

Spring 2017

Comparing Critical Chain Project Management with Critical Path Method: A Case Study

Behzad Montazeri

Western Kentucky University, behzad.montazeri393@topper.wku.edu

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COMPARING CRITICAL CHAIN PROJECT MANAGEMENT WITH CRITICAL
PATH METHOD: A CASE STUDY

A Thesis
Presented to
The Faculty of the Department of Architectural and Manufacturing Sciences
Western Kentucky University
Bowling Green, Kentucky

In Partial Fulfillment
Of the Requirements for the Degree
Master of Science

By
Behzad Montazeri

May 2017

COMPARING CRITICAL CHAIN PROJECT MANAGEMENT WITH CRITICAL PATH
METHOD: A CASE STUDY

Date Recommended 4/13/2017

A. Mark Doggett
A. Mark Doggett, Director of Thesis

Shahnaz Aly
Shahnaz Aly

Neal A. Downing
Neal A. Downing

T. Lattin
Dean, Graduate School

4/18/17
Date

I dedicate this thesis to my parents and my brother, who I miss dearly and supported me in all of my endeavors.

ACKNOWLEDGMENTS

Most of all I extend my appreciation to my thesis committee, in support of earning my graduate degree and completing my thesis. Also, I would like to express my gratitude to the faculty of Architectural and Manufacturing Sciences at Western Kentucky University.

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COMPARING CRITICAL CHAIN PROJECT MANAGEMENT WITH CRITICAL PATH METHOD: A CASE STUDY

Behzad Montazeri

May 2017

57 Pages

Directed by: A. Mark Doggett, Shahnaz Aly, and Neal A. Downing

Department of Architectural and Manufacturing Sciences Western Kentucky University

Scheduling is a major task in project management. The current scheduling technique, Critical Path Method (CPM), has been widely applied for several decades, but a large number of projects fail to be completed on time and schedule delays occur in many projects. This raises question about the validity of the current project scheduling system. Critical Chain Project Management (CCPM), derived from Theory of Constraints, is a relatively new alternative approach toward scheduling projects. This study compared CCPM and CPM to determine which scheduling method delivers a shorter project duration and has a better usage of resources. A scheduling software called ProChain was used to reschedule a CPM based construction project using CCPM. The study concluded that the CCPM has the possibility to deliver shorter project duration and better resource usage in comparison to CPM. It was revealed that ProChain has limitation in the process of transforming a CPM schedule to a CCPM schedule. For example, ProChain treats any tasks without any predecessor as a project terminating task and puts a project buffer after it.

Introduction

Project management changed substantially between 1950s and 1960s with appearance of the Critical Path Method (CPM) technique for scheduling. Despite the fact that CPM and the invention of computers enabled the success of Apollo, projects almost always seem to be behind schedule. Although the advance of personal computers has brought sophisticated scheduling techniques, there has been little progress in improving the on-time delivery of projects (Leach, 2014; Umble & Umble, 2000).

An alternative scheduling method to CPM, offered by Dr. Goldratt, is informally known as Critical Chain. Created by Dr. Goldratt based on his Theory of Constraints, CCPM pulls out self-embedded safety-times (contingency) in tasks and puts them at the project level. A growing number of companies implementing this project scheduling methodology have reported success. For example, Harris Corporation, by applying critical chain concepts, was able to complete the project of building the first eight-inch wafer facility in less than 14 months with activities, such as construction of the facility, installing new equipment, and training new workers. The industry norm for this type of project is between 28 to 36 months (Umble & Umble, 2000).

Problem Statement

In 1990, the Department of Energy (DOE) began implementing reforms to strengthen its project management practices. Although the DOE has taken many steps to improve its project management practices, they still experience significant problems completing projects on time. In 1996, the DOE reported schedule slippage in at least half of its 34 ongoing projects. In 2009, the DOE showed a cumulative delay of 45 years for its ongoing construction projects. A list of delayed projects follows:

1- Reports from March 2012 showed eight to 12 years of delay from the initial plan for the construction of a chemistry and metallurgy research replacement nuclear facility.

2- Reports from December 2012 showed nearly a decade of slippage from the initial plan for construction waste treatment and immobilization plant.

3- In 2013, the DOE reported three years of delay in the start of operation of a Mixed Oxide (MOX) fuel fabrication facility and two years of delay in the start of operation of Waste Solidification Building project in South Carolina. DOE noted that most schedule delays are attributed to the inconsistent usage of project management tools and techniques (GAO, 2013). The constant delays in projects deliveries raise the suspicion that conventional techniques widely used to schedule projects are conceptually flawed (Umble & Umble, 2000).

Significance of Research

Globalization has increased the intensity of competitiveness in business. The increased number of competitors and networked firms working in collaboration to design, build, sell, and support new products and services has made development speed a critical factor for success. This matter makes project scheduling a key issue in project management (Cerveny & Galup, 2002). Goldratt asserted in his book *Critical Chain* that time is more important than cost for project managers and empirical studies support his claim. Studies have concluded that a project that is on-time, but over-budget by 50 percent, will earn four percent less. Studies have forecasted that a project that is late by six months, but on-budget, will earn 33 percent less than an on-time project. These facts demonstrate the strategic importance of reducing project time (Hoel & Taylor, 1999; Goldratt, 1997).

A successful project is a project that satisfies three necessary conditions. The first necessary condition is scope. It sets a minimum standard for the project results while cost and schedule are the second and third necessary conditions usually setting the maximums. These necessary conditions are interdependent. Projects that take longer to complete cost more and also increase the opportunity for change of the project scope. Projects that cost more take longer to complete and the more changes to scope, the more cost and length of the project. Therefore, it is a benefit to finish projects as soon as possible (Leach, 2014). Improving construction scheduling and shortening the length of the projects results in better usage of human resources and efficient usage of financial resources. Improving resource usage creates the possibility of executing more construction projects within a certain period of time (Budd & Cooper, A project Management approach to increasing agency margins, 2004).

Scheduling a project is a critical task for successful construction project management. Commercially available project management software packages for scheduling use the bar chart, the Critical Path Method (CPM), and the program evaluation and review technique (PERT) for scheduling analysis. In general, CPM is the first choice for scheduling purposes. CPM identifies the critical path and the total length of a project. As mentioned before, one of the pitfalls of CPM is its neglect of resource contention, making the produced schedules unreasonable. In order to address this issue, CPM uses resource leveling techniques, resulting in suboptimal schedules. The critical chain scheduling technique, derived from the theory of constraints, is an alternative to CPM scheduling and can make scheduling more effective (Lu & Li, 2003).

Statement of Purpose

This study compared the CPM and CC scheduling methods in the construction industry by transforming the schedule of a project that originally used CPM scheduling method with the CC scheduling method instead. This study looked at the concepts and methodology of CPM and CC scheduling methods, the differences between CC scheduling and CPM, and the project duration difference between using these two methods for a construction project.

Research Questions

Goldratt's book *Critical Chain* applied his theory of constraints to project management by developing a method for scheduling projects that cuts project times. Goldratt believed that estimate times are inflated and carry safety times embedded in each of them that results an increased duration of the project. Goldratt suggested that project times can be decreased by using 50 percent expected activity times instead of using inflated times and adding a project buffer to the end for estimating errors in activity task times (Hoel & Taylor, 1999; Goldratt, 1997). This study examined the claim of CC scheduling, which is the reduction of the project time using CC method instead of CPM by answering these questions:

- 1- Which scheduling method delivers the shorter planned project duration in this study?
- 2- Which scheduling method makes the most efficient usage of time in this study?

Efficient usage of time was measured based on man-hours consumed. A Spent man-hour is the actual man-hour spent on site during the execution of any given activity (i.e. actual work in the MS Project software).

Assumptions

- Each task within a project is statistically independent.
- The selected project is executed in a single project environment.

Delimitations

This study is conducted under the following delimitation:

- This study is a project for which original execution plan was about 7 months.

Limitation

This study is limited by the following:

- The resulting critical chain schedule was not going to be executed; hence, the practicality of the created schedule is unknown.

Definition of Terms

Buffer: Time or budget allowance used to protect the scheduled delivery dates on a project.

Critical Activity: An activity located on the critical chain

Critical Chain (CC): The longest set of dependent activities, with explicit consideration of resource availability, to achieve a project goal.

Critical Chain Project Management (CCPM): The system of project schedule planning and execution deployed by Theory of Constraints practitioners including the critical chain schedule, buffer management, and pipelining for multiple projects, but not including many or most features of professional project management as codified by the PMBOK (Leach, 2014).

Critical Chain Schedule (CCS): A late finish schedule controlled by the critical chain, including a critical-chain completion buffer (project buffer) and feeding buffer.

Critical Path (CP): The longest sequence of activities in a network. Usually, a sequence with zero float.

Critical Path Method: The original innovation in using networks and defining a critical path.

Early Finish (EF): The earliest day on which an activity can finish.

Early Start (ES): The earliest day on which an activity can begin.

Feeding Buffer: A time buffer at the end of a project activity chain that feeds the critical chain.

Float or Slack: The amount of time that a task in a project network can be delayed without causing a delay to subsequent tasks ("free float") or the project completion date.

Late Finish (LF): The latest day on which an activity can finish without prolonging the project duration.

Late Start (LS): The latest day on which an activity can begin without prolonging the project duration.

Literature Review

Critical Path Method: Traditional Method for Managing and Scheduling Projects

The most common used scheduling method is the Critical Path Method (CPM), which was originally developed by two companies, DuPont and Remington Rand in the 1950s. Current project management body of knowledge and project management practitioners consider CPM as the primary scheduling procedure. Computer software using CPM are widely available with capability of handling projects with thousands of activities. The critical path by itself is representative of the longest possible path within a network of processor/successor activities. Critical path duration represents the minimum time that is required to complete a project. Delays in the critical path will result in an increase of time required to complete the project. It is possible for a project to have more than one critical path (Hendrickson & Au, 1989; Weber, 2005).

The process of creating a critical path method network. Creation of a CPM scheduling network for a project starts by listing the activities that need to be executed to complete the project and determining their logical relationships. Four types of relationships exist between activities: finish to start (FS), start to start (SS), start to finish (SF), and start to finish (SF). CPM allocates a specific duration to each task. Arranging the tasks based on their logical relationship, the sequence with the longest duration will be determined as the critical path (CP). This path determines the project length and alteration of the duration of tasks located on this path will cause changes in the project duration. In a project, more than one path through the network may be the longest path, but one will be selected as the CP. The other paths must be either equal in length or shorter than this path. It should be noted that the alteration of task durations in paths that

have equal length as the CP may result in change of the CP. Figure 1 is an example of a CPM network. The critical path for this network is ADFGJK. Each node in the figure has several boxes with numbers showing a different aspect of each particular task (refer to the legend). In the process of creating this chart, unlimited resources were considered (Hendrickson & Au, 1989; Weber, 2005; Kerzner, 2009). After creation of the network, the resources are allocated and dependence to resource contention of the network is rescheduled. This process is known as resource leveling. In general, the result of rescheduling is a longer critical path. Project managers make every attempt to reallocate resources to find the shortest critical path, but unfortunately this is not an easy task, considering that float times were not intentionally planned as safety (Kerzner, 2009).

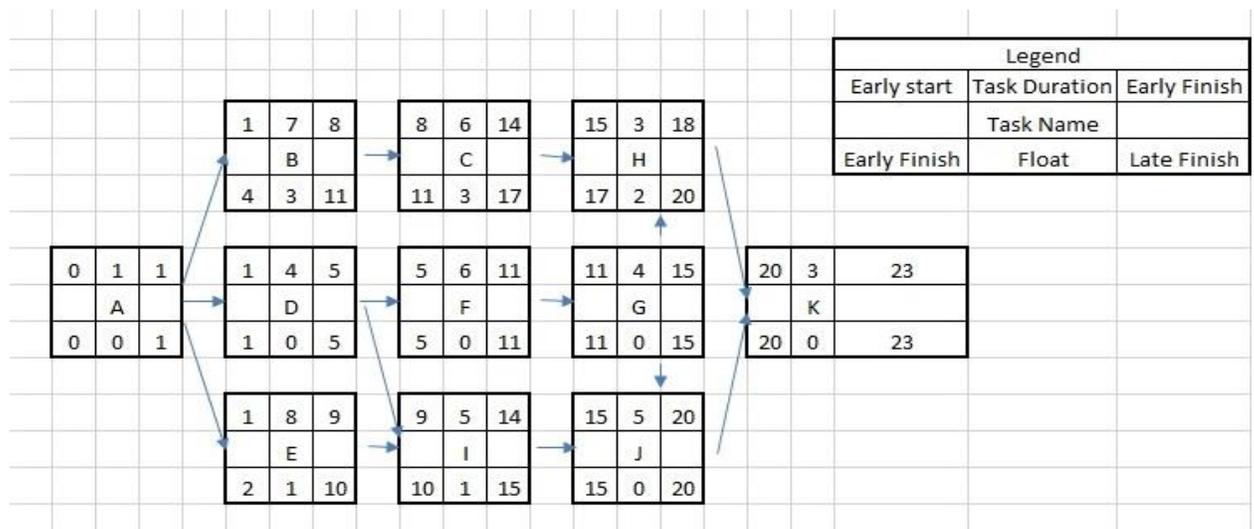


Figure 1. Standard Critical Path Method Logic Method.

Resource contention is often a major problem in projects. CPM assumes unlimited availability of resource, which is an invalid assumption in the real world. In practical situations, the amount of resources available are finite and these resources are shared by activities or projects. CPM schedules the project based on the dependencies of the tasks

and afterward allocates resources to each task and performs resource leveling. The hidden assumption for this way of scheduling is the existence of an acceptable way to account for resource contention and resource leveling. In order to overcome this drawback, analytical and heuristic techniques for resources leveling in a CPM network plan have been developed. Although many algorithms exist for resource leveling, there is no optimum method for resource leveling. Algorithms with the aim of finding the shortest CPM schedule face a combinatorial explosion problem in mathematics. An alternative approach is to use heuristic methods that apply priority rules based on activity characteristics. The result may satisfy the logical and technical aspects of the project, but it is not optimal to achieve the shortest project duration. In most cases, application of the resource leveling algorithms lengthens the overall schedule (Leach, 2014; Lu & Li, 2003; Umble & Umble, 2000; Yang, 2007).

