RELATIONSHIP OF TIME LAG BUFFER TO MATERIAL STOCKPILE BUFFER LEVELS

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ABSTRACT

This paper presents observations of buffer implementation and usage during the construction of a five-story, full-scale, reinforced concrete, earthquake test structure. Over 40 private industry partners performed a majority of the construction work in-kind, each covering a different scope of work. Activity durations were often longer than expected, particularly because research interests often resulted in changes in scopes of work for partners, sometimes requiring design work.

Due to the fluctuation between the initial baseline construction lookahead schedule developed early in the project, and the pace of actual construction, inventory often sat in the laydown area or in the workface area for lengthy periods of time. This was true even though a pull approach was used to coordinate activities.

A simulation experiment was used to determine the impact on inventory levels of activity durations exceeding planned durations. Because material lead times were on the order of the planning horizon, orders for upcoming activities were often made without knowledge of delays in intermediate activities, resulting in additional inventory time on the site. The simulation experiment exhibited a similar behavior, and showed that excess inventory levels increase rapidly with the degree to which actual durations extend beyond planned durations.

KEYWORDS

Buffers, production control, inventory control.

INTRODUCTION

The research described in this paper took place during the construction of the largest earthquake test structure ever constructed at an earthquake research facility located in San Diego, California. The research facility is dedicated to the construction and analysis of various test structures ranging in size from masonry shear walls, to wind turbines, to the 23m (75ft) test structure observed herein.

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Initial project planning began with the request and approval of a grant through the National Science Foundation (NSF), the California Seismic Safety Commission, and the Network for Earthquake Engineering Simulation. Several universities participated in the research, including the University of California at San Diego, San Diego State University, Howard University, and Worcester Polytechnic Institute.

The purpose of the research was to construct and test under simulated shaking a full-scale, multi-story building outfitted with a complete array of building non-structural component systems (BNCSs), in order to observe the static and dynamic behavior of the structure and of the BNCSs (Chen et al. 2012). A unique aspect of the test protocol was a live fire test conducted at the conclusion of the final earthquake test, to analyze the post-earthquake effects of a fire on the building fire prevention systems (FPS).

The majority of the grant support was used for instrumentation and graduate student support. The project had a limited budget for the execution of construction activities, relying almost entirely on private industry support for material and labor donations to cover most of the construction scope, especially in the BNCSs. The project experienced variation between planned and actual activity start times, primarily for two reasons. First, the building was built as a test subject, and as a consequence scope changes occurred frequently as new performance objectives or possible new BNCSs from new partners arose. Second, the funding mechanism for the building relied heavily on in-kind contributions of labor and materials, which produced an environment for performing the work different than the typical project.

INDUSTRY SUPPORT AND PROJECT CHARACTERISTICS

To date, over 50 private industry partners have contributed monetary, material and/or labor donations for the completion of a majority of construction activities. Industry supporters ranged from multinational corporations based far from the project site, to local industry suppliers and trade organizations in San Diego. The authors include those responsible for the construction management of the structure, and for the coordination of the installation of the BNCSs (Chen et al. 2012). An advisory board funded structural construction; however, the general contractor performing the structural concrete work provided it at a considerable discount to the project and made a monetary donation.

The in-kind nature of most of the work by partners introduced a change to the risk/reward dynamic as compared to "typical" construction. An implication of this was that the for-profit work in some partners' portfolios could sometimes take precedence over this project, especially if activity start times changed. Scheduling and activity coordination challenges were frequently encountered during construction due to the nature of the research objectives, as well as the realities faced when managing in-kind work. For example, in many cases labor was available in defined windows when the industry sponsor could make travel arrangements, and these windows could be very difficult to change.

The entire motivation for building this structure was to use it to test the earthquake performance of the BNCSs. This introduced additional complexity to the project. First, as the project developed, new partners were contacted or became aware of the project, and wanted to participate. Participation meant the opportunity to install elements of interest to the partner and obtain data about the performance of those elements. This occurred throughout the design and construction process, often requiring design changes. Further, the construction was conducted at an operating test facility. The shake table is but one of several testing devices at the site, and other tests at the site continued during construction. Some characterization testing also had to be performed on the test structure itself, especially after structural completion. As a consequence, it was common for construction activities to be interrupted for the execution of structural testing at certain intervals.

