

WORKFLOW STABILIZATION WITH FINE-GRAINED WORK PACKAGING AND NEAR REAL-TIME PROGRESS MONITORING

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ABSTRACT

Detailed understanding on the efficiency of construction workflow is critical to improve execution performance. Building on previous efforts, the hypothesis of the study is that minimizing the size of work packages and also increasing the frequency of progress monitoring stabilizes workflow variability, so that deviations from the baseline can be timely and proactively corrected. While a significant amount of efforts have been successfully reported on location-based scheduling and fine-grained work packaging, the study also proposes to incorporate a near real-time monitoring approach to proactively assess progress and identify corrective actions as deviations occur. While fine-grained work packages can facilitate a more instantaneous control on the executed work, such rapid control can result in a proactive response to progress issues on the site.

An intervention test on the drywall construction for a new hospital facility revealed the effectiveness of this fine-grained planning and monitoring approach. In phase I or control, a classical Critical Path Method (CPM) to plan for the execution of the drywall package was used. In phase II or intervention, work packages at the task level were defined, and further split the task-level work packages according to work zones locations. Such packaging enabled flexible resource allocation in response to unidentified constraints. Progress was monitored on a daily basis, so that deviations from planned work were proactively corrected. Based on four performance metrics, the results indicate that the fine-grained work plan and near real-time monitoring approach significantly improved the performance of phase II relative to phase I.

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KEYWORDS

Workflow stabilization, lean production, project controls, productivity, resource allocation.

INTRODUCTION

The construction industry in the United States (U.S.) has historically represented a significant bottleneck to further improving economic efficiency. Economic efficiency refers to the use of resources to maximize the production of goods and services (Levin et al. 1976). According to Bureau of Labor Statistics (BLS), more than five million workers were employed by the construction sector during 2012 despite the current economic recession (Bureau of Labor Statistics 2013). Data from U.S. Census Bureau indicate that the construction industry generated over 900 billion dollars (equivalent to 5.5% of Gross Domestic Product of U.S.) in 2013 (United States Census Bureau 2013). This economically impactful and global construction industry, however, seriously suffers from stagnant and declining productivity when compared to the rest of non-farming industries, such as manufacturing. Previous studies suggest that it is possible to significantly enhance construction productivity and achieve 25% to 50% in cost savings through leaning the project delivery process and reducing non-value added efforts (e.g., idling of workers and equipment) (Alarcón and Mardones 1998; Dobbs et al. 2013).

Compared to manufacturing, construction work is executed in less controlled environments that involve uncertainty factors related human, equipment, resource, supply chain, location, environmental, and other conditions. These conditions have spatial and temporal variations, and their unique combinations frequently lead to variations in construction productivity, resource demands and allocation, and variations in workflow. Such variations indicate less stable workflows, and inefficiencies in production systems (Ōno and Bodek 1988). For instance, spatial-temporal conflicts between construction processes and variable conditions impact productivity and hence lead to stoppages and variations in workflow that result in less efficient construction processes (Guo 2002; Randolph Thomas and Horman 2006; Seppänen 2009). Some quantitative studies revealed that more than 50% of labor inefficiencies are directly or indirectly related to poor workflow management (Thomas et al. 2003).

Past studies have highlighted the criticality to reliably plan for and control workflow. While a significant amount of efforts (Ballard et al. 2007; Kenley and Seppänen 2009; Seppänen et al. 2010; Liu et al. 2011; Hamzeh et al. 2011; Seppänen et al. 2013) have been successfully reported on the efficiency of various approaches to location-based scheduling and fine-grained work packaging, the proposed approach incorporates a near real-time monitoring approach to proactively assess progress and identify corrective actions as deviations occur. In reality, it is difficult to collect data and diagnose production processes during construction at granularities necessary to accurately monitor work and resource flow. Weekly progress updates do not suffice to capture the detailed workflow changes to proactively respond to such variations. Complementary, averaging productivities in large work areas (e.g., a floor) blur spatial details of workflows. Additionally, field managers and engineers cannot invest the necessary time to track such small work packages in detail. Hiring full-time workers to record detailed construction activities results in extra costs and