There are several methods to decrease the length of the rescheduled critical path, but each carry their own difficulties and are not always practical (Kerzner, 2009). These methods are mentioned below.

- Transferring resources from tasks with float to tasks located in the critical path. This may cause the changing of the non-critical task to a critical task. In addition, the resources that are used in different tasks are not always the same.
- Elimination of some parts of the project. This means changing the scope of the project, which is not an option in most cases.
- Addition of more resources (i.e., crashing). This method increases the cost of the project.

- Increasing the number of work hours per day. This method also increases the cost of the project and is not always an option.

Another down side of CPM scheduling is consideration of having fixed time for activities. This consideration stems from the assumption that the productivity of a given resource is stable. Practical observation shows that productivity varies considerably, especially in the construction industry (Jaafari, 1984).

Jaafari (1984) mentioned the following as the arguments against CPM in construction projects:

- 1- CPM does not satisfy the planning needs of construction projects.
- 2- The assumption that project activities have fixed and discrete natures is untrue, especially in projects with repetitive or linear activities.
- 3- Construction planning essentially involves giving equal attention to all processes critical (cost wise) and not just determining an incidental path related to the activity duration.
- 4- Resource allocation, smoothing or leveling procedures are incapable of ensuring full continuity for production crew or processes, which are the backbone of operational planning in construction process, especially in repetitive cases.
- 5- Even with electronic advancement, CPM scheduling is expensive to run. Status reports take time to reach managers and decision makers and are not updated on a real time basis, and by the time they receive their information tend to be outdated
- 6- Practical integration of CPM-based progress and cost control has been extremely difficult, expensive, and non-productive.

An Alternative Approach

Another approach to scheduling projects is the Critical Chain Project Management (CCPM) method, derived from Theory of Constraints (TOC). CCPM recognizes the importance of resource contention and defines the critical chain (CC) as the sequence of dependent events that prevents the projects from completing in a shorter interval. Resource dependencies determine the critical chain as much as task dependencies. CCPM scheduling considers dependencies a result of usability of resources in advance, not just their logical relationships (Leach, 2014; Yang, 2007). CCPM also suggests that delays in project deliveries stem from human behavioral issues, such as multitasking, student syndrome, Parkinson law, and sandbagging (Budd & Cerveney, 2010; Leach, 2014).

Multitasking. In traditional management, human resources are allocated to more than one task. This act is known as multitasking. This phenomenon resulted from the fast-paced, technologically-driven world. Traditional management encourages multitasking and assumes it increases productivity. Although simulations such as the Tony Rizzo's bead game demonstrate that application of multitasking prolongs completion of projects. The reason for such prolongation is the required time by the human resource to re-familiarize themselves with the task, or in operational terms, the set-up time. This set-up time would not be needed if the resource would have continued executing a particular task till it was finished. Multitasking also induces additional stress on resources (Adler & Benbunan-Fich, 2012; Rubinstein, Meyer, & Evans, 2001; Roggenkamp, Park, & Tsimhoni, 2005; Budd & Cerveney, 2010).

Student syndrome. The name student syndrome is derived from the student behavior for procrastination. For example, students request an extension for an assignment that is two weeks away while in best case scenario, they start the assignment only few hours before it is due. This potential behavior not only applies to students, but to every human. Figure 2 shows typical human resource behavior towards an allotted task. Having been allotted a task, the human resource normally and after a short period of time, tries to save or reserve their work effort. Finding out that the allotted task will not be done at the designated time, there is a break point in the behavior of the human resource. Increasing stress leads to the tension of the resource (Bartoska & Subrt, 2012; Budd & Cervený, 2010; Leach, 2014).

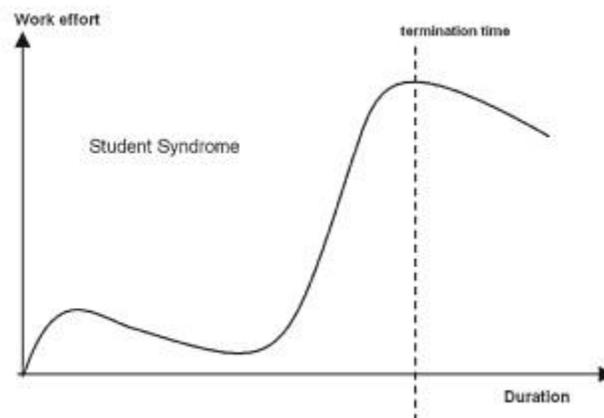


Figure 2. The variability of work effort during the “Student Syndrome”. Adopted from “The effect of human agent in project management,” by J. Bartoska, and T. Subrt, 2012, *Central European Journal of Operations Research*, 20(3), p.372. Copyright 2011 by Springer-Verlag.

Parkinson’s Law. Few people force themselves to carry out tasks in the shortest period of time using the maximum effort available (road-runner ethics). Human resources, due to their natural character, are inclined to reserve their vital energy during work effort. They are not motivated to surpass their natural behavior unless they are

exposed to some sort of stress from loss of profit (Bartoska & Subrt, 2012). This behavioral issue of human resources to expand work so as to fill the time available for its completion is known as Parkinson's Law. Krakowski (1974) pointed out that the slack of project activities in the CPM scheduling network may eventually be absorbed by Parkinson's Law effect. In many cases, this elasticity of work in its demand on time is a major cause for project delays (Gutierrez & Kouvelis, 1991).

Sandbagging. In many cases, a resource that finished a task early avoids turning it in. The reason for such behavior may include the discounted task duration for future activities or the fear of additional assigned work. Therefore, most experienced resources avoid turning in a finished work early and will only turn it in on the due date. This act is similar to Parkinson's Law and will extend a task to consume its full allotted time. Therefore, any embedded safety in the task duration will be consumed and will not be passed on to the next activities (Budd & Cerveney, 2010).

Critical Chain Project Management

Theory of Constraints (TOC) was initially introduced by Goldratt in his book *The Goal*. TOC is based on the principle that every system has a weakest link (constraint or bottleneck) that affects throughput. Total throughput of the system is dependent on this constraint; otherwise, the throughput will increase. TOC is a management technique to continuously improve the systems' performance. TOC offered five steps for continuous improvement of systems. The five focusing steps of TOC are:

- 1- Identify the constraint
- 2- Exploit the constraint
- 3- Subordinate everything else to the constraint

- 4- Elevate the constraint
- 5- Prevent inertia from becoming the constraint, repeat the process (Goldratt, 1986; Yang, 2007).

CCPM was introduced by Goldratt in his book *Critical Chain* in 1997. CCPM methodology was the application of Dr. Goldratt's Theory of Constraints to project management. This method gained attention among practitioners as a method for resource scheduling in projects. What differentiates CCPM scheduling is its attention to both precedence and resource dependencies. This distinguishes CCPM from CPM, which is based only on technological relationships and does not consider resource availability (Tukel, Rom, & Eksioglu, 2006; Goldratt, 1997).

In the project management environment, the goal is to complete the project as soon as possible; hence, the constraint that dominates the project is the CC. The duration of the project is the aggregation of critical chain activities' duration. CCPM challenges traditional CPM management as being impractical by not considering resource contention and embedding too much contingency in each individual task. CCPM takes out individual contingency and allocates a contingency time (project buffer) at the end of the project. This is why the duration of a CC schedule may be shorter than a CPM schedule. CC scheduling concentrates all the safety time at the end of the project to protect the target date against variations and maintain focus on critical activities (Yang, 2007).

CCPM considers that the original duration of tasks are estimates on the likelihood of 90 to 95 percent and they should be reduced to the point where the likelihood is 50 percent. This pooled safety time or contingency from individual tasks can be allocated at the end of the project. It should be noted the project buffer is part of the project schedule

and duration (Raz, Barnes, & Dvir, 2003; Blackstone, Cox III, & Schleier Jr, 2009).

CCPM provides the following as the rationale for decreasing the original duration:

- 1- Every activity in the project is exposed to some degree of variation
- 2- Task/activity owners provide estimates containing a margin of contingency to ensure that they complete the task on time
- 3- In many cases, the activity will be completed sooner than its due date and will not require the entire contingency margin
- 4- Since protection times are embedded within tasks; if it is not needed, it is wasted. The next activity will not start till the scheduled time due to unavailability of resources. Therefore, when it becomes apparent that the embedded safety time is unnecessary, the incentive for finishing the activity early will vanish (Parkinson law). On the other hand, any delays in the completion of the tasks on the critical chain propagate to the successor tasks. Hence, gains are lost, delays are passed on in full. Even if there is enough safety time hidden within tasks, the project is likely to be late
- 5- CCPM does not split attention among numerous tasks (multitasking). Empirical studies shows that multitasking increases each task duration (Raz, Barnes, & Dvir, 2003).

Assuming each task is statistically independent, half of the tasks will be completed after the 50 percent and half before; therefore, CCPM suggests that the project buffer can be less than the sum the contingency margins of the individual tasks. It is unlikely that all the tasks on the critical chain be completed after their 50 percent mark; hence, the protection against uncertainty is improved by combining all the hidden contingencies embedded in individual tasks. This matter can be supported by a statistical theory that the standard deviation of the sum of a number of mutually independent

random variables is less than the sum of the individual standard deviation. This process can be executed on the non-critical chain activities (Raz, Barnes, & Dvir, 2003).

In a CCPM schedule, three types of buffer exist to protect the target date from variations. The project buffer protects the project date completion. The feeding buffer protects the critical chain against disruption from other chains. The resource buffer is for notifying the scheduler of a new resource being employed on the critical chain. Many techniques exist for determining the buffer length. Determining a reasonable buffer is an important task. Large buffers generate a schedule that resemble the traditional CPM schedule and short buffers fail to protect the schedule from variations (Yang, 2007; Newbold, 1998).

Buffer Sizing

Cut and Paste Method (C&PM). The most important buffer is the project buffer, because it protects the project schedule from uncertainty. As rule of thumb, Goldratt proposed 50 percent of the Critical Chain duration as the project buffer and half of the non-critical chains' duration that join the Critical Chain as the feeding buffer. This is a linear approach to buffer sizing and as the duration of the project increases, the length of the project buffer increases. Using the 50 percent rule may lead to allocation of an unnecessarily overestimated project buffer, but the advantage is its simplicity. This method is known as the Cut and Paste Method (C&PM) (Ashtiani, Jalali, Aryanezhad, & Makui, 2007; Goldratt, 1997; Herroelen & Leus, 2000; Tukel, Rom, & Eksioğlu, 2006; Newbold, 1998).

Root Square Error Method (RSEM). The Goldratt's approach is probably sufficient for most purposes; although, Newbold (1998) offered a more realistic approach

for buffer sizing considering the risk variation that exists among tasks. His approach assumed a lognormal distribution for the probability of a task completion. Also, it assumed that a task should be completed within the worst-case duration estimates around 90 percent of the time. The difference between the average expected duration and the worst-case duration will be approximately two standard deviation. If w_i is the worst-case duration and a_i is the average duration, the standard deviation would be $(w_i - a_i)/2$. Considering that Central Theorem applies, the sum of distributions will be normally distributed. Assuming the required buffer that is two standard deviation, the buffer will be:

$$2 \times \sigma = 2 \times \sqrt{((w_1 - a_1)/2)^2 + ((w_2 - a_2)/2)^2 + \dots + ((w_n - a_n)/2)^2} \quad (1)$$

This approach is known as Root Square Error Method (RSEM). It should be noted that these calculations are very approximate and further modification based circumstance may be required for adjusting the buffers sizes (Newbold, 1998).

Modified RSEM. However, the assumption that difference between the average expected duration and the worst-case duration will be approximately two standard deviation will not hold (Herroelen & Leus, 2000). To resolve this matter, Ashtiani et al. (2007) suggested replacing the denominator in the standard deviation formula with 1.3 as a more realistic approach. The resulting formula was:

$$2 \times \sigma = 2 \times \sqrt{((w_1 - a_1)/1.3)^2 + ((w_2 - a_2)/1.3)^2 + \dots + ((w_n - a_n)/1.3)^2} \quad (2)$$

The common assumption in the previous buffer sizing methods is that 50 percent of the safe estimate corresponds to variability in task duration. Although this 50 percent is not a reflection of variability since the distribution of task durations is typically skewed to the right. It is possible that the actual task duration would be much longer than

predicted. While there might be more instances of shorter than predicted durations, these deviations will be relatively small. Therefore, in process buffer sizing one should be explicit about the underlying assumption regarding task duration (Goldratt, 1997; Tukel, Rom, & Eksioglu, 2006).

In the cases where the resource usage is close to the total resource availability, the probability that a delay will occur increases; therefore, larger buffers should be allocated to protect the due dates. Similarly, for a given number of tasks, when the number of precedence activity relationships increase, the probability of a delay increases. Since the tasks are more interrelated in this case, any delays in a task will affect all of its successors. Thus, the buffer size should be increased (Tukel, Rom, & Eksioglu, 2006).

Adaptive procedures. The buffer sizing method that takes into account the project characteristics, level of uncertainty, resource utilization, and network complexity are adaptive procedures. Adaptive Procedures with Resource Tightness (APRT) considers resource tightness, which is represented by Resource Factor (RF). It is a utilization factor. RF is the ratio of total resource usage to the total resource availability for each resource. Network complexity is represented as the ratio of the total number of precedence relationships to the total number of tasks (Tukel, Rom, & Eksioglu, 2006).