A pull approach to scheduling and coordinating work was adopted, but was challenging to implement in practice, especially for delivery lead times because durations and start times changed very frequently. Scheduling challenges were further compounded because duration estimates often proved inaccurate (and usually were optimistic), thereby prompting frequent updating of the schedule for distribution to industry partners. Contractors had to overcome these challenges while remaining flexible to absorb the possibility of additional scope based on evolving testing objectives. These challenges made the project an opportunity to observe activity and inventory behaviors in an extremely variable environment.

PROJECT SUMMARY

The building constructed for this research project was a five-story two-bay, cast-in-place reinforced concrete structure, with each floor having an area of approximately 60 m^2 (650 ft^2). The structure had a floor-to-floor height of 4.3 m (14 ft), for a total structural height of 22.9 m (75 ft) above the shake table. Roof-mounted equipment brings the total height to 26.8 m (88 ft). Structural design was completed according to current applicable codes, and BNCSs were installed to current codes and/or standards of practice. Floor penetrations were provided for stairs, an elevator, and a number of BNCS connections. Each floor slab was 203 mm (8 in.) thick, with four layers of grade 60 reinforcing steel.

The foundation for the structure was built atop the shake table, roughly at ground level. The foundation consisted of 1.5 m (5 ft) thick beams, and was attached to the table with high strength threaded rods. Underneath the table, computer-controlled hydraulic actuators can apply motions to a pre-recorded pattern (commonly based on an actual earthquake record) along one axis, with a peak acceleration of up to 1.2 g (with a 400 ton payload), a peak velocity of 1.8 m/s, and a maximum stroke of ±0.75m. After completion, the structure was tested with a number of simulated earthquakes, and subjected to fire testing to determine the post-shaking efficacy of the FPS. Additional information about the table is readily available (Restrepo et al. 2005).

BUFFER IMPLEMENTATION

A number of strategies for dealing with production variability have been used in the industry. In this project, variability was high, so it was possible to observe the impacts of that variability, and of the strategies used to address it. Pull planning sessions were conducted with project participants during the design phase, during the pre-construction phase, and at the end of the structural construction phase. The purpose of these events was to encourage communication among project participants (particularly among the partners conducting site operations), to obtain handoff requirements, and to obtain duration and lead time estimates. This paper will focus on the last of these objectives. Table 1 summarizes buffer observations for several key activities on this project, which were noted by the authors during execution of the project.

Table 1: Buffer Performance Observations during Construction Activities

Activity Description	Material Delivery Date	Pl'd Start Date	Est'd Dur.(w days)	Actual Start Date	Actual Duration (wdays)	% Diff. in Dur.	Invent. Dur.(cal. days)
Foundation Formwork	5/4/11	5/4/11	5	5/4/11	11	220%	0
HRC T-Headed Reinforcing Steel for Foundation	5/4/11	5/4/11	1	6/10/11	1	0%	37
DYWIDAG Tie-Down Rod and Post-Tensioning PVC Pipe	5/6/11	6/20/11	4	6/10/11	10	250%	35
Base Isolator Steel Bottom Plates *	5/13/11	5/16/11	1	5/16/11	4	400%	3
Temporary Steel Isolators *	5/19/11	5/23/11	4	5/20/11	8	200%	1
Stair Embeds	6/6/11	7/11/11	1	7/14/11	1	0%	38
Firestopping Cast In Device	6/6/11	7/15/11	1	7/14/11	1	0%	38
Foundation Post Tensioning Steel	6/7/11	7/25/11	4	9/23/11	5	125%	108
Foundation Reinforcing Steel	6/10/11	6/10/11	5	6/10/11	15	300%	0
Prefabricated Reinforcing Steel Column Ties and Column Erection	6/15/11	6/16/11	4	6/15/11	3	75%	0
Column Formwork First Floor	6/20/11	6/28/11	2	6/29/11	4	200%	9
Prefabricated Steel Stairs Floors 1-2	6/24/11	7/21/11	1	8/13/11	1	0%	50
Prefabricated Steel Stairs Floors 3-5	6/24/11	8/2/11	2	10/10/11	2	0%	108
Steel Embeds for Precast Cladding	7/13/11	8/1/11	1	8/2/11	1	0%	20
Elevator Installation	11/8/11	10/25/1 1	20	12/12/11	60	300%	34
HVAC Installation *	12/5/11	11/3/11	6	12/21/11	2	33%	16
Ceiling Installation Floors 1-2	12/5/11	11/7/11	5	1/17/12	3	60%	43
Ceiling Installation Floors 3-5	12/5/11	11/8/11	4	2/20/12	3	75%	77
Precast Cladding Panels *	12/19/11	11/8/11	5	12/19/11	4	80%	0
Base Isolator Installation *	12/23/11	1/9/12	8	2/27/12	4	50%	66