interferences with existing work in progress. The combination of small work packages and detailed monitoring is presumed to be synergic. Thus, fine-grained work packages can facilitate a more instantaneous control on the executed work, while such rapid control can result in a proactive response to progress issues on the site. Also since, every construction project is unique because of its own combination of human, environmental, material, equipment, location, resource, and other, sometimes unique, conditions, it is difficult to isolate the impacts of multiple interacting factors in uncertain construction environments for determining their impacts on workflow stabilization. As a result, the lack of detailed workflow monitoring systems limits studies on how to quantify and diagnose workflow stabilization issues in an objective manner.

Building on previous efforts, this paper examines how the combined fine-grained work packaging and real-time monitoring approach enables detailed workflow stabilization and daily progress monitoring. The success of the combined approach is tested through an intervention in the drywall activity for a healthcare facility project. This project has two phases with similar drywall construction packages, and with the exact same crews and environments. In the first or control phase, we adopted CPM-based work planning at activity level approach. In the second or intervention phase, we divided work packages of drywalls into daily-monitored work zones for detailed workflow monitoring and flexible resource allocation. Within each work zone, we decompose work into its smallest discernible entity, the tasks, and tracked the resource uses and progress of the individual tasks. We collected detailed task-level productivity data on a daily basis, focusing on tasks related to drywall construction. Through this intervention, the results were obtained.

BACKGROUND RESEARCH

Previous studies indicate that traditional project control approaches, such as Critical Path Method (CPM) and Earned Value Management (EVM), have limitations to stabilize construction workflow (Koskela and Howell 2008). CPM and EVM mainly focus on logic constraints between construction tasks, while showing limited considerations to the use of resources and locations of those resources during the execution of the planned tasks.

Recent research efforts have been focusing on developing new planning and project control methods to address the limitations of CPM- and EVM-based approaches. Researchers adopted and extended workflow-based approaches in production systems management used in manufacturing practices. Lean construction was conceived from lean manufacturing partially to plan for execution with a workflow stabilization focus and hence to minimize the waste of materials, time, and effort (Koskela and Howell 2008).

The Last Planner System™ (LPS) is an implementation mechanism of Lean Construction (Ballard 1997; Ballard 2000). It aims at enhancing the reliability of the weekly work plan. According to Ballard, LPS is a production planning approach that integrates pull planning, look-ahead planning with constraint analysis, weekly work planning based upon reliable promises, and learning based upon analysis of Plan Percent Complete (PPC) and reasons for variance to improve workflow (Ballard et al. 2007). In LPS, the last planner is the ultimate individual responsible for planning the actual the execution of the work. This approach introduces a transfer of accountability

from management to the workforce. Pre-fabrication, modularization, pull scheduling, and integrated project delivery are also techniques with an increasing presence in the construction market that tend to result in increased efficiency and more stable workflows. Such techniques are often used to complement the implementation of the LPS. Additional approaches to stabilize workflow during planning have included Location Based Management System (Kenley and Seppänen 2009; Seppänen et al. 2010; and Seppänen et al. 2013). All these approaches share in common the production perspective on the project delivery process (Ballard 2001). Such production approach emphasizes the minimization of waste and the maximization of end value while satisfactory performing the project. Building on the success of these and other efforts, this study proposes a combined approach to enhance workflow variation with a fine-grained production planning and near real-time monitoring functions, as discussed below. While fine-grained work packages can facilitate a more instantaneous control on the executed work, such rapid control can result in a proactive response to progress issues on the site.