Assuming $r(i, q)$ is the resource usage of activity i for resource type q ; d_i the duration of activity i ; $Rav(q)$ is the availability of resource type q ; T is the length of the critical chain; and VAR_i is the variance of activity i . For each feeding chain:

$$RF(q) = (\sum_i r(i, q) * d_i) / T * Rav(q); \text{ For each resource type } q \quad (3)$$

$$r' = \max_q \{RD(q)\} \quad (4)$$

$$K = 1 + r' \quad (5)$$

$$SUM = 0 \quad (6)$$

For every activity i on the longest path terminating at the critical chain:

$$SUM = SUM + VAR_i \quad (7)$$

$$BUFFER\ SIZE = K * sqrt(SUM) \quad (8)$$

The Adaptive Procedure with Density (APD) assumes $TOTPRE$ is the total number of precedence relationship on a sub-network that feeds the critical chain and $NUMTASK$ is the total number of tasks on the subnetwork (Tukel, Rom, & Eksioglu, 2006). For each feeding chain the K is:

$$K = 1 + (TOTPRE/NUMTASK) \quad (9)$$

$$SUM = 0 \quad (6)$$

For every activity i on the longest path ending by feeding to the critical chain:

$$SUM = SUM + VAR_i \quad (7)$$

$$BUFFER\ SIZE = K * sqrt(SUM) \quad (8)$$

In the process of selecting the buffer size, a project manager should consider selecting a method that results in a shorter project completion schedule, but also one that can be met with a high degree of probability. Simulations comparing C&PM, RSEM, APRT, and APD (not the modified RSEM) indicated that the C&PM and RSEM methods perform well in terms of probability of meeting the target due date, but buffer sizes are considerably larger, especially with C&PM. C&PM is considered to be a good enough method due to its simplicity, but simulation studies indicated that C&PM schedule is 17 to 25 percent longer than either of the adaptive methods (APRT and APD). Adding large

buffers to the project schedule push the target due date further to the future, but the probability of passing the due date only decreases marginally. In a project environment where the uncertainty level is relatively low, adaptive procedures are good choices, but in high uncertainty environments, specifically large projects, the probability of meeting on-time completion can be as low as 60 percent. The RSEM holds the middle ground between C&PM and adaptive procedures (Tukel, Rom, & Eksioglu, 2006; Bie, Cui, & Zhang, 2012).

In most buffering methods, all activities in the project are assumed to be independent of each other. However, this is an unrealistic assumption because effects of resource sharing and common environmental risk factors on some activities is inevitable. Uncertainty of the project increases as the duration of these risk-related activities tend to vary together. Therefore, previous approaches may underestimate the required buffer size to protect the target due dates. Adaptive procedure with Activity Dependence (APAD) considers these dependencies and calculates buffer size differently (Bie, Cui, & Zhang, 2012). Assuming:

- N is the total number of activities in the critical chain
- M is the number of the activities affected by the risk factor in the critical chain
- K_i is the percentage of uncertainty if duration activity i explained by the risk factor
- VAR_i is the variance of the duration of activity i .

For each feeding chain, the longest path ending at the critical chain should be determined, N will be the number of activities on this path, M will be the number of

activities affected by the risk factor on this path, K_i will be the percentage of uncertainty of duration of activity i explained by the risk factor on this path, and VAR_i will be the variance of the duration of activity i on this path. The project buffer size of the feeding buffer can be calculated as:

$$Dependence\ degree(DD) = M/N \quad (10)$$

$$Dependence\ factor(DF) = \sum_i K_i/M \quad (11)$$

$$r = DD * (exp(DF^2) - 1) \quad (12)$$

$$Buffer\ size = (1 + R) * (2 * (\sum_i VAR_i)^{1/2}) \quad (13)$$

The two characteristics representing the dependencies of a project are seen in the calculation as Dependence Degree (DD) and Dependence Factor (DF). Computational experiments suggested that ADAP provides better protection to target dates compared to methods that assume the independency of tasks, when at least either DD or DF is at a high level (Bie, Cui, & Zhang, 2012).

Fuzzy numbers. In non-routine projects, due to the unavailability of the statistical data, regular CCPM buffer sizing methods cannot be applied. In order to overcome this downfall, Long and Ohsato (2008) developed another buffer sizing method based on the square root of the sum of the squares of the safety times estimated by fuzzy numbers. The safety time of each activity is determined as the difference between suitable deterministic duration and the high agreement duration in the model of trapezoidal fuzzy numbers TrFN (a, b, c, d). The high agreement duration is calculated by using an agreement index (AI), which is defined as the percent of the fuzzy event (A)

inside the boundaries of the fuzzy event (B). Calculations with fuzzy numbers allow the incorporation of uncertainty on parameters. Assuming st_i is the safety time of activity i , t_i^h is the high agreement duration, t_i^d is the suitable deterministic duration, and P is the number of tasks in the critical chain in the initial deterministic schedule. The project buffer size is calculated (Long & Oshato, 2008; Bie, Cui, & Zhang, 2012):

$$st_i = t_i^h - t_i^d \quad (14)$$

$$Buffer\ Size = \max_{p=1,\dots,P} \left(\sum_{i \in p} st_i \right)^{1/2} \quad (15)$$

Buffer Management

The purpose of buffers is to protect the schedule from variation. The project buffer is depleted as delays along the critical chain accumulate. In order to inform project managers about the status of the project in terms of on-time completion of tasks/project versus the consumed buffer, the CCPM uses fever charts. To produce fever charts, the project buffer is divided into three equal sections. The first one-third section of the buffer is the green zone or the expected variation zone. This section is expected to be consumed due to inherent task uncertainties. In this case, project managers do not need to take excessive corrective actions as it may cause wasted time and loss of focus. The second one-third of the buffer is the yellow zone or normal variation. Consumption of the second third of the buffer is caused by inherent uncertainty of task duration prediction. Consumption of the second third of the buffer is not a reason to raise alarms, but projects managers should start to create plans to recover the lost time. It is important to only create plans, but not to execute them. In the yellow zone, project managers should start to be prepared. These plans should only be executed if consumption of the last third of the

buffer starts to take place. The last third of the buffer is the abnormal variation or the red zone and is the result of special cause of variation. In this section, project managers need to take actions to avoid missing the deadlines and restore buffer. Procedures are the same for the feeding buffers. In case of feeding buffers, if the project buffer still contains adequate safety time, immediate actions might not be necessary even if the feeding buffer status is red. Figure 3 illustrated buffer variation areas (Budd & Cerveny, 2010; Deming, 1986).

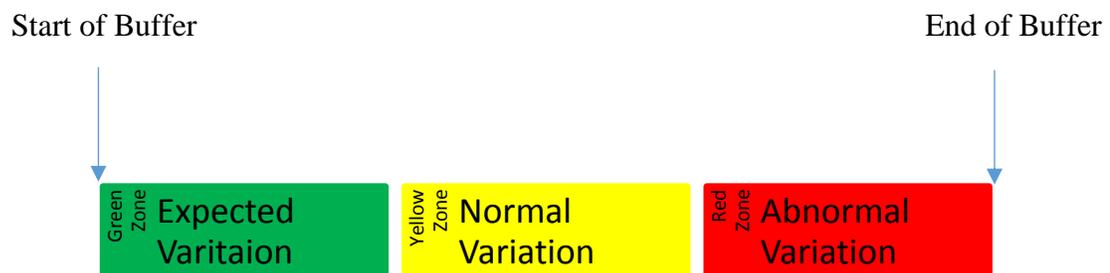


Figure 3. Buffer Variation Area. Adopted from “A Practical Guide to Earned Value Project Management”, 2nd ed., by C. I. Budd, and C. S. Budd, 2010. Copyright 2010 by Management Concepts, Inc.

Critical Chain Scheduling

In the process of scheduling in the single project environment, there are seven generic steps.

- 1- Create the initial plan, containing the logical relationships and durations that have safety time removed.
- 2- Load level, by eliminating all resource contention, working from the end to start of the project (first backward pass).
- 3- Detect the Critical Chain, which is the longest path of resource and task dependencies (second backward pass)
- 4- Calculate and insert the project buffer, identifying the buffer points

5- Calculate and insert the feeding buffer for all the paths feeding to the critical chain, resolving any newly created/discovered resource contention.

6- Add resource buffers to ensure timely notification of resources that have no predecessors and to all resources that have work assigned on the critical chain.

7- Analyze the schedule and evaluate options to complete the project at an earlier date; make selected changes, review and approve changes, and update the schedule. This is recommended for longer projects or if the project completion date is far in the future (Budd & Cerveney, 2010; Newbold, 1998).

Criticism of Critical Chain Scheduling

Existing scheduling software do not carry an optimal algorithm for resource leveling and resource-constrained scheduling. These software simply rely on priority rules for generating a precedence and resource feasible schedule. Based on these rules, the scheduling priority is given to an activity on the basis of activity attributes, such as latest start time (LST), latest finish time (LFT), and so forth. Computational experiments suggests that LST and LFT rules may be the best priority rules, but it is still possible to generate a project schedule that is lengthier than average. These scheduling software consider schedule information as proprietary information and do not provide detailed description of the rules that are in use. These software may generate a baseline schedule that might be far from the optimum. It is suggested that Primavera Project Planner delivers the best resource-constrained project scheduling performance (Herroelen & Leus, 2000; Kolisch, 1999). CCPM theory does not offer a prescribed resource leveling algorithm for the numerous algorithms that have been published in the operations

research literature; therefore, there is no specific way to achieve the optimum baseline schedule (Raz, Barnes, & Dvir, 2003).

Decreasing Work in Progress (WIP) is considered one of the most important measurements of a project schedule. The aim of the CC scheduling method is to minimize the WIP and schedule tasks as late as possible while keeping the project due date sufficiently protected. This decreases the chance of rework if a design problem is discovered. Also, it concentrates or maximizes the use of cash by pushing out investment until it is absolutely needed (Herroelen & Leus, 2000).

CCPM considers multitasking as the biggest killer of lead time. Some studies show that multitasking actually improves productivity at certain level, but too much multitasking has a negative effect. It is a well-known fact that taking action ahead of time (preemption) for a task is harmful for the flow time of jobs; however, it is also a well-known project scheduling fact that activity preemption may decrease the duration of a project (Herroelen & Leus, 2000; Adler & Benbunan-Fich, 2012; Appelbaum, Marchionni, & Fernandez, 2008; Raz, Barnes, & Dvir, 2003).

Depending on how the baseline schedule is generated, different sequences in a baseline schedules with a different critical sequence will be created. Suboptimal procedures creating schedules for a resource-constrained project may yield a different feasible schedule with different critical sequences. Even alternative optimal schedules may exhibit different critical sequences. Creating a good baseline schedule is not easy, but it is an important a task. There are instances that commercial software produces a baseline where the duration is above the optimum (Herroelen & Leus, 2000).

Feeding buffers are placed whenever a non-critical chain activity joins the critical chain to protect the critical chain from delays taking place on the activities on the feeding chain. Feeding buffers are inserted after that critical chain is identified. When feeding buffers are inserted by pushing back the feeding chain, the critical chain might not be the longest sequence. This becomes more important for a projected schedule in which every gating task (tasks without predecessors) is set to start at its scheduled time in the baseline schedule and the road runner mentality dictates the start times of the other activities. It may cause for the critical chain, which determines the length of the project, to start later and push back a non-critical chain. This is rather counter-intuitive. A complicated situation might be created after inserting buffers to a feeding chain that feeds another chain or is being fed by another chain of activities. This happens if the buffers are inserted by pushing back a chain of activities. Contention of resources may be complex to resolve (Herroelen, Leus, & Demeulemeester, 2002).

CCPM assumes that all task owners overestimate task durations and embed safety time in the task before with a 95 percent confidence level. Also, execution of each task will be expanded to fill the allotted time (Parkinson's Law). However, CCPM falls short on providing proof for task overestimation assumption and Parkinson's Law. Hill, Thomas and Allen (2000) provided contradictory results. In a major financial organization, out of 500 analyzed tasks durations, eight percent of the actual task times were equal to estimation, 60 percent of the tasks were reported as complete in less than the estimated time (in support of overestimation, but against Parkinson's Law), and 32 percent of tasks were completed after the estimated time indicating that the contingency factor, if it existed at all, was certainly not sufficient for the 95 percent confidence level.

CCPM also does not address the issue of how a project manager should determine the embedded contingency factor. It is likely that task owners embed more safety time in their estimates, with the knowledge that their estimates will be reduced (Raz, Barnes, & Dvir, 2003).

Previous Case Studies

Using a theoretical, but realistic, set of time estimates for tasks involved in creating an advertisement campaign, CCPM showed a 20% reduction in project length compared to PERT/CPM method, from 29 weeks to 23 weeks. In this case, the estimated task duration was shortened by 50 percent and used the C&PM for setting the buffer times (Budd & Cooper, 2004). In a similar study in the advertising industry, in a multi project environment, CCPM showed a reduction of between 31 to 43 percent in the project duration compared to PERT/CPM (Budd & Cooper, 2005). In a case study by Yang (2007), the concept of CC scheduling was used to shorten the total construction time, but achieved opposite results. The original schedule under CPM was 366 days and after rescheduling using the CCPM the duration was 515 days. This case study makes the impression that the CCS does not have shorter duration than CPM, but by excluding the project buffer from the CCPM schedule, this scheduling method delivers shorter duration in comparison to the CPM schedule.

Literature Conclusion

By holding buffers at the project level versus task level, Critical Chain Project Management tries to decrease project duration and increase the project schedule fidelity (reliability) (Doyle, 2010). CCPM minimizes the negative effects of student syndrome and Parkinson's Law and eliminates multitasking, resulting in reduced time in schedules.

By reducing the schedule duration, the possibility of budget overruns and scope creep are reduced. Using Critical Chain Project Management provides improvements in aspects such as schedule, resource, budget, scope, and quality, resulting in heightened returns for stakeholders (Hilbert & Robert, 2010). In order to achieve this duration reduction, every completed activity should be reported immediately to carry out other activities (road runner ethics) and absorb benefits of early completion of a task. Under CPM, any delays in tasks will be passed on to the next activities and cause project delays, but any early completion will not advance the project due to sandbagging and Parkinson Law. In CCPM, delays in tasks will be absorbed by the project buffer instead of being passed on to the next activity and delaying the whole project.