*Note: * indicates activity not included in original construction schedule due to subsequent change in scope. Activity dates and durations are based on the construction start date of April 1, 2011, from the original CPM schedule dated 4/1/2011 for structural construction activities (due to material delays affecting construction, schedule dated 7/8/2011 used), while NCS activities are based on the CPM schedule dated 10/14/11*

Construction management personnel, in order to compensate for potential delays and mishaps, often lengthen duration estimates (Gonzalez et al. 2006). Or, a contractor, knowing that a particular material is uncommon or has a long lead time, may order additional material if there is a likelihood that the material may not be readily procurable at a future date. These buffers represent inventory and thereby waste, which should be avoided (Koskela, 1992). Much has been written about the appropriate sizing of buffers (Alves and Tommelein 2004, Gonzalez et al. 2006, Horman and Thomas 2005).

Horman and Thomas (2005) investigated buffers and their impact on labor performance. They focused on material stockpiles, time lag buffers, and capacity buffers. They defined time lag buffers as the insertion of a deliberate pause between activities. They defined capacity buffers as the availability of production resources (such as labor or equipment) to be deployed to the project in response to the availability of work to complete. Gonzalez et al. (2006) discuss other ways time can be used as a buffer, including the deliberate over-estimate of an activity's duration. All three of these buffers could occur at any point in time as well as simultaneously. The function of buffers to absorb variability between construction activities, or shield downstream activities from variability, has been well documented (Ballard & Howell, 1998).

Clearly, activity durations were often different than original estimates (Table 1). In some cases estimates were optimistic (too short compared to actual), and in other cases they were pessimistic (too long compared to actual). One consequence of this was longer than expected time periods for inventory to be stored on the site. Figure 1 shows the cumulative inventory-days for all activities in Table 1. An inventory-day was defined as the inventory for a given activity stored on the site for one day, which allowed addition of inventories of materials with different native units. Partial inventory-days were tracked as inventories were consumed during activities.

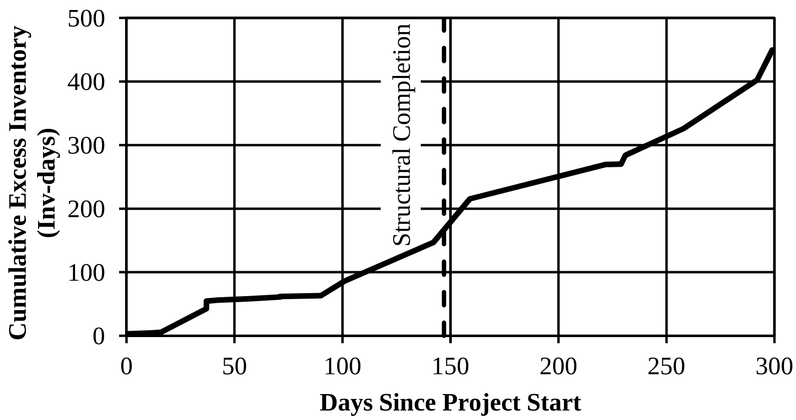

Figure 1: Excess Inventory On Site Based on Table 1 Activities

Typically on this project, inventory to support a given activity was designed to arrive with a time lag buffer of 1 to 2 days. Once ordered, an actual (rather than estimated) lead time became known, and these too were often different than estimated values. When activity starts were delayed, commonly the delivery date for materials on order could not be readily adjusted to accommodate that change. As a consequence, for many activities there was inventory on site longer than planned. On this project, arrival times and inventory levels for activities were recorded. While Tommelein et al. (1999) showed that negative variations in duration for activities may not benefit system duration, Figure 1 shows that negative variations also do not benefit the inventory levels for the system. The consequences of the excess inventory were significant on this project, because space was quite limited. Inventory storage at this site could be described as categorized by Thomas et al. (2005)

- Semi-permanent (outside) storage area– sometimes called a laydown area, where materials are stored prior to being used in the project (Figure 2).
- Staging area – usually next to the exterior of the building, where materials are located prior to being hoisted into the building (Figure 3).
- Workface – an area inside the building convenient to where the work takes place (Figures 4 and 5).