A FRAMEWORK TOWARDS DATA-DRIVEN PLANNING AND CONTROLS

This study examines a work planning and monitoring framework towards a data-driven planning and controls to improve the performance in the delivery of capital facility projects. This framework is part of the long-term vision for accumulating productivity data in a historical database to reveal the most likely production rate of certain crews (e.g., square feet of walls produced in one hour by a crew). In such vision, the project planning starts with the extraction of quantities from 2D/3D as-designed data or models (e.g., Building Information Models). Cost-planning then uses historic productivity rates for determining the appropriate amount of resources needed (e.g., labors, materials, equipment), since the most likely work hours of certain types of crews needed for completing a certain unit of construction can be ascertained (e.g., hours of a crew needed for a square foot of wall). At the same time, schedule-planning can estimate the durations of the construction activities based on the actual availability of resources. The following equation shows the relationship between quantities of construction, labor resources, and durations of tasks. In the equation below, productivity is defined as input of work (work hours) divided by output of work (e.g. square foot of drywall) –which is a frequent expression of productivity in construction even though represents the inverse of the traditional productivity equation (output / input) –so that Task Duration is expressed in hours.

$$\text{Task Duration} = \text{Task Quantity} \times \text{Production Rate} \div \text{Number of Crew}$$



Compared with project planning, in which engineers adopt the historical production rates for planning construction tasks and resources, in project controls engineers are envisioned to monitor the actual production rates in the field and add these actual productivity data into the historical database. In addition, they are to adjust resource allocation according to actual production rates for stabilizing workflows. Specifically, project engineers are to record actual production rates and identify anomalous

deviations from historical records. Production management process aims at adjusting production rates through re-sequencing work packages and re-allocating resources. Production management is to also trigger cost controlling and relevant cost analyses for determining the optimal adjustment strategy of construction workflows.

After the execution of a construction project, the project team works together with data analysts to synthesize productivity data and relevant information into the historical database. Continuously updated historical database guides general contractors and decision makers to achieve more reliable project planning and effective controls in future projects. Moreover, this historical database can guide decision makers in prequalifying and selecting contractors.

RESEARCH METHODOLOGY

The next sections detail the research methodology undertaken in this study.

FINE-GRAINED WORK PACKAGING FOR DATA-DRIVEN PROJECT CONTROLS

The core of the project control framework described above is the collection of detailed historical productivity data into the historical database. The challenge lies in the granularities of data productivity and progress records to be collected. Weekly progress reports and average productivity report of large work zones fail to capture spatial-temporal variations in construction progress. Diagnosing detailed reasons behind anomalous and instable workflows with aggregate productivity data is not possible. A fine-grained work packaging strategy is developed to facilitate effective collections and organization of detailed productivity data and details of events within workflows (e.g., stoppages, site changes). Specifics of this strategy are:

- Along the time dimension and a Work Breakdown Structure (WBS), this fine-grained work packaging approach divides work into its smallest identifiable, entity, the task. Along the spatial dimension, this approach split the workspaces into work zones, so that work packages are further reduced.
- A single construction task executed in multiple work zones is thus an aggregation of multiple work packages corresponding to the executions of that task in multiple zones. Several interrelated tasks (layout, framing of studs, hanging drywall, etc...) result in an activity, for instance drywall. Figure shows the seven work zones on the first floor of the Banner MD Anderson Cancer Centre observed in this research.

This task-level and geo-centered work packaging enables project engineers to track individual tasks at discrete locations for detailed tracking and diagnosis of construction workflow and resource use. Compared with conventional CPM and PERT methods, this flow-based approach provide more spatial-temporal details to guide engineers to optimal resource allocation when individual packages have abnormally slow activities or idling resources. Allocation resources across multiple packages can reduce the amounts of idling resources or labors while re-allocating them to under-performed work packages requiring additional resources.

In practice, this fine-grained work packaging requires significant amounts of efforts for detailed data collection and database maintenance. It also requires trust, alignment, and communication between contractors, subcontractors, and engineers.

