tsao, C.Y., Tommelein, I.D., Swanlund, E., and Howell, G. (2000). "Case Study for Work Structuring: Installation of Metal Door Frames." Proc., 8th Conf., Int. Group Lean Constr., Univ. of Sussex, Brighton, UK.