Methodology

Participants and Procedure

The intention for this study was to determine if CPM or CCPM delivers the shorter project duration in a specific construction project. In order to fulfill this intention, the researcher acquired a project that was already scheduled and planned using CPM and rescheduled it using the CCPM scheduling method. The intended project was in the construction industry and had an original duration of seven months.

The acquired data was the construction of a concourse section in a mall at a university. The data was provided by a faculty member in the Architectural and Manufacturing Sciences (AMS) department at Western Kentucky University. The data was already scheduled using the CPM scheduling method. The task durations for the project were predicted based on a 90 percent probability of being completed on time, as confirmed by the data provider. The schedule was also part of a larger project and this part of the schedule was exported for manageability purposes for this study. The exported project had 157 tasks, including summary and milestone tasks. These tasks were scattered between seven Work Breakdown Structures (WBS) with no logical relationships existing among them.

The procedure created a single project environment to avoid the complexities that exist in a multi-project environment. This kept the comparison between CPM and CCPM scheduling method simple enough to facilitate demonstration of the differences between the two methods. Since each construction project is unique, the selected project was typical in construction, as confirmed by the provider.

As discussed in the literature review, the traditional project scheduling method of CPM uses estimates that have a 90 to 100 percent probability of on-time completion. Critical chain uses estimates that have 50 percent probability of on-time completion. Goldratt suggested cutting conservative estimates in half will achieve this objective. Therefore, in the process of changing the CPM schedule, each activity duration was decreased by half (Goldratt, 1997; Blackstone, Cox III, & Schleier Jr, 2009). The original duration for task dependent activities was kept based on their original times. Task dependent activities are activities where the allocated number of resources has no impact on the determination of duration. In other words, the activity is supposed to take a certain amount of time to be performed irrespective of the resources it has, such as concrete curing.

In the process of adding buffers in CC scheduling, the C&PM was used due to its simplicity and the fact it creates the longest CC schedule, as discussed in the literature review. Therefore, if this schedule is shorter than the CPM schedule, the rest of buffer sizing methods will also create shorter schedules than the CPM method.

The following steps were followed for establishing the CCS:

- 1- Established a project basic information schedule using the data provided by the original schedule. This schedule included activities, resources and calendar, and assignment of resources and calendar.

- 2- Leveled the resource, to minimize work-in-progress activities as late as possible to avoid multi-tasking, after considering resource contention.

- 3- Identified the critical chain, considering all logical and resource-dependency relationships between activities.

- 4- Generated all buffer activities and assigned relationships.
- 5- Inserted buffers into the schedule network.

The necessary information for the above steps follows:

- To resolve resource contention, the activity with the lower ID number in the Work Breakdown Structure (WBS) had higher priority and the ID was used to level resource contention.
- As mentioned, 50 percent of the critical chain length was the length of the project buffer (C&PM). Similarly, 50 percent of the feeding chain was used as the length of the feeding buffer.
- Buffer activities were assigned a finish to start (FS) logical relationship with their related chain.

Instruments and Materials

The software used for checking and reading the original CPM schedule was Microsoft Project™ (MSP). The selection of this software was based on its ability to handle project scheduling. The software that was used for scheduling based on CCPM was ProChain™, which is a commercial software that can be overlaid on Microsoft Project™. This software was selected for its ability to execute CC scheduling and its ability to be overlaid on MSP. The ProChain software was funded by Western Kentucky University's graduate school for the purpose of this study.

Threats to Validity

1- The assumption that every task had 50 percent embedded contingency in it might not be true for every task. Each task may have had a different amount of embedded contingency in it.

2- As this project was in construction, the result might not be applicable to other types of projects.

3- The data might have carried a modified task duration rather than the original estimates reported.

4- The actual use of CCPM was not studied, since it was not executed in reality.

Analysis

Comparison between these two scheduling methods was done based on the final scheduling duration. A Gantt chart demonstrated differences between the two scheduling methods. In order to compare efficient usage of man power, the percentage of actual work completed was used to compare the two methods (actual work / total actual work) after consumption of 25, 50, and 75 percent of the duration of the project. In MS project, percent complete is really percentage duration completed in the project and is calculated as actual duration divided by total duration. Actual work completed in the MS project is defined as the man-hour that was used divided by total actual work, which is the total man-hours needed.

Findings

The original plan before resource leveling was 199 days. The project had 15 resource groups. Before resource leveling, nine of the resource groups were over allocated. By running the 'level resource' function embedded in MSP, the resources were leveled. In the process of resource leveling, MSP is able to adjust individual resource assignments on an activity and create splits in remaining works. After resource leveling the project duration was 218 days. This schedule can be found in Appendix A.

ProChain software treats separate terminating tasks as endpoints that need to be protected with project buffers; therefore, there should be only one task with no successors and a project should have only one task or milestone that terminates a project network. The provided schedule contained seven tasks (ID numbers 11, 42, 88, 67, 104, 141, 157) without any successors. If the CC scheduling process would have been executed with this condition, ProChain software would have identified each of these tasks as the end of a project network and placed a project buffer in the end of each of them. In order to avoid this complication, the task 'project completion' was defined as the successors of these tasks. The result of this action created only one project buffer and avoided the creation of multiple project buffers. ProChain version 12 executes critical chain scheduling different than the traditional CC scheduling method described in the literature review. With the default settings, feeding buffers are not created in ProChain 12. In order to resolve this matter and schedule the project based on the traditional CC scheduling method and creation of feeding buffers, the option of traditional critical chain mode was activated under the ProChain options, and project/feeding buffers were set as half of the critical/feeding chain duration.

In order to achieve task durations with a 50 percent probability of being completed on-time, the task durations were cut in half. After these modifications, the rescheduling function for the project, based on the CCPM, was executed. Project duration decreased to 173 days, with one project buffer (36 days) and 12 feeding buffers. The length of the critical chain was 115.5 days. The project buffer duration is less than half of the critical chain duration because ProChain does not include time of the predecessor when tasks are overlapped due to lead and lag times on the linkages (or, in certain cases with FF links, the successor). The effect of overlapping on buffer sizing is similar with other link types (SS, FF, and SF). When there is a lead time, the duration of that lead time does not contribute to the buffer size. The schedule based on the CCPM can be found in Appendix B.

Discussion

Feeding buffers' duration are calculated as half of the duration of its feeding chain. In some cases, adding the feeding buffer duration to the original duration of a feeding chain may result in an alteration. Consider the scenario illustrated in Figure 4. Task A, with duration of seven days, and task B with the duration of 6 days, both feed task C with duration of three days. In this scenario, task A and C are the critical tasks, creating the critical chain, and task B is the feeding chain. By adding the feeding buffer to the feeding chain, the total length of the feeding chain will be nine days. Based on the CCPM concept, the length of the project will be the length of the critical chain plus the project buffer, which will be 15 days. As illustrated in the figure, the length of the project now is 17 days instead of being 15 days. By putting a feeding buffer for task B as the feeding chain, this chain was pushed back for two days.

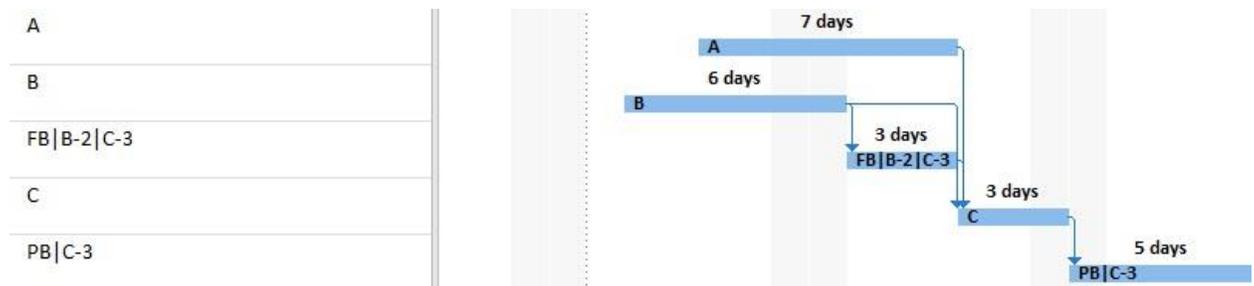


Figure 4: Complications of Feeding Buffer.

The original data contained a 'must start-on' constraint on the starting tasks in each WBS. As a result, the duration of the project was under the influence of this constraint rather than solely being dependent on the length of the critical chain and the buffers. The combined effect of a 'must start-on' constraint for starting tasks and their successive tasks being scheduled as late as possible creates an unnecessary buffer

extension. An example of this can be seen between task ID 4 (starting task) and task ID 13 in Appendix B.

In the CCPM, feeding buffers are used to protect the critical chain from uncertainties that exist in the feeding chain. Feeding buffers are connected to the feeding chains using a FS relationship, but no resources are allocated to them. If a task runs late on a feeding chain, that chain starts to consume its feeding buffer. No resource is allocated to feeding buffers because it is not predictable which tasks will run late; therefore, the resources to be used in the feeding buffers is unknown. There might be a case where resources that are consuming the feeding buffer are actually needed elsewhere on other tasks. This will result in further resource contentions and complications.

It is true that each task's on-time completion in a schedule is independent, but the probability of a project on-time completion is the combined effect of its tasks. Consider a project containing two consecutive tasks, each having 50 percent chance of on-time completion. The probability of on-time completion of the project is the integration of the tasks' on-time completion probabilities, in this case 25 percent. The more tasks a project contains, the more uncertainty the project has to face. The traditional solution is to add safety time to each individual task. By adding safety time to each task, the probability of on-time completion of each individual task is increased; hence, the combined probability which is the on-time completion probability of the project is increased. However, this a faulty solution. Consider X_i is the on-time completion probability of task i and Y is the on-time completion probability of the project ($0 < X, Y < 1$); therefore, $Y = X_1 \times X_2 \times \dots \times X_i$. Now as number of task goes higher (i) the probability of on-time completion gets smaller ($\lim_{i \rightarrow \infty} X_1 \times X_2 \times \dots \times X_i = 0$ if $0 < X < 1$), because $X_i < 1$ (mathematically any

number multiplied by a number less than 1 gets smaller). In the end, no matter how much safety time is added to each task to ensure its on-time completion of the project, it get closer to zero, as the number of tasks increase.

In CCPM, the probability of on-time completion is the combined effect of feeding chains and the critical chain. In CCPM, X can be defined as probability of on-time completion of each chain. The CCPM approach is to concentrate the safety times at higher levels i.e. in feeding buffers and project buffer; therefore, increasing X 's. At the same time, by creating chains the number of i 's is decreased; hence, the number of times a number less than one is multiplied to another number less than one is decreased. The combined effect of decreasing i and increasing X , is increased probability of on-time completion of the project (Y).

Compared to CCPM scheduling method, the CPM scheduling system is more forgiving. Under CCPM, determining the correct logical relationship between activities is necessary since activities without any relationship will be pushed to be executed as late as possible. Also, activities without any successor will be treated as endpoints and create complications as discussed earlier, resulting in wrong construction procedures. Conversely, activities without clear preceding and succeeding relationship will be arranged in their as soon as possible dates under CPM. By executing activities as soon as possible the, possibility of later complications are avoided.

The goal in CC scheduling is to create a shorter project duration and a lean schedule. It starts by creating task networks of logical relationships among tasks of finish-to-start and adding buffers afterwards. The result is a shorter project duration. However, as it can be observed in the current study schedule, complicated relationships

commonly appear in construction projects, i.e. a mixture of finish-to-finish, start-to-start, or start-to-finish logical relationships. Therefore, a conclusion might be that CC scheduling with the ProChain software is not suitable for projects containing complicated logical relationships, as it may create complications in buffer sizing procedures.

Conclusion

The first research question was to determine which scheduling method deliver a shorter project schedule. The duration of the analyzed project, after cutting the task durations to half and rescheduling using the CC method, was decreased to 173 days. This duration is more than the sum of critical chain duration and project buffer due to push backs created by the feeding buffers and extensions caused by the ‘must start-on’ constraint on the starting tasks. The length of the project without its project buffer is 137 days, different than the critical chain length (115.5 days), containing the push backs created by the feeding buffers and ‘must start-on’ constraints. See Table 1.

Table 1

Project information on different scenarios

Situation	Total Project Duration	Project Buffer	Net Project Duration
Original project without resource leveling based on CPM	199 days	0	199 Days
Original project with resource leveling based on CPM	218	0	218
Original project based on CCPM	173	36	137

Compared to the CPM schedule, the schedule under CCPM is 45 days shorter. Completion of the project in 173 days means complete consumption of project buffer, which is very unlikely (worst case scenario). There is a possibility that the project under CC schedule could be completed in 137 days without consumption of the project buffer, but it is very unlikely (best case scenario). The most probable scenario is consumption of at least some of project buffer duration and reaching the yellow zone of the buffer. Considering this scenario, the project would be completed somewhere in the yellow zone (between day 149 and 161) of the buffer. This average time saving under CCPM is about 25 percent. The length of the project without a project buffer is 137 days. This means if all the tasks, each having a 50 percent chance of on-time completion, were completed on-time, no buffer would be used and project would be completed on day 137. If all tasks were late and all of the buffer was consumed, the project would be completed on day 173. Comparing the project network between CC scheduling method and CPM reveals that the project under CC scheduling would be completed earlier even if the buffers were consumed completely. This provides evidence that CCPM can produce more condensed schedules. Based on this, the critical chain scheduling method delivers projects faster. Therefore, it is a suitable alternative to CPM scheduling. See Table 2.

Table 2

Completion of project based on different scheduling methods

	Scheduling based on CCPM			Scheduling based on CPM
	Completion in the green zone buffer (best case scenario)	Completion in the yellow zone buffer (most probable scenario)	Completion in the red zone buffer (worst case scenario)	On-time completion (most probable but not with 100 % chance)
Project Length	137-149 Days	149-161 Days	161-173 Days	218

The second research question was which scheduling system makes a more efficient usage of time. For this study, after 25 percent duration of the project was consumed, the percentage of actual work performed by CPM was 25 percent, which is lower than the 38 percent under CCPM in a similar situation. After half of the project duration was consumed, the actual work completed using CPM was 50 percent and 72 percent for CCPM. Finally, after 75 percent of the project duration was consumed, the percentage of actual work completed for CPM was 75, and 85 percent for CCPM. These numbers showed that not only the CC schedule delivers shorter project duration, but also better usage of resources.