Construction sites change every day, and daily observations are necessary for such data collection. However, contractors require touchable benefits before investing into detailed data collection. Also, fine-grained data is critical for quantifying benefits of fine-grained work packaging. In order to validate the planning and monitoring approach, this study used the above facility to test such approach for a drywall activity through an intervention.

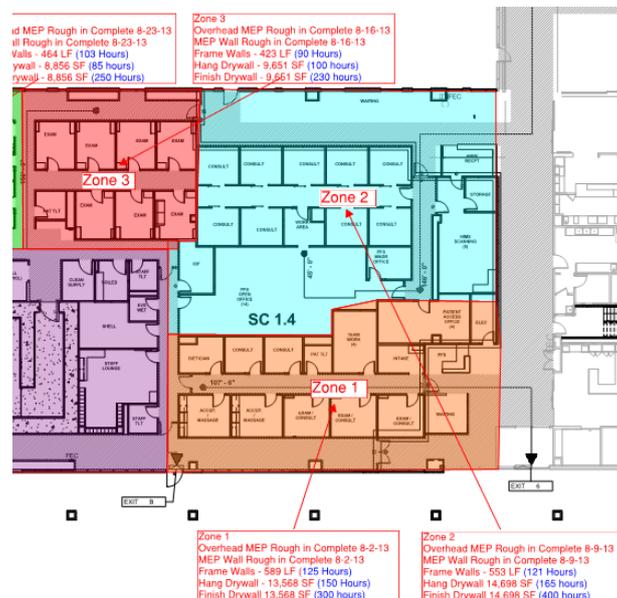


Figure 1: Work Zones on Level 1 (First Floor) of the Studied Healthcare Facility

INTERVENTION TEST

Aiming at testing the proposed fine-grained work packaging approach for workflow stabilization, the authors selected the drywall activities in the two-phased Banner MD Anderson Cancer Centre project. This multi-disciplinary healthcare facility includes medical, radiation, surgical oncology, pathology, laboratory, and diagnostic imaging services, in addition to other supportive clinical services. The gross acclimatized area, for each phase, is above 100,000 square feet. The contractor started phase I of this project in 2009 and is now completed. Phase II of this project began in 2013 and has been completed in in the same year.

In first or control phase, the contractor managed the project, including the drywall activities, using traditional CPM and PERT methods without an Integrated Project Delivery (IPD) approach. Engineers planned the execution of large work packages in the first or control phase, and then monitored the production progress on a weekly basis. In the second or intervention phase, the contractor adopted the fine-grained work packaging and daily workflow monitoring for drywall activities. For both phases, the contractor provided the management team and the drywall crews, the composition of which remained almost identical. Such management and crew stability, along with the same geographical location, weather, very similar workspaces, work conditions, and level of uncertainty for the same healthcare facility, indicates that drywall activities of two phases share similar main influencing factors – other than the planning and controls approach based on fine-grained work packages.

In this case, the drywall activity for the first phase became the control measure in the intervention test, while the drywall activity for second phase represents the actual intervention. This set-up of the intervention test increased the reliability of the obtained results.

SCHEDULE OF CONSTRUCTION AND TASK DEPENDENCIES

Construction schedules of drywalls have tight relationships with mechanical, electrical, and piping (MEP) work packages. The relationships between drywall construction and MEP installation activities can influence the efficiency of drywall progress. In this project, the drywall activity involved four main tasks: wall layout, framing, hanging of drywall, and taping. In terms of dependencies, installations of the MEP ducts should be predecessors of “hanging of drywall” because MEP ducts intersect through drywalls, as shown in Figure 2. Unfortunately, the MEP contractor used the conventional CPM-based approach to control the MEP installation activities in this project. As shown in the workflow stabilization results, this inability to streamline the MEP installation workflow in phase II of the project led to some disruption of drywall installation work and undermined the observed benefits of the fine-grained work packing approach.