Figure 2: Concrete Shoring Stockpiled in Semi-permanent Area

Figure 3: Concrete Formwork Stockpiled in Staging Area near Building

Figure 4: Wall Framing Materials Stockpiled at the Work Face

Figure 5: Material and Equipment Storage Confines due to Limited Floor Space in Workface Area

The increase in inventory shown in Figure 1 results from project management taking into account the planned start date of an activity, plus any lead-time in material delivery, as well as the addition of a time-lag buffer. If, for example, an activity encounters a delay *after* assets have been ordered, then an excess accumulation of inventory will be the result. The negative effects of having inventory on site are well known, ranging from wasteful double handling to loss of material due to damage. Due to the limited floor space, material had to be offloaded in the semi-permanent area until space was made available in the staging area, then hoisted to the workface. This resulted in double handling for almost every piece of material delivered to the site. In order to better understand this behavior, a simulation experiment was conducted.

SIMULATION EXPERIMENT

A simple project consisting of 4 activities was used for this experiment (Figure 6). Each activity was assumed to have two assets needed in order to conduct the activity. For this simulation, assets represent physical goods, not labor or equipment. Each activity has an estimated duration and each asset has an estimated lead time, all assigned at the beginning of the simulation. These values represent the expected values for planning purposes as construction starts, the sorts of values that were used to allow partners to make initial travel plans or try to free up crews for time windows when they would be needed. Estimates of times were assigned stochastically, by a random draw from a triangular distribution. Both activity durations and order lead times were assigned based on a triangular distribution having a 90% probability of producing a value between about ½-1 work week, and a 10% probability of a longer duration (on the order of 2 weeks for order lead times and 1.5 weeks for activity durations). These values are generally in keeping with the observations in the project.

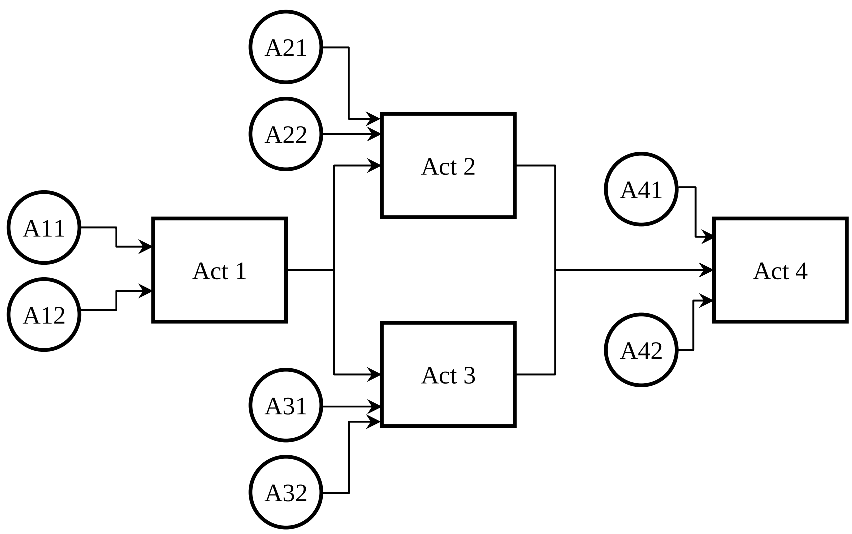

Figure 6: Simulation Experiment Network

Once lead time and duration estimates were in place, it was possible to develop an initial schedule. The earliest time at which an asset (A_{ij} in Figure 6, where i represents the related activity number and j the asset number) needed to be ordered was selected as the project "start." Items were ordered as needed in the first week of the project, based on their estimated lead times. Once the orders were *actually* placed, new lead time information was developed, and a new lookahead plan could be developed. Based on that, work that could be conducted in that week was started.

This process was repeated each week. A lookahead plan was consulted to see, based on the estimated durations and lead times, what work would be ready to start. Once activities were started or orders were made, new duration or lead time information was made available. However, as experienced on the subject project, even if delivery lead times proved shorter than initially planned, or predecessor activities became ready earlier, activities were not moved up to start dates earlier than that shown on the lookahead plan.