Under CC scheduling, the critical chain is determined not only based on the duration of the task and logical relation among tasks, but also on the resource dependences. The difference between CCPM and CPM not only exist in how to approach resource dependencies, but also in their management approach. Creation of only one critical chain helps project managers to focus the bulk of their attention on the critical

activities (i.e. the critical chain). In CCPM, it is necessary to complete the critical activities as early possible. In contrast, there is the possibility in CPM scheduling that multiple critical paths may be created. This may cause focus confusion. It may also result in multi-tasking when executing projects.

Critical Chain Project Management, derived from Theory of Constraints, is an alternative approach toward scheduling projects. By addressing Critical Path Method weaknesses in estimating task durations, removing individual safety times embedded in each task, and inserting buffers at a project level, CCPM may be able to reduce the duration of projects. This study was a test of this assertion. Comparing the project network under CPM and CCPM for this study reveals that CCPM has the possibility of a 19 percent (worst case scenario and using complete project buffer) to 36 percent (not using project buffer at all) time saving in comparison to CPM. CCPM not only delivered shorter project deliveries, but also demonstrated better usage of resources.

Many scheduling textbooks do not contain CC scheduling methods. In order to achieve the overall benefits of CCPM, such as shorter project duration, centralized contingency, better resource usage, and focused attention, it is essential to educate project practitioner's about CCPM. Current commercial scheduling software packages (e.g. Primavera) do not include CC scheduling methods. Incorporating this method in commercial software with a comparison function would allow the differences between CPM and CCPM scheduling methods to be analyzed. Complete application of CCPM in the construction industry requires further studies.

Further Research

CC challenges the duration estimate used in CPM as being impractical. Because CPM embeds safety times in task levels, it is essential to revise the duration of each activity using CCPM. In order to achieve more realistic estimations and achieving task duration with 50 percent probability of on time completion, Goldratt suggested cutting duration estimated task times by half. However, in the construction industry, the productivity of different working crews and their working rates are very unpredictable; therefore, cutting the task duration by half seems unreasonable. Although some data is available with regard to tasks durations and productivity of crews in construction from commercial databases, it is necessary to develop data that can be used for estimating the duration of tasks with 50 percent chance of on-time completion for the application of CCPM.

As observed in this experiment, the completion of the project takes place faster than the CPM, raising the possibility of faster consumption of cash resources. Faster consumption of cash resources may be considered as a negative point. At the same time, better usage of labor resources, as observed, may result in cost reduction. Therefore, the combined effect of faster project execution and better resources usage on cash flow is unknown. Studies are required in order to set up an appropriate performance measurement system under CCPM.

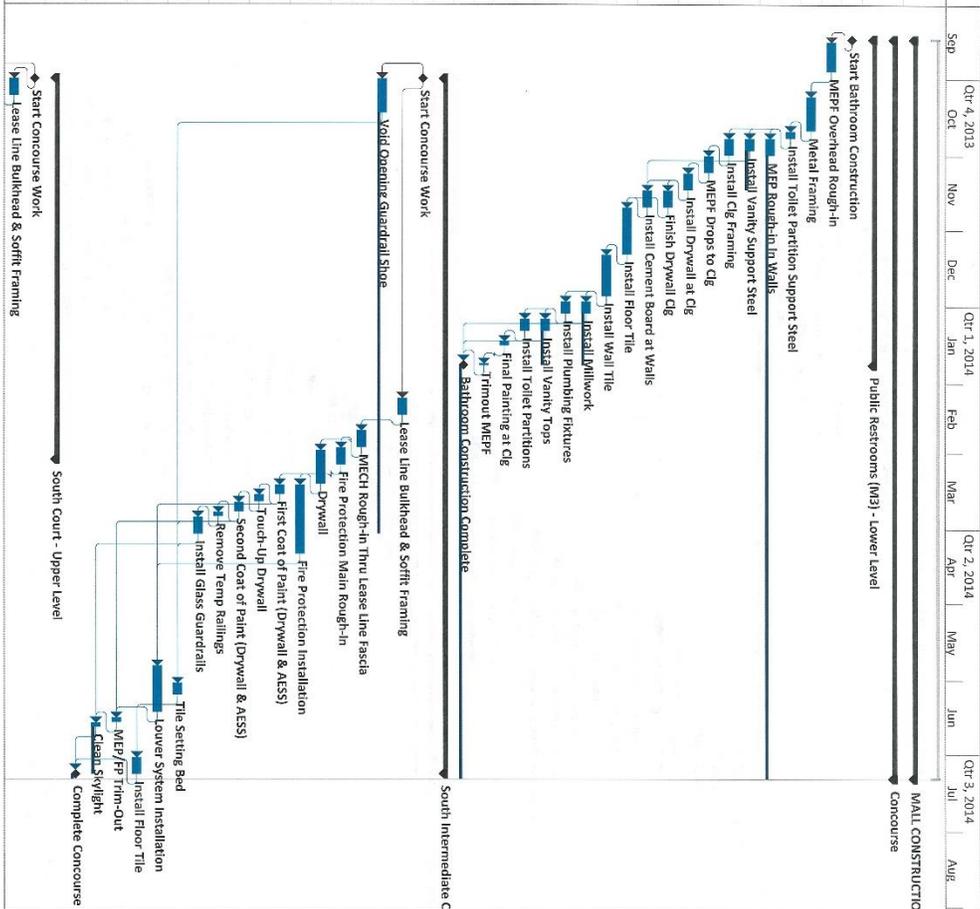
The buffer method allocation used in this study was C&PM and considering the 50 percent length of the chain as the buffer size creates the biggest buffer compared to other buffer sizing methods, such as RSEM. The question of how to decide a reasonable buffer size is essential for successfully running a CC schedule in the construction

industry. This issue requires empirical studies, considering various construction projects using different buffer sizes. Further studies to find practical buffer sizing methods for different types of construction projects is recommended. Also, modified buffer sizing systems for practical usage in different projects that are exposed to different level of risks and uncertainties is required. For example, locations with more severe weather conditions require a lengthier project buffer compared to locations with more stable weather conditions. Different seasons may require different buffers.

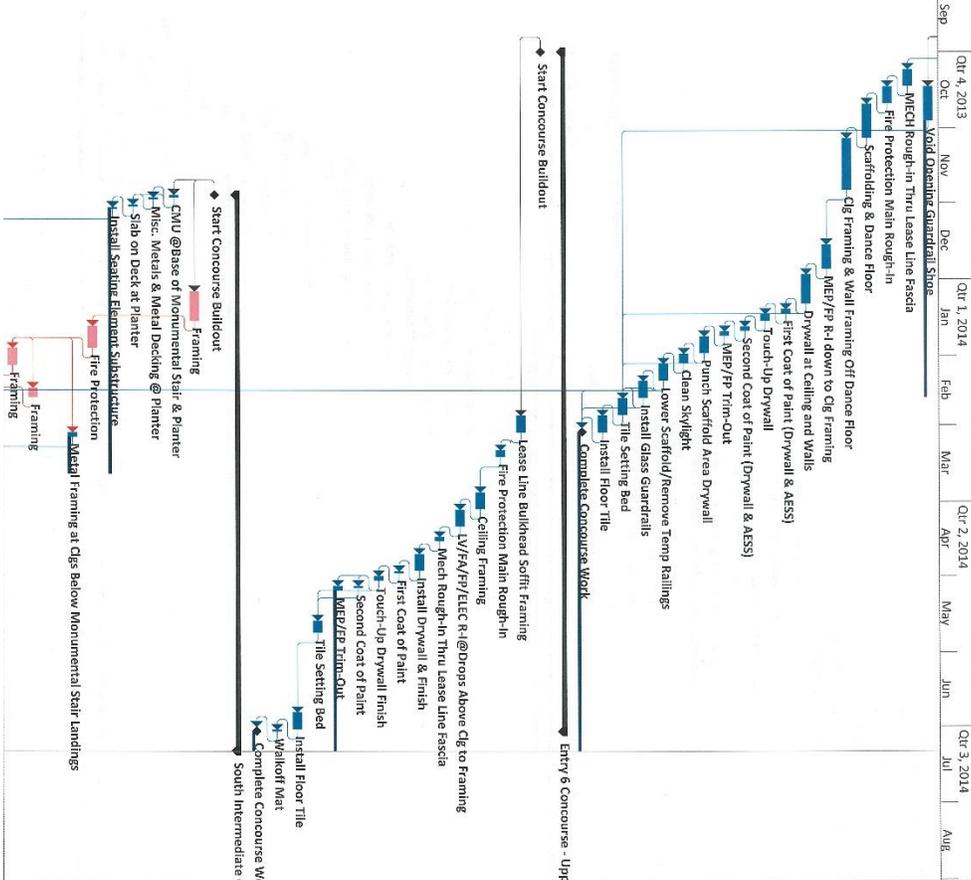
In this experiment, part of a bigger schedule was exported and considered as a project and its schedule. As mentioned earlier, no logical relationship existed between its WBS's in this schedule. This is due to the fact that this schedule was for a large construction project where multiple crews were working simultaneously for a different WBS and their work outcome did not have any effect on other WBS. In order to achieve a more coherent and realistic picture, rescheduling of the entire project would be required. This data was unavailable at the time of this experiment.

Appendix A: CPM Schedule

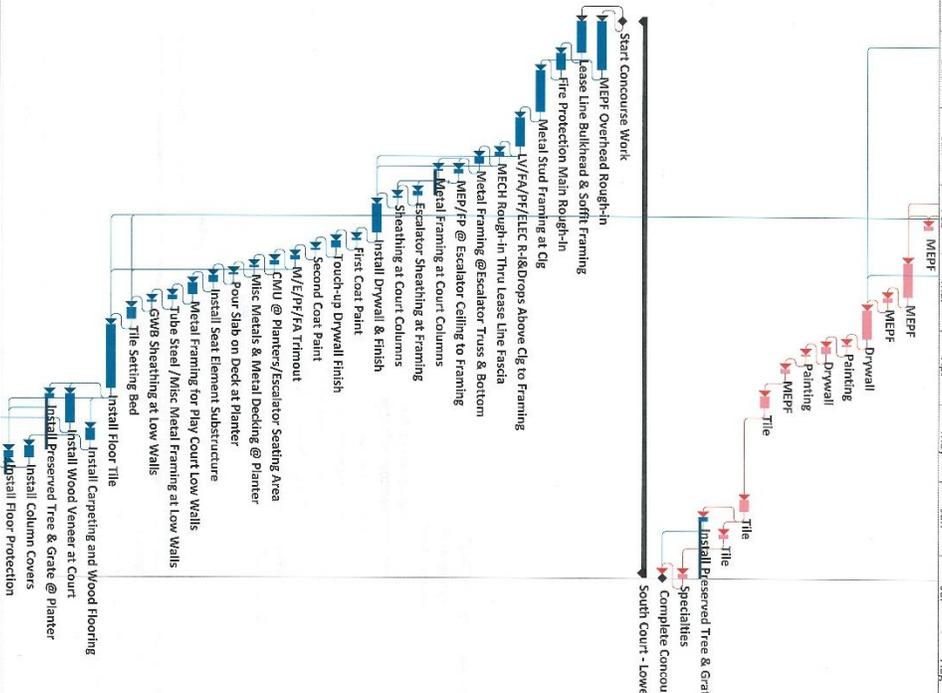
ID	Task Name	Duration	Start	TF	Resource Names
0	University Town Center - 2013-10-01	218 days	Sun 9/15/13 0 days		
1	1 MALL CONSTRUCTION	218 days	Sun 9/15/13 0 days		
2	1.1 Concourse	218 days	Sun 9/15/13 0 days		
3	1.1.1 Public Restrooms (M3) - Lower Level	99 days	Sun 9/15/13 119 d...		
4	1.1.1.1 Start Bathroom Construction	0 days	Sun 9/15/13 0 days		
12	1.1.1.9 MEP Overhead Rough-in	10 days	Mon 9/16/13 120 da...		MEPF
13	1.1.1.10 Metal Framing	10 days	Tue 10/8/13 120 da...		Framing
14	1.1.1.11 Install Toilet Partition Support Steel	3 days	Tue 10/22/13 120 da...		Specialties
15	1.1.1.12 MEP Rough-in in Walls	5 days	Fri 10/25/13 184 da...		MEPF
16	1.1.1.13 Install Vanity Support Steel	3 days	Fri 10/25/13 182 da...		Millwork/Tops
17	1.1.1.14 Install Cig Framing	5 days	Fri 10/25/13 120 da...		Framing
18	1.1.1.15 MEP Drops to Cig	5 days	Fri 11/1/13 120 da...		MEPF
19	1.1.1.16 Install Drywall at Cig	5 days	Fri 11/8/13 120 da...		Drywall
20	1.1.1.17 Finish Drywall Cig	5 days	Fri 11/15/13 120 da...		Drywall
21	1.1.1.18 Install Cement Board at Walls	5 days	Fri 11/15/13 120 da...		Tile
22	1.1.1.19 Install Floor Tile	15 days	Fri 11/22/13 120 da...		Tile
5	1.1.1.2 Install Wall Tile	15 days	Wed 12/11/13 120 da...		Tile
6	1.1.1.3 Install Millwork	5 days	Mon 12/30/13 134 da...		Millwork/Tops
7	1.1.1.4 Install Plumbing Fixtures	5 days	Mon 12/30/13 120 da...		MEPF
8	1.1.1.5 Install Vanity Tops	5 days	Mon 1/6/14 129 da...		Millwork/Tops
23	1.1.1.20 Install Toilet Partitions	5 days	Mon 1/6/14 120 da...		Specialties
9	1.1.1.6 Final Painting at Cig	2 days	Wed 1/15/14 119 da...		Painting
10	1.1.1.7 Trimout MEPF	1 day	Fri 1/24/14 119 da...		MEPF
11	1.1.1.8 Bathroom Construction Complete	0 days	Fri 1/24/14 119 da...		
24	1.1.2 South Intermediate Court - Upper Level 205 days	205 days	Tue 10/1/13 2 days		
25	1.1.2.1 Start Concourse Work	0 days	Tue 10/1/13 0 days		
26	1.1.2.2 Lease Line Bulkhead & Soffit Framing	5 days	Fri 2/7/14 2 days		Framing
27	1.1.2.3 Void Opening Guardrail Shoe	10 days	Tue 10/1/13 128 da...		Railing
29	1.1.2.5 MECH Rough-in Thru Lease Line Fascia	5 days	Thu 2/20/14 2 days		MEPF
28	1.1.2.4 Fire Protection Main Rough-in	5 days	Thu 2/27/14 15 days		Fire Protection
32	1.1.2.8 Drywall	10 days	Fri 2/28/14 2 days		Drywall
30	1.1.2.6 Fire Protection Installation	20 days	Fri 3/14/14 15 days		Fire Protection
33	1.1.2.9 First Coat of Paint (Drywall & AESS)	2 days	Fri 3/14/14 2 days		Painting
34	1.1.2.10 Touch-Up Drywall	3 days	Tue 3/18/14 2 days		Drywall
35	1.1.2.11 Second Coat of Paint (Drywall & A.2 days)	2 days	Fri 3/21/14 2 days		Painting
31	1.1.2.7 Remove Temp Railings	2 days	Tue 3/25/14 2 days		Railing
40	1.1.2.16 Install Glass Guardrails	5 days	Thu 3/27/14 2 days		Railing
38	1.1.2.14 Tile Setting Bed	5 days	Mon 6/2/14 2 days		Tile
41	1.1.2.17 Louver System Installation	15 days	Mon 5/26/14 15 days		Specialties
39	1.1.2.15 Install Floor Tile	5 days	Wed 7/2/14 2 days		Tile
36	1.1.2.12 MEP/FP Trim-Out	2 days	Mon 6/16/14 15 days		MEPF
37	1.1.2.13 Clean Skylight	2 days	Wed 6/18/14 15 days		General Labor
42	1.1.2.18 Complete Concourse Work	0 days	Tue 7/8/14 2 days		
68	1.1.4 South Court - Upper Level	114 days	Tue 10/1/13 93 days		
69	1.1.4.1 Start Concourse Work	0 days	Tue 10/1/13 0 days		
70	1.1.4.2 Lease Line Bulkhead & Soffit Framing	5 days	Tue 10/1/13 33 days		Framing