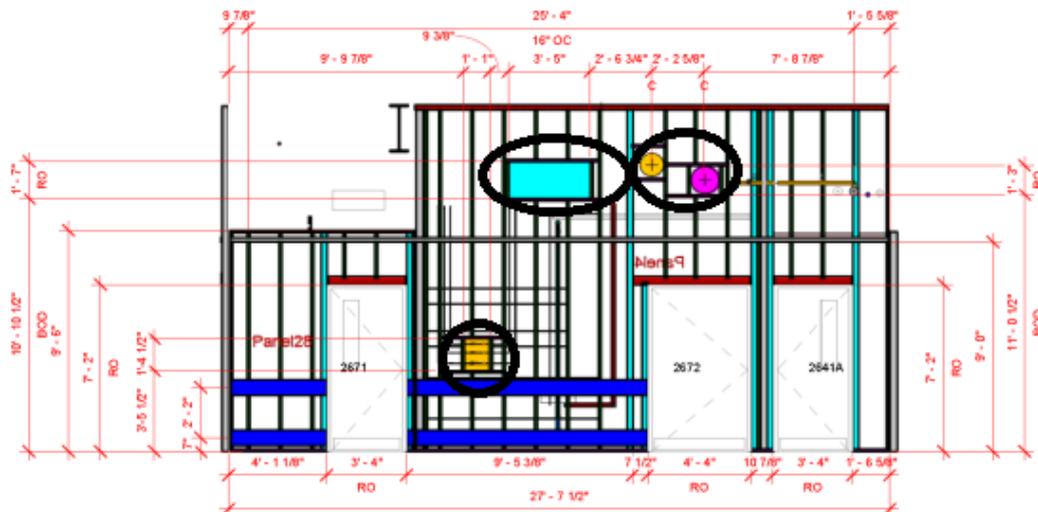


Figure 2: A Frame of the Drywall and Openings (encircled) through the Frame for MEP Ducts

FINE-GRAINED WORK PACKAGING AND DATA COLLECTION

In phase II of this construction project of the healthcare facility, the foremen reported a daily production log by individual tasks in each work zone. Figure 3 shows the decomposition of a task, “Framing” in drywall workflows, into multiple tasks associated with multiple work zones. The left part of Figure 3 shows that the contractors planned the tasks in individual work zones on a daily basis. The contractor recorded daily production reporting for these fine-grained work packages.

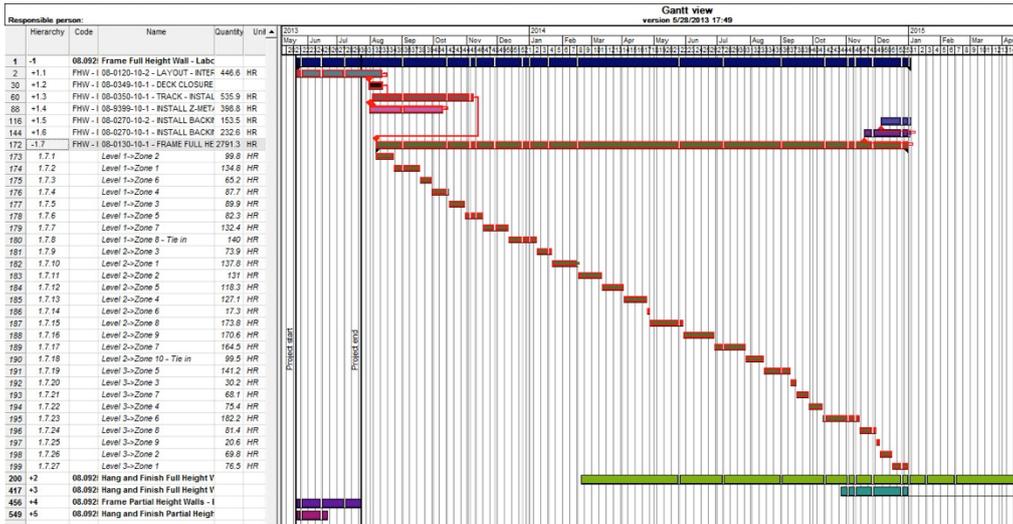


Figure 3: Fine-Grained Work Packaging for Daily Productivity Progress Assessment at Individual Work Zones (Locations)