The simulation was run 1,000 times for a given set of conditions, in order to develop some statistical sense of parameter dependencies. The specific parameter under consideration in this particular case was the accuracy of the duration estimates used in the project. In order to consider this impact, a factor was applied to the durations assigned to activities when they actually started. The same distribution was used for the actual durations as the initial estimated or planned durations, but the random draw from that distribution was then multiplied by the factor. For example, for a factor of 0.8, the randomly assigned actual duration would be drawn from the same distribution as used for the planned duration, and then it would be multiplied by 0.8. This means that the actual duration for any given activity in any given simulation could be longer than planned, but on average the actual durations would be 80% of the planned durations, which would represent pessimistic (or possibly "conservative") duration estimating. Figure 7 shows the relationship between inventory levels and the actual/planned duration factor.

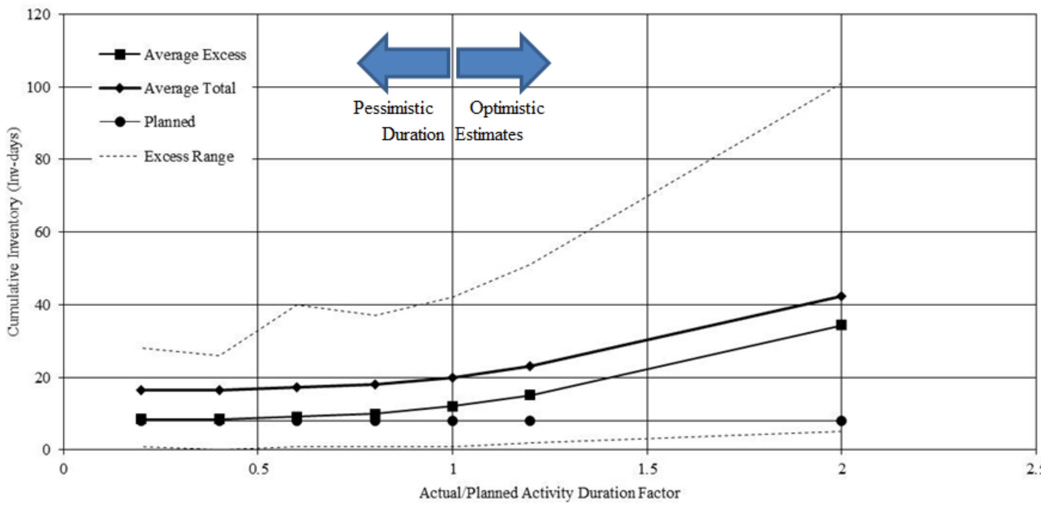

Figure 7: Cumulative Inventory Levels Versus Actual/Planned Duration Factor for Network Simulation Shown in Figure 6

On Figure 7, the total inventory level in inventory-days is composed of two parts: planned and "excess." Planned inventory days are based on an order time lag, built into the planning system. For purposes of this simulation, the objective was to have materials on site for one day before the related activity would start; since there were 8 assets in the simulation this corresponds to 8 inventory-days, one for each asset. "Excess" inventory was defined as those inventory-days over and above the planned level.

The impact of work flow variability on project performance is well-known and has been studied for some time (e.g., Tommelein et al. 1999). The parade game shows that positive variations in duration of work that flows in a linked production system can add to the overall process time, but negative variations cannot easily be captured. Figure 7 shows that something similar occurs for inventory levels. Increases in duration tend to drive up the total number of inventory-days on the project, as materials delivered to a a particular activity's target start time end up having to wait out delays. However, when duration estimates are optimistic, for a project like this it was very difficult for partners to respond to an earlier arrival date, typically because of planning needs for the availability of labor. As a result, inventory-days tend to only grow compared to planned levels when durations increase, but not to diminish when durations decrease, as observed in the field.

Note that Figure 7 shows that, as the degree of optimism in duration estimating increases, excess inventory days increase, and the rate of increase accelerates. In addition, the range of inventory levels (shown as dashed lines on Figure 7) also tends to increase dramatically. However, in no case did inventory levels decrease, as shown by the positive sign on the minimum values of the range.

CONCLUSIONS

This paper reports the inventory levels observed during the construction of a test structure for simulated earthquake shaking. Material buffers during the construction phase were observed to be much larger and to have much longer durations on site than originally planned. In addition, many activities had durations that exceeded the expected durations developed in pull planning sessions at earlier stages in the work.

Tracking of material buffer levels demonstrated that excess inventory tended to grow throughout the project life cycle. A simulation experiment demonstrated that the results observed were to be expected, and that both inventory levels and the variability of inventory levels can increase rapidly as duration estimates become more optimistic. Additional study of the excess inventory growth problem should be conducted, and seems to lend itself to a simulation approach.

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