ID	Task Name	Duration	Start	TF	Resource Names
84	1.1.4.16 Void Opening Guardrail Shoe	10 days	Tue 10/15/13 17:00 da...		Railing
71	1.1.4.3 MECH Rough-in Thru Lease Line Fascia	5 days	Tue 10/8/13 13:33 days		MEPF
72	1.1.4.4 Fire Protection Main Rough-in	10 days	Tue 10/15/13 33 days		Fire Protection
73	1.1.4.5 Scaffolding & Dance Floor	10 days	Tue 10/22/13 33 days		Scaffold
74	1.1.4.6 Cfg Framing & Wall Framing Off Dance Floor	10 days	Tue 11/5/13 33 days		Framing
75	1.1.4.7 MEP/FP R4-down to Cfg Framing	10 days	Wed 12/18/13 31 days		MEPF
76	1.1.4.8 Drywall at Ceiling and Walls	10 days	Mon 12/30/13 31 days		Drywall
77	1.1.4.9 First Coat of Paint (Drywall & AESS)	2 days	Mon 1/13/14 31 days		Painting
78	1.1.4.10 Touch-Up Drywall	3 days	Wed 1/15/14 31 days		Drywall
79	1.1.4.11 Second Coat of Paint (Drywall & AESS)	2 days	Mon 1/20/14 31 days		Painting
80	1.1.4.12 MEP/FP Trim-Out	2 days	Wed 1/22/14 31 days		MEPF
81	1.1.4.13 Punch Scaffold Area Drywall	5 days	Fri 1/24/14 31 days		Concrete
82	1.1.4.14 Clean Skylight	2 days	Fri 1/31/14 31 days		General Labor
83	1.1.4.15 Lower Scaffold/Remove Temp Rail 5 days	5 days	Tue 2/4/14 93 days		Scaffold
87	1.1.4.19 Install Glass Guardrails	5 days	Tue 2/11/14 93 days		Railing
85	1.1.4.17 Tile Setting Bed	5 days	Tue 2/18/14 93 days		Tile
86	1.1.4.18 Install Floor Tile	5 days	Tue 2/25/14 93 days		Tile
88	1.1.4.20 Complete Concourse Work - Upper Level	201 days	Mon 3/3/14 93 days		General
89	1.1.5.1 Start Concourse Buildout	0 days	Tue 10/1/13 0 days		
90	1.1.5.2 Lease Line Bulkhead Soffit Framing	5 days	Tue 2/25/14 6 days		Framing
91	1.1.5.3 Fire Protection Main Rough-in	3 days	Tue 3/11/14 6 days		Fire Protection
92	1.1.5.4 Ceiling Framing	5 days	Fri 3/28/14 6 days		Framing
94	1.1.5.5 LV/FA/FP/ELEC R-@Drops Above Cfg to Framing	5 days	Fri 4/4/14 6 days		MEPF
95	1.1.5.6 Mech Rough-in Thru Lease Line Fascia	2 days	Tue 4/15/14 6 days		MEPF
96	1.1.5.7 Install Drywall & Finish	5 days	Tue 4/22/14 6 days		Drywall
97	1.1.5.8 First Coat of Paint	1 day	Tue 4/29/14 6 days		Painting
98	1.1.5.9 Touch-Up Drywall Finish	2 days	Thu 5/1/14 6 days		Drywall
99	1.1.5.10 Second Coat of Paint	1 day	Mon 5/5/14 6 days		Painting
102	1.1.5.13 MEP/FP Trim-Out	2 days	Mon 5/5/14 47 days		MEPF
100	1.1.5.11 Tile Setting Bed	5 days	Mon 5/19/14 6 days		Tile
101	1.1.5.12 Install Floor Tile	5 days	Wed 6/25/14 6 days		Tile
103	1.1.5.14 Walkoff Mat	1 day	Wed 7/2/14 6 days		General Labor
104	1.1.5.15 Complete Concourse Work	0 days	Wed 7/2/14 6 days		
43	1.1.3 South Intermediate Court - Lower Level 164 days	164 days	Thu 11/28/13 0 days		
45	1.1.3.1 Start Concourse Buildout	0 days	Thu 11/28/13 0 days		
44	1.1.3.2 Lease Line Bulkhead Soffit Framing	10 days	Mon 1/6/14 0 days		Framing
61	1.1.3.18 CMU @Base of Monumental Stair 2 days	2 days	Thu 11/28/13 79 days		Masonry
62	1.1.3.19 Misc. Metals & Metal Decking @ 11 day	1 day	Fri 11/29/13 79 days		Misc Metals
63	1.1.3.20 Slab on Deck at Planter	1 day	Mon 12/2/13 79 days		Concrete
65	1.1.3.22 Install Sealing Element Substructure	1 day	Tue 12/3/13 79 days		Specialties
49	1.1.3.6 Fire Protection Main Rough-in	7 days	Mon 1/20/14 0 days		Fire Protection
46	1.1.3.5 Metal Framing at Cigs Below Monumental Stair Landings	2 days	Tue 3/4/14 11 days		Framing
47	1.1.3.4 Metal Framing at Columns	2 days	Fri 2/14/14 0 days		Framing
50	1.1.3.7 Ceiling Framing	5 days	Wed 1/29/14 0 days		Framing



ID	Task Name	Duration	Start	TF	Resource Names	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
48	1.1.3.5 MEP/FP Rough-In Down to Cig/Fan 2 days	2 days	Tue 2/18/14	0 days	MEPF												
51	1.1.3.8 LV/FA/FP/ELEC R-1@Drops Above C10 10 days	10 days	Wed 3/5/14	0 days	MEPF												
52	1.1.3.9 Mech Rough-In Thru Lease Line Fas 2 days	2 days	Wed 3/19/14	0 days	MEPF												
53	1.1.3.10 Install Drywall & Finish 10 days	10 days	Mon 3/24/14	0 days	Drywall												
54	1.1.3.11 First Coat of Paint 1 day	1 day	Mon 4/7/14	0 days	Painting												
55	1.1.3.12 Touch-Up Drywall Finish 3 days	3 days	Tue 4/8/14	0 days	Drywall												
64	1.1.3.21 Second Coat of Paint 1 day	1 day	Fri 4/11/14	0 days	Painting												
56	1.1.3.13 MEP/FA LV Trim-Out 2 days	2 days	Thu 4/17/14	0 days	MEPF												
57	1.1.3.14 Tile Setting Bed 5 days	5 days	Mon 4/28/14	0 days	Tile												
58	1.1.3.15 Install Floor Tile 5 days	5 days	Mon 6/9/14	0 days	Tile												
59	1.1.3.16 Solid Surface @ Low Walls & Wall 2 days	2 days	Mon 6/23/14	0 days	Tile												
60	1.1.3.23 Install Preserved Tree & Grates @ 2 days	2 days	Mon 6/16/14	17 days	Specialties												
67	1.1.3.17 Install Upholstery & Trim 2 days	2 days	Wed 7/9/14	0 days	Specialties												
105	1.1.3.24 Complete Concourse Work 162 days	162 days	Thu 7/10/14	0 days	Specialties												
106	1.1.6.1 Start Concourse Work 0 days	0 days	Thu 11/28/13	0 days													
107	1.1.6.2 MEP Overhead Rough-in 15 days	15 days	Thu 11/28/13	0 days	MEPF												
108	1.1.6.3 Lease Line Bulkhead & Softit Framin 10 days	10 days	Thu 11/28/13	0 days	Framing												
109	1.1.6.4 Fire Protection Main Rough-in 5 days	5 days	Wed 12/11/13	0 days	Fire Protection												
138	1.1.6.33 Metal Stud Framing at Cig 15 days	15 days	Wed 12/18/13	0 days	Framing												
139	1.1.6.34 LV/FA/FP/ELEC R-1@Drops Above C10 10 days	10 days	Mon 1/6/14	2 days	MEPF												
100	1.1.6.5 MECH Rough-In Thru Lease Line Fas 2 days	2 days	Mon 1/20/14	2 days	MEPF												
126	1.1.6.21 Metal Framing @ Escalator Truss 83 days	83 days	Wed 1/22/14	2 days	Framing												
127	1.1.6.22 MEP/FP @ Escalator Ceiling to Fas 2 days	2 days	Mon 1/27/14	2 days	MEPF												
129	1.1.6.24 Metal Framing at Court Columns 1 day	1 day	Wed 2/5/14	2 days	Framing												
128	1.1.6.23 Escalator Sheathing at Framing 2 days	2 days	Fri 2/7/14	2 days	Framing												
130	1.1.6.25 Sheathing at Court Columns 1 day	1 day	Mon 2/10/14	2 days	Millwork/Tops												
140	1.1.6.35 Install Drywall & Finish 10 days	10 days	Mon 2/10/14	2 days	Drywall												
111	1.1.6.6 First Coat Paint 1 day	1 day	Mon 2/24/14	2 days	Painting												
112	1.1.6.7 Touch-up Drywall Finish 3 days	3 days	Tue 2/25/14	2 days	Drywall												
113	1.1.6.8 Second Coat Paint 1 day	1 day	Fri 2/28/14	2 days	Painting												
114	1.1.6.9 M/E/FP/FA Trimout 2 days	2 days	Mon 3/3/14	2 days	MEPF												
119	1.1.6.14 CMU @ Planters/Escalator Seating 2 days	2 days	Wed 3/5/14	2 days	Masonry												
120	1.1.6.15 Misc Metals & Metal Decking @ P 1 day	1 day	Fri 3/7/14	2 days	Misc Metals												
121	1.1.6.16 Pour Slab on Deck at Planter 1 day	1 day	Mon 3/10/14	2 days	Concrete												
122	1.1.6.17 Install Seat Element Substructure 3 days	3 days	Tue 3/11/14	2 days	Specialties												
123	1.1.6.18 Metal Framing for Play Court Low 3 days	3 days	Fri 3/14/14	2 days	Framing												
124	1.1.6.19 Tube Steel /Misc Metal Framing a 2 days	2 days	Wed 3/19/14	2 days	Framing												
125	1.1.6.20 GWB Sheathing at Low Walls 1 day	1 day	Fri 3/21/14	2 days	Drywall												
131	1.1.6.26 Tile Setting Bed 5 days	5 days	Mon 3/24/14	2 days	Tile												
115	1.1.6.10 Install Floor Tile 20 days	20 days	Mon 3/31/14	2 days	Tile												
116	1.1.6.11 Install Carpeting and Wood Floor's 5 days	5 days	Mon 5/12/14	2 days	Millwork/Tops												
132	1.1.6.27 Install Wood Veneer at Court 10 days	10 days	Mon 4/28/14	2 days	Millwork/Tops												
137	1.1.6.32 Install Preserved Tree & Grate @ 12 days	12 days	Mon 4/28/14	2 days	Specialties												
117	1.1.6.12 Install Column Covers 5 days	5 days	Mon 5/19/14	2 days	Millwork/Tops												
136	1.1.6.31 Install Floor Protection 3 days	3 days	Wed 5/21/14	2 days	General Labor												