One of the authors coordinated the daily reporting efforts by foremen. This author observed that most of the foremen completed the daily logs in an accurate and correct manner. Sometimes, though, foremen were reluctant to fill the daily logs and continued with the regular weekly reporting due to various reasons. Thus, the author actually invested 16 hours per week to report the daily productivity data and ensure the quality of the reported data. Figure 4 is a daily-updated status report of fine-grained work packages. Each column represents a construction task, such as “Wall Layout.” Each row represents a work zone that belongs to certain floors of the healthcare facility (level 1, level 2, and level 3). Each rectangular cell in this report represents a work package. Numbers inside those cells represent the dates of Estimated Start (ES), Estimated Finish (EF), Actual State (AS), and Actual Finish (AF). These four numbers indicates the status of the work package at the time of reporting. Colours of cells visualize such status of work packages: green means completed work packages; red means that the task has not begun; yellow means delayed work packages; and black means no such task for that work zone.



Figure 4: Sample of Daily Updated Work Report by Zone Location

METRICS FOR MEASURING PROJECT CONTROL PERFORMANCE

Characterizing the impacts of fine-grained work packaging approach on project performance during the intervention requires not only detailed field data, but also performance metrics of construction projects. The authors use the following performance metrics:

- **Craft labor productivity:** measures the amount of resources needed for completing a square foot of drywall. Thus, productivity is expressed as the ratio of output (square feet) divided by input (typically units of work per work hour), even though in this article for clarity purposes the units are square feet per minute.
- **Resource balancing:** measures the performance of resource management to avoid intensive use of certain type of resources within short time period or in certain small areas. Abnormally intensive resources uses, especially when toward the end of projects (“last-minute efforts”), are results of poor project planning and coordination, and can lead to congestions, unnecessary overtimes. It will create significant temporary needs of large amounts of resources that could be avoided through proactive planning and resource allocation. To meet the deadline of project completion, such imbalanced resource uses can cause overtime of workers and logistics challenges due to last-minute intensive work.
- **Number of Requests for Information (RFI):** measures the communication efficiency across project teams. It can also serve as indicators about how detailed work packaging help reduce wastes and redundancies.
- **Percentage of overtime to total work-hours:** measures the performance of resource and workload management. Higher percentages of overtime to total work-hours usually indicate poor planning and less responsive resource allocation, so that workers need to work overtime in certain time periods, especially the time close to the project completion point. This is an accepted strategy in the industry amongst projects following the CPM method to achieve the specified duration.
- **Percentage of hours spent on rework to total work-hours:** this metric measures the performance of communication and coordination of project teams. Less flexible resource allocation and less detailed workflow monitoring can cause miscommunications between collaborating engineers and result in reworks.

PRELIMINARY RESULTS

Comparing the four performance metrics between the control and intervention phases, the authors found that in the second phase drywall performance significantly improved. As shown in Table , the performance results of the intervention phase are significantly better than those of the control phase. As this table shows, the resource consumption of drywall construction resulted in a 17% improvement. Figure 5 shows that the use of resources in drywall construction activities did not accumulated towards the end of the second or intervention phase. This is evidence, for this project, of a well-planned and executed workflow that prevents near last-minute type efforts on the site. The authors are in the process of acquiring and summarizing resource use data from the control, which is less detailed than that of the intervention. Initial

observations indicate that the use of resources is more intensive at the end of the control phase.