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ID	Task Name	Duration	Start	TF	Resource Names	SEP	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
133	1.1.6.28 Install Stone and Stainless Base	5 days	Mon 5/12/14 2 days		Title												
134	1.1.6.29 Install Upholstery & Trim & Signage	5 days	Mon 5/19/14 2 days		Specialties												
135	1.1.6.30 Install Solid Surface Material at Pk15	5 days	Mon 5/26/14 2 days		Title												
138	1.1.6.13 Concourse Work Complete	0 days	Fri 5/30/14	2 days													
141	1.1.6.36 Install Play Equipment (by Owner)	15 days	Wed 6/18/14 2 days		Specialties												
142	1.1.7 Entry 1 Concourse - Lower Level	146 days	Thu 12/5/13 12 days														
144	1.1.7.2 Start Concourse Buildout	0 days	Thu 12/5/13 0 days														
145	1.1.7.3 Lease Line Bulkhead Soft Framing	5 days	Tue 2/18/14 14 days		Framing												
146	1.1.7.4 Fire Protection Main Rough-in	3 days	Thu 3/6/14	13 days	Fire Protection												
147	1.1.7.5 Ceiling Framing	5 days	Fri 3/21/14	11 days	Framing												
148	1.1.7.6 LV/FA/FP/ELEC R-4@Drops Above C5	5 days	Fri 3/28/14	11 days	MEPF												
149	1.1.7.7 Mech Rough-in Thru Lease Line Fas2	5 days	Fri 4/11/14	11 days	MEPF												
150	1.1.7.8 Install Drywall & Finish	5 days	Tue 4/15/14	11 days	Drywall												
151	1.1.7.9 First Coat of Paint	1 day	Tue 4/22/14	11 days	Painting												
152	1.1.7.10 Touch-Up Drywall Finish	2 days	Tue 4/29/14	11 days	Drywall												
153	1.1.7.11 Second Coat of Paint	1 day	Thu 5/1/14	11 days	Painting												
154	1.1.7.14 MEP/FP Trim-Out	2 days	Thu 5/1/14	49 days	MEPF												
155	1.1.7.12 Tile Setting Bed	5 days	Mon 5/5/14	12 days	Title												
143	1.1.7.13 Install Floor Tile	5 days	Mon 6/16/14 12 days		Title												
143	1.1.7.1 Walkoff Mat	1 day	Mon 6/23/14 12 days		General Labor												
157	1.1.7.15 Concourse Work Complete	1 day	Tue 6/24/14	12 days													