The authors used the other three metrics at the “phase” level: we generated these results for all construction activities in both phases, not just for drywall construction. At this perspective of overall project performance, the number of RFIs reduced by more than 67% from the first to the second phase. Percentage of overtime for has an improvement of 43%; percentage of rework has an improvement of 66%. These results cannot be generalized since they are only representative of a single project.

Table 1: Comparison of the Project Performance in Phase I (Conventional Project Control) and Phase II (Fine-Grained Work Packaging)

Scope	Performance Metric	Phase I	Phase II
Drywall Construction Activities	Craft Labor Productivity	0.175 sf/min	0.212 sf/min
	Resource Balancing	Intensive uses of resources toward the end of project	More balanced uses of resources along time line
	Number of RFI	850	275
All Construction Activities	Percentage of Overtime	3.7%	2.7%
	Percentage of Rework	6.6%	2.2%

This study also contributes with the following observation that the MEP execution planned with conventional CPM-based methods negatively influenced drywall progress. Figure 1 at the beginning of this paper shows how MEP construction causes delays between the framing of the dry wall and the hanging of the drywall. Specifically, the left part of Figure 1 represents all tasks before framing the drywall, while drywall construction has to wait for MEP installation through the drywall to be completed.

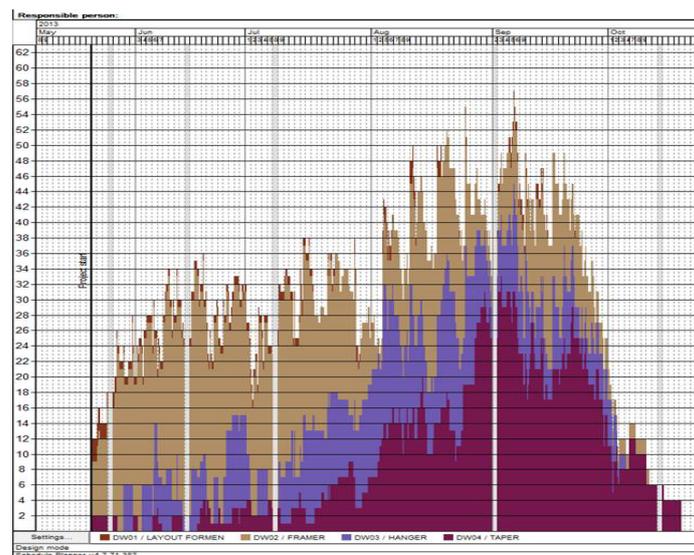


Figure 5: Resource Uses in Drywall Construction Activities in Phase II

CONCLUSIONS

The fine-grained work packaging and daily monitoring approach proposed in this study has shown the potential to reduce and proactively respond to workflow and progress variability. This study therefore provides factual evidence that work efficiency is not only subject to planning, but also likely subject to the level of detail of workflow monitoring, which, at the same time, enables a proactive and rapid response. Small work packages defined at the smallest identifiable work, i.e. task, proved for a complex healthcare facility to provide for a flexible work planning in front of unplanned constraints and events, and to enable flexible resource allocation during execution of tasks to ensure continuous utilization of work resources in a stable manner. Such results are valuable for an industry that is always requesting evidence of positive cost to benefit ratios prior to the adoption of new processes or technologies. From our experience in implementing this effort, the proposed planning approach could be extended to multiple activities for the benefit of the project –there appears not to be any potential scalability issues.

The authors also identified costs and challenges from implementing the fine-grained work packaging approach. Daily reporting and monitoring requires significant data collection efforts that could make unfeasible the implementation of the near real-time monitoring approach to all project activities, unless such data collection and analysis were automated. Processing and managing the collected data into a historical database requires additional efforts, though the authors perceive the long-term importance of building a historical database. Major barriers of realizing the value of fine-grained work packaging lie in the tedious manual process of data collection, analysis, and reporting. Future research should investigate the benefits and the investment costs to undertake the proposed approach, including investment into efficient and effective data collection technologies.

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