Project: University Town Center -
Date: Wed 3/15/17

Task Split

Milestone Summary

Project Summary

External Milestone

Inactive Milestone

Manual Task

Duration-only

Manual Summary Rollup

Manual Summary

Start-only

Finish-only

Deadline

Critical

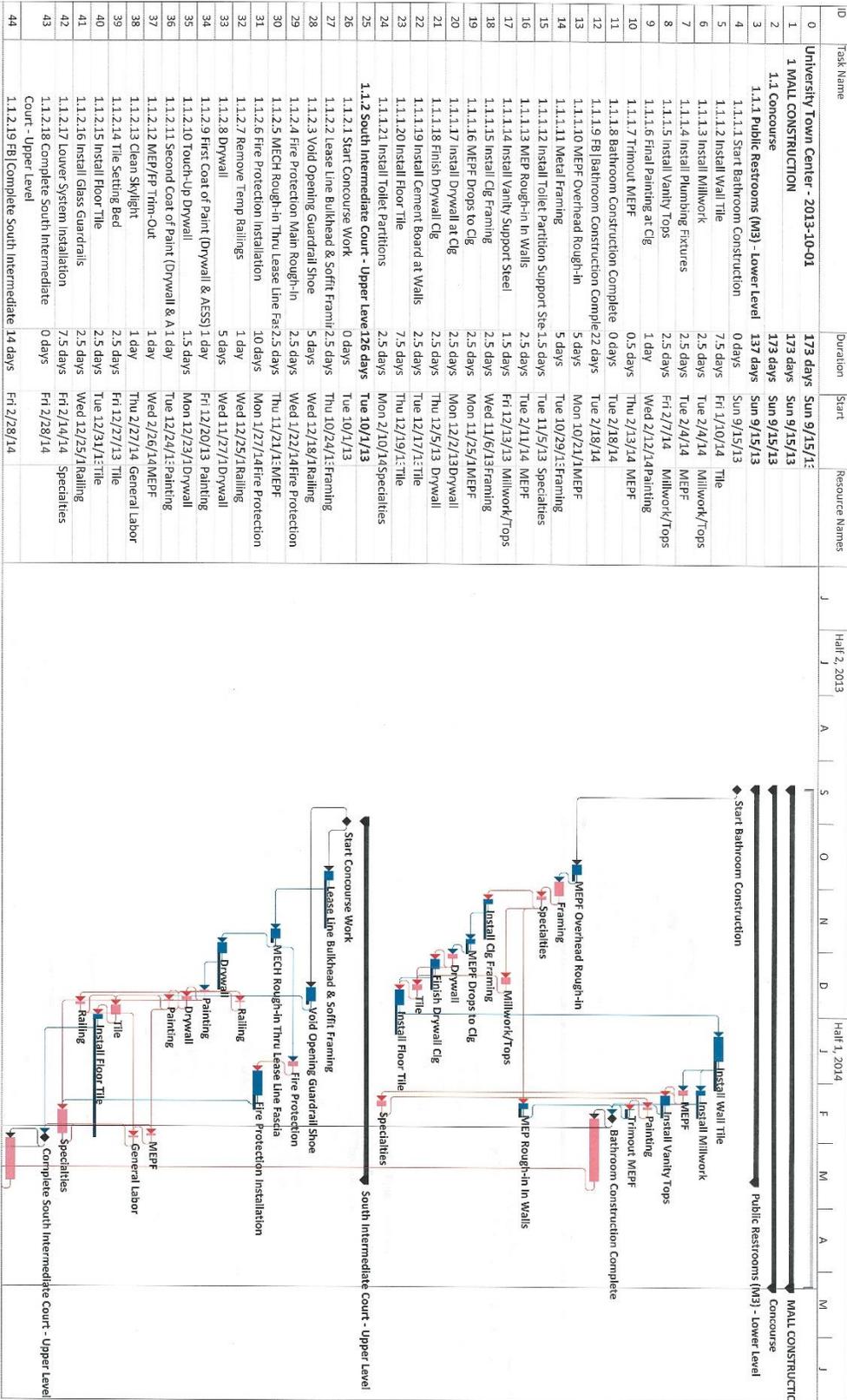
Critical Split

Progress

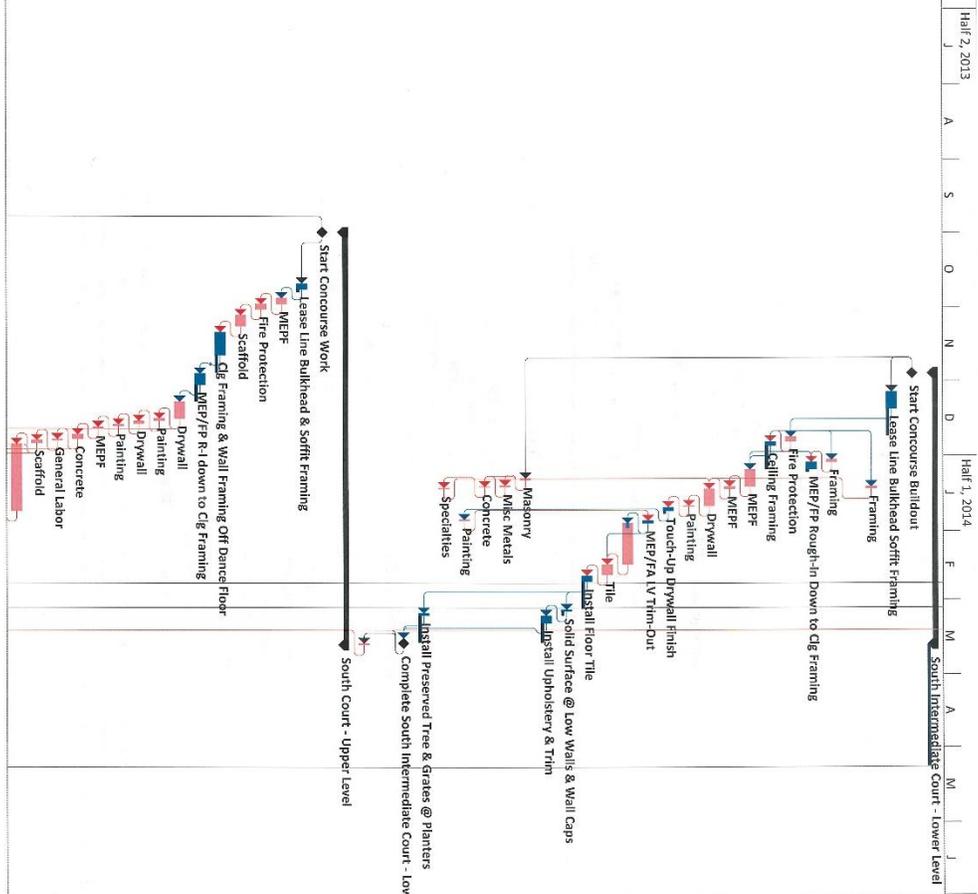
Manual Progress

Slack

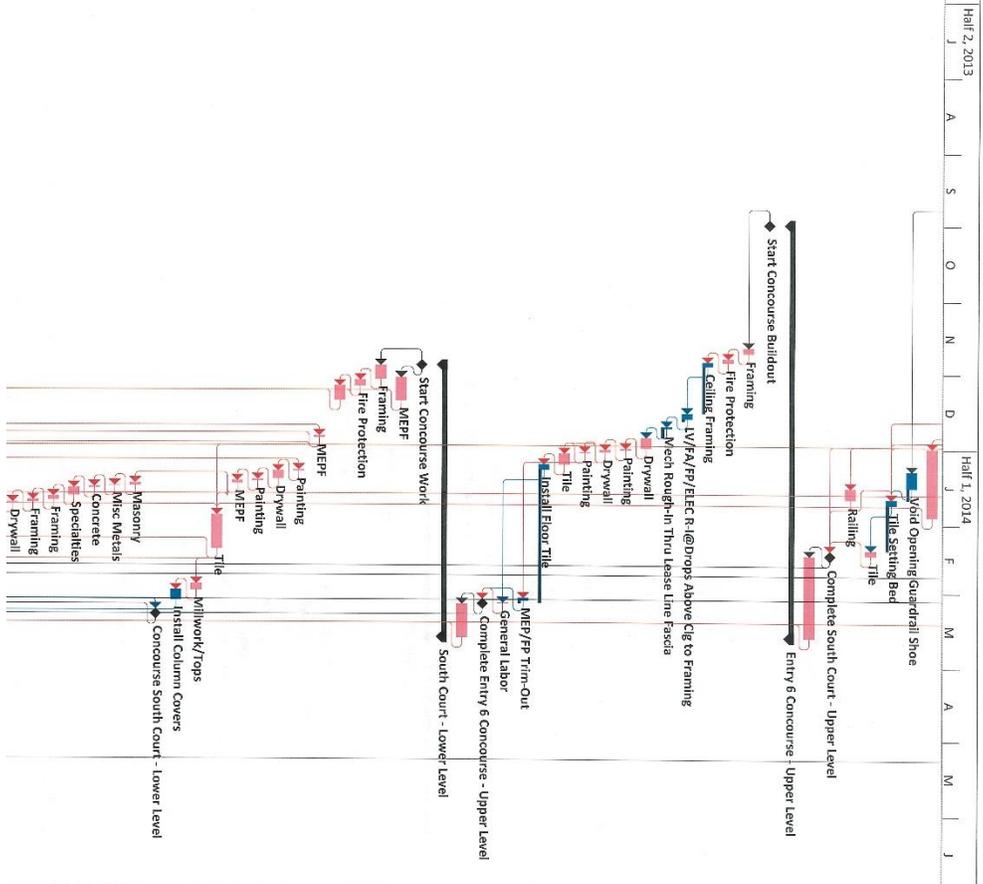
Appendix B: CCPM Schedule



ID	Task Name	Duration	Start	Resource Names
45	1.1.3 South Intermediate Court - Lower Level 83 days	Thu 11/28/13		
46	1.1.3.1 Start Concourse Buildout	0 days	Thu 11/28/13	
47	1.1.3.2 Lease Line Bulkhead Soffit Framing	5 days	Thu 12/5/13	Framing
48	1.1.3.3 Metal Framing at Clgs Below Monumental Stair Landings	1 day	Mon 1/13/14	Framing
49	1.1.3.4 Metal Framing at Columns	1 day	Thu 1/2/14	Framing
50	1.1.3.5 MEP/FP Rough-In Down to Clg Fram 1 day	MEPF	Fri 1/3/14	MEPF
51	1.1.3.6 Fire Protection Main Rough-In	3.5 days	Tue 12/24/13	Fire Protection
52	1.1.3.7 Ceiling Framing	2.5 days	Wed 12/25/13	Framing
53	1.1.3.8 LV/FA/FP/ELEC R-1@Drops Above C5 days	MEPF	Mon 1/6/14	MEPF
54	1.1.3.9 Mech Rough-In Thru Lease Line Fas 1 day	MEPF	Mon 1/13/14	MEPF
55	1.1.3.10 Install Drywall & Finish	5 days	Tue 1/14/14	Drywall
56	1.1.3.11 First Coat of Paint	0.5 days	Tue 1/21/14	Painting
57	1.1.3.12 Touch-Up Drywall Finish	1.5 days	Wed 1/22/14	Drywall
58	1.1.3.13 MEP/FA LV Trim-Out	1 day	Mon 1/27/14	MEPF/FA LV Trim-Out
59	1.1.3.14 FB MEP/FA LV Trim-Out-2641	1.3 days	Tue 1/28/14	MEPF
60	1.1.3.15 Tile Setting Bed	2.5 days	Fri 2/4/14	Tile
61	1.1.3.16 Install Floor Tile	2.5 days	Wed 2/19/14	Tile
62	1.1.3.17 Solid Surface @ Low Walls & Wall 1 day	MEPF	Wed 3/5/14	MEPF
63	1.1.3.18 Install Upholstery & Trim	1 day	Fri 3/7/14	Specialties
64	1.1.3.19 CMU @Base of Monumental Stair 1 day	Masonry	Fri 1/10/14	Masonry
65	1.1.3.20 Misc. Metals & Metal Decking @ F0.5 days	MEPF	Mon 1/13/14	Misc Metals
66	1.1.3.21 Slab on Deck at Planter	0.5 days	Mon 1/13/14	Concrete
67	1.1.3.22 Second Coat of Paint	0.5 days	Mon 1/27/14	Painting
68	1.1.3.23 Install Seating Element Substructure 0.5 days	Specialties	Tue 1/14/14	Specialties
69	1.1.3.24 Install Preserved Tree & Grates @ 1 day	Specialties	Thu 3/6/14	Specialties
70	1.1.3.25 Complete South Intermediate Court - Lower Level	0 days	Wed 3/19/14	
71	1.1.3.26 FB Complete South Intermediate	1 day	Wed 3/19/14	
72	1.1.4 South Court - Upper Level 126 days	Tue 10/1/13		
73	1.1.4.1 Start Concourse Work	0 days	Tue 10/1/13	
74	1.1.4.2 Lease Line Bulkhead & Soffit Fram 1.5 days	Framing	Tue 10/22/13	Framing
75	1.1.4.3 MECH Rough-In Thru Lease Line Ra 2.5 days	MEPF	Mon 10/28/13	MEPF
76	1.1.4.4 Fire Protection Main Rough-In	2.5 days	Wed 10/30/13	Fire Protection
77	1.1.4.5 Scaffolding & Dance Floor	5 days	Mon 11/4/13	Scaffolding
78	1.1.4.6 Clg Framing & Wall Framing Off Dar 7.5 days	Framing	Mon 11/11/13	Framing
79	1.1.4.7 MEP/FP R-1 down to Clg Framing	5 days	Thu 11/28/13	MEPF
80	1.1.4.8 Drywall at Ceiling and Walls	5 days	Mon 12/9/13	Drywall
81	1.1.4.9 First Coat of Paint (Drywall & AESS) 1 day	MEPF	Mon 12/16/13	MEPF
82	1.1.4.10 Touch-Up Drywall	1.5 days	Tue 12/17/13	Drywall
83	1.1.4.11 Second Coat of Paint (Drywall & A1 day	MEPF	Thu 12/19/13	MEPF
84	1.1.4.12 MEP/FP Trim-Out	1 day	Fri 12/20/13	MEPF
85	1.1.4.13 Punch Scaffold Area Drywall	2.5 days	Mon 12/23/13	Concrete
86	1.1.4.14 Clean Skylight	1 day	Wed 12/25/13	General Labor
87	1.1.4.15 Lower Scaffold/Remove Temp Rai 2.5 days	Scaffolding	Wed 12/25/13	Scaffolding
88	1.1.4.16 FB Lower Scaffold/Remove Temp 20 days	Scaffolding	Fri 12/27/13	Scaffolding



ID	Task Name	Duration	Start	Resource Names
89	1.1.4.17 FB Lower Scaffold/Remove Temp 20 days	20 days	Tue 12/23/13	
90	1.1.4.18 Void Opening Guardrail Shoe	5 days	Fri 1/10/14	Railing
91	1.1.4.19 Tile Setting Bed	2.5 days	Tue 1/21/14	Tile
92	1.1.4.20 Install Floor Tile	2.5 days	Fri 2/11/14	Tile
93	1.1.4.21 Install Glass Guardrails	2.5 days	Fri 1/17/14	Railing
94	1.1.4.22 Complete South Court - Upper Lev 0 days	0 days	Fri 2/14/14	
95	1.1.4.23 FB Complete South Court - Upper Lev 0 days	0 days	Fri 2/14/14	
96	1.1.5 Entry 6 Concourse - Upper Level	126 days	Tue 10/9/13	
97	1.1.5.1 Start Concourse Buildout	0 days	Tue 10/9/13	
98	1.1.5.2 Lease Line Bulkhead Soffit Framing	2.5 days	Wed 11/20/13	Framing
99	1.1.5.3 Fire Protection Main Rough-in	1.5 days	Mon 11/25/13	Fire Protection
100	1.1.5.4 Ceiling Framing	2.5 days	Tue 11/26/13	Framing
101	1.1.5.5 LV/FA/FP/ELEC R@Drops Above C2.5 days	2.5 days	Tue 12/17/13	MEPE
102	1.1.5.6 Mech Rough-in Thru Lease Line Fas 1 day	1 day	Mon 12/23/13	MEPE
103	1.1.5.7 Install Drywall & Finish	2.5 days	Fri 12/27/13	Drywall
104	1.1.5.8 First Coat of Paint	0.5 days	Wed 1/1/14	Painting
105	1.1.5.9 Touch-up Drywall finish	1 day	Wed 1/1/14	Drywall
106	1.1.5.10 Second Coat of Paint	0.5 days	Thu 1/2/14	Painting
107	1.1.5.11 Tile Setting Bed	2.5 days	Fri 1/3/14	Tile
108	1.1.5.12 Install Floor Tile	2.5 days	Tue 1/7/14	Tile
109	1.1.5.13 MEP/FP Trim-Out	1 day	Mon 3/3/14	MEPE
110	1.1.5.14 Walkoff Mat	0.5 days	Wed 3/5/14	General Labor
111	1.1.5.15 Complete Entry 6 Concourse - Upper Level	10 days	Thu 3/6/14	
112	1.1.6 South Court - Lower Level	83 days	Thu 11/28/13	
113	1.1.6.1 Start Concourse Work	0 days	Thu 11/28/13	
114	1.1.6.2 MEPF Overhead Rough-in	7.5 days	Tue 12/3/13	MEPE
115	1.1.6.3 Lease Line Bulkhead & Soffit Frami 5 days	5 days	Thu 12/26/13	Framing
116	1.1.6.4 Fire Protection Main Rough-in	2.5 days	Wed 12/18/13	Fire Protection
117	1.1.6.5 FB Fire Protection Main Rough-in	14 days	Fri 12/6/13	MEPE
118	1.1.6.6 MECH Rough-in Thru Lease Line Fas 1 day	1 day	Fri 12/27/13	MEPE
119	1.1.6.7 First Coat Paint	0.5 days	Fri 1/10/14	Painting
120	1.1.6.8 Touch-up Drywall finish	1.5 days	Fri 1/10/14	Drywall
121	1.1.6.9 Second Coat Paint	0.5 days	Tue 1/14/14	Painting
122	1.1.6.10 ME/FP/FA Trimout	1 day	Tue 1/14/14	MEPE
123	1.1.6.11 Install Floor Tile	10 days	Tue 1/28/14	Tile
124	1.1.6.12 Install Carpeting and Wood Floor 2.5 days	2.5 days	Wed 2/25/14	Millwork/Tops
125	1.1.6.13 Install Column Covers	2.5 days	Fri 2/28/14	Millwork/Tops
126	1.1.6.14 Concourse South Court - Lower Lev 0 days	0 days	Mon 3/10/14	
127	1.1.6.15 CMU @ Planters/Escalator Seating 1 day	1 day	Wed 1/15/14	Masonry
128	1.1.6.16 Misc Metals & Metal Decking @ P.O 5 days	5 days	Thu 1/16/14	Misc Metals
129	1.1.6.17 Pour Slab on Deck at Planter	0.5 days	Fri 1/17/14	Concrete
130	1.1.6.18 Install Seat Element Substructure	1.5 days	Fri 1/17/14	Specialties
131	1.1.6.19 Metal Framing for Play Court Low	1.5 days	Tue 1/21/14	Framing
132	1.1.6.20 Tube Steel/Misc Metal Framing at 1 day	1 day	Wed 1/22/14	Framing
133	1.1.6.21 GWB Sheathing at Low Walls	0.5 days	Thu 1/23/14	Drywall
134				



ID	Task Name	Duration	Start	Resource Names	Half 2, 2013	Half 1, 2014
135	1.1.6.2.2 Metal Framing @Escalator Truss 81.5 days	81.5 days	Mon 12/30/13	Framing		
136	1.1.6.2.3 MEP/FP @ Escalator Ceiling to Fra.1 day	1 day	Tue 12/31/13	MEPF		
137	1.1.6.2.4 Escalator Sheathing at Framing 1 day	1 day	Wed 1/1/14	Framing		
138	1.1.6.2.5 Metal Framing at Court Columns 0.5 days	0.5 days	Wed 1/1/14	Framing		
139	1.1.6.2.6 Sheathing at Court Columns 0.5 days	0.5 days	Thu 1/2/14	Millwork/Tops		
140	1.1.6.2.7 Tile Setting Bed 2.5 days	2.5 days	Fri 1/24/14	Tile		
141	1.1.6.2.8 Install Wood Veneer at Court-3 days	3 days	Tue 2/11/14	Millwork/Tops		
142	1.1.6.2.9 FB Install Wood Veneer at Court-3 days	3 days	Tue 2/18/14	Tile		
143	1.1.6.30 Install Stone and Stainless Base 2.5 days	2.5 days	Fri 2/21/14	Specialties		
144	1.1.6.31 Install Upholstery & Trim & Signage 2.5 days	2.5 days	Mon 3/3/14	Specialties		
145	1.1.6.32 Install Solid Surface Material at Pl.2.5 days	2.5 days	Thu 3/6/14	Tile		
146	1.1.6.33 FB Install Floor Protection-2685 3 days	3 days	Wed 3/5/14	General Labor		
147	1.1.6.34 Install Floor Protection 1.5 days	1.5 days	Mon 3/3/14	General Labor		
148	1.1.6.35 Install Preserved Tree and Grate @ 11 day	11 days	Fri 2/28/14	Specialties		
149	1.1.6.36 Metal Stud Framing at Cig 7.5 days	7.5 days	Thu 12/12/13	Framing		
150	1.1.6.37 LV/FA/FP/ELEC R-8/Drops Above (5 days	5 days	Tue 12/24/13	MEPF		
151	1.1.6.38 Install Drywall & Finish 5 days	5 days	Fri 1/3/14	Drywall		
152	1.1.6.39 Install Play Equipment (by Owner) 7.5 days	7.5 days	Mon 3/10/14	Specialties		
153	1.1.7 Entry 1 Concourse - Lower Level 77 days	77 days	Thu 12/5/13	General Labor		
154	1.1.7.1 Walkoff Mat 0.5 days	0.5 days	Wed 3/5/14	General Labor		
155	1.1.7.2 Start Concourse Buildout 0 days	0 days	Thu 12/5/13	Framing		
156	1.1.7.3 Lease Line Bulkhead Soffit Framing 2.5 days	2.5 days	Wed 2/5/14	Framing		
157	1.1.7.4 Fire Protection Main Rough-in 1.5 days	1.5 days	Mon 2/10/14	Fire Protection		
158	1.1.7.5 Ceiling Framing 2.5 days	2.5 days	Tue 2/11/14	Framing		
159	1.1.7.6 LV/FA/FP/ELEC R-@Drops Above 2.5 days	2.5 days	Fri 2/14/14	MEPF		
160	1.1.7.7 Mech Rough-in Thru Lease Line Fas 1 day	1 day	Tue 2/18/14	MEPF		
161	1.1.7.8 Install Drywall & Finish 2.5 days	2.5 days	Wed 2/19/14	Drywall		
162	1.1.7.9 First Coat of Paint 0.5 days	0.5 days	Mon 2/24/14	Painting		
163	1.1.7.10 Touch-up Drywall Finish 1 day	1 day	Mon 2/24/14	Drywall		
164	1.1.7.11 Second Coat of Paint 0.5 days	0.5 days	Tue 2/25/14	Painting		
165	1.1.7.12 Tile Setting Bed 2.5 days	2.5 days	Wed 2/26/14	Tile		
166	1.1.7.13 Install Floor Tile 2.5 days	2.5 days	Fri 2/28/14	Tile		
167	1.1.7.14 MEP/FP Trim-Out 1 day	1 day	Tue 3/4/14	MEPF		
168	1.1.7.15 Complete Entry 1 Concourse - Low 0.5 days	0.5 days	Wed 3/5/14	MEPF		
169	1.1.7.16 FB (Complete Entry 1 Concourse - 10 days	10 days	Thu 3/6/14	MEPF		
170	1.1.8 Project Completion 36 days	36 days	Thu 3/20/14	MEPF		
171	1.1.8.1 Project completed 0 days	0 days	Thu 3/20/14	MEPF		
172	1.1.8.2 PB (Project completed-2718 36 days	36 days	Thu 3/20/14	MEPF		

Project: University Town Center -
Date: Wed 3/15/17

Task Split

Milestone Summary

Project Summary

External Milestone

Inactive Task

Inactive Milestone

Inactive Summary

Manual Task

Duration-only

Manual Summary Rollup

Manual Summary

Start-only

Finish-only

Deadline

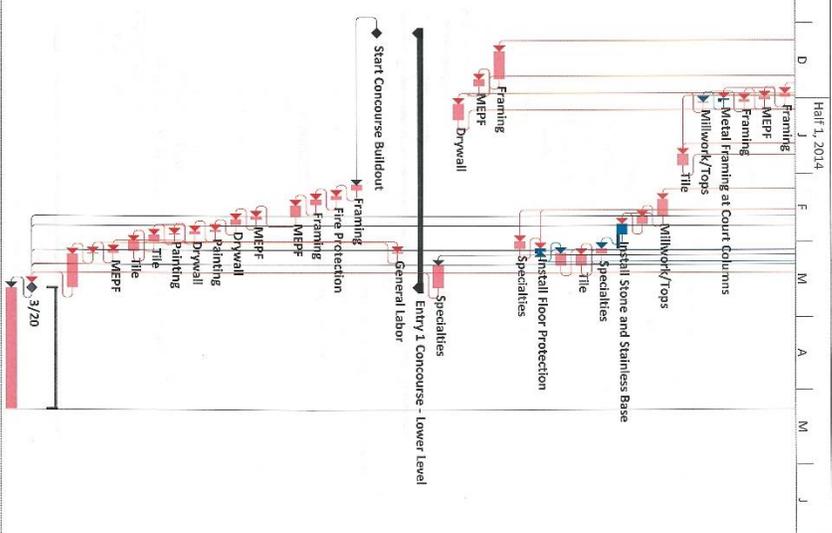
Critical

Critical Split

Manual Progress

Slack

Progress



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