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Geometric Information Scheduling to Identify and Resolve Spatial Conflicts And Increase Efficiency of Space Use on Construction Projects

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Geometric Information Scheduling to Identify and Resolve Spatial Conflicts
And Increase Efficiency of Space Use on Construction Projects

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One of the major problems with construction scheduling is the identification and avoidance of spatial conflicts between activities. These conflicts can lead to rework and delays which translate into increased construction costs. Historically, the construction manager is responsible for identifying and eliminating activity time-space conflicts based on his/her experience. Previous studies proposed time-space conflict resolution through schedule modification. This research develops a new procedure that identifies potential time-space conflicts between activities while generating the construction schedule. Each activity is modeled as a rectangular cuboid with coordinates oriented along the {x-y-z} planes. The approach consists of sequencing the rectangles into the site and forms the basis of the schedule. Heuristics are used to optimize the space usage resulting in the most efficient construction schedule for the given construction space. A major advantage of this approach is the relative simplicity of the process and thus the increased likelihood of implementation on construction sites. In a case study, the process was validated by producing a construction schedule for a completed interior renovation project. The geometric information schedule process reduced the CPM network schedule submitted by the contractor by 31.6%. The results of the study are favorable and confirm potential use for this process in practice. This research expands time-space management concepts previously presented and defines these concepts in a user-friendly fashion.

This dissertation by Edward Phillip Schied, Jr. fulfills the dissertation requirement for the doctoral degree in Program of Civil Engineering approved by Associate Professor Gunnar Lucko, Ph.D., as Director, and by Chair and Professor Lu Sun, Ph.D., and Professor Poul Lade, Ph.D. as Readers.

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Associate Professor Gunnar Lucko, Ph.D., Director

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Chair and Professor Lu Sun, Ph.D., Reader

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Professor Poul Lade, Ph.D., Reader

Dedication

To my wife Carol, daughter Hannah, and son Jack who constantly encouraged me to get busy and stay with my research even when the last thing I wanted to do was write.

To my parents who always supported me and urged me to do my best at whatever endeavor I pursued.

To my brother John who was the inspiration for the initial marriage of construction scheduling and industrial techniques. John has spent his entire professional career in the auto industry and his work with lean manufacturing processes initially caused me to think of applying knowledge from his industry to mine.

To my cousin, Dr. C. Keith Groty who promotes within me the drive to improve myself as a scholar, a father, and an engineer.

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Acknowledgements

For 11 years I was the Structural Engineer for Baltimore County Public Schools. During that tenure, one of my tasks was to manage construction projects within the various system structures. Often these projects were completed concurrently with students present in the structure. Therefore the task was to complete the construction within budget as well as keeping the students and staff safe while the work progressed. The desire to complete the projects successfully lead to thoughts of how to manage the space on the projects and thus the impetus for this research.

As I write these words I am grateful for the knowledge, encouragement and assistance of all my friends, colleagues and instructors who have been instrumental in the completion of this research.

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CHAPTER 1

Introduction

1.1 Research Motivation

Good planning is essential for successfully completing any project. In the construction industry, the Critical Path Method (CPM) of scheduling is widely considered the industry standard (Galloway 2006). CPM is utilized to produce a project schedule resulting in the least amount of time based on the information supplied concerning the required activities. The advantages of this type of scheduling include a clearly defined sequence of activities, creation of comprehensive milestone dates and similar metrics used by contractors and owners to gage performance, and a clearly defined listing of resource requirements. For all the strengths of the CPM method, its greatest limitation is the inability to define time-space conflicts that can result from activity interaction in the physical world. Mallasi (2005) suggested workspace interference was a factor in decreasing productivity by as much as 40%. Earlier, Yamin and Harmelink (2001) identified time and money as the scarcest resources on any project. In spite of these findings, the identification and correction of potential conflicts remains the responsibility of the construction manager and his or her experience. It is reasonable to assume that eliminating time-space conflicts on a project will result in substantial savings to contractors and owners yet only in the past decade has the industry started considering their resolution as a priority.

Previous studies have been conducted concerning conflict identification on construction sites and the subsequent resolution of the identified problems has lead to the concept of space management (Guo 2002; Thabet and Beliveau 1994; and Winch and North 2006). These previous studies shared a common resolution technique that included schedule modification as a means of resolving time-space conflicts. Start times for conflicting activities can be modified based on the free float identified for the various activities. Free Float (FF), also known as Activity Float (AF), is defined as the difference between the earliest time an activity can start, compared to the latest time that same activity can start, without extending the overall project duration. (Lucko et al. 2007) The disadvantage of this method of conflict resolution is the requirement that a schedule must be generated prior to identification of potential time-space solutions. The purpose of this research is to create a scheduling technique that can identify time-space conflicts concurrent with developing the project schedule

Inspiring change can come to any industry by reviewing other related or dissimilar industries, learning from their experiences, and applying that knowledge to the initial industry practices. As an example, a well known hospital greatly improved their productivity by immersing themselves into the Japanese style of management practiced by the Toyota Motor Company of Japan (Taylor 2011). By applying just-in-time concepts used on the automobile assembly line, the hospital reduced patient wait time and identified other areas of waste within their system. Members of this hospital now present training sessions for other hospitals. Using a similar line of thinking, a solution to time-space conflict resolution in the construction industry might be identified in a dissimilar industry. Recent advances in three dimensional (3-D) computer graphics have made it possible for design professionals to graphically identify construction activities as solid shapes. In the abstract sense, these 3-D activity simulations resemble cartons stacked upon one another much like parcels packed into storage bins.

Typically, the packing industry seeks to optimize the number of 3-D cartons packed within a minimum volume of a container (Tsai and Li 2006). Extending that philosophy to the construction scheduling industry yields a model based on individual activities packed in a similar fashion to boxes in a crate. If each activity can be defined as a 3-D rectangular space, then it is reasonable to assume that the same methods used for packing boxes into a container can apply to packing the construction activities within a clearly defined work space. The purpose of this research is therefore to develop a scheduling tool the construction manager can implement that identifies activity time-space conflicts and creates a schedule based on the activities' spatial needs and constraints.

The first section of this study is a review of theories and practices associated with construction planning. These theories form the basis to develop the time-space resolution strategy presented in this study. Once the strategy is defined, the challenge faced is to adapt current algorithms associated with the packing industry to conflict resolution in the construction industry; specifically interior construction activities associated with renovation of existing structures. Throughout this study references will be made to site management planning and similarities identified between site construction and interior work will be noted. However, the emphasis of this study is to identify interior time-space construction conflicts confined within the limits of the structural envelope, while the management of site work is left for future study. The final sections are case studies of actual projects and validation of the theory.

1.2 Construction Scheduling

1.2.1 Objectives

The purpose of construction scheduling is to model various activities into a network representation that allows for easy identification of sequencing, a clear definition of completion milestones to monitor progress, an accurate definition of the required resources and the identification of potential conflicts either labor, equipment or construction. Conflicts between activities can lead to reduced productivity and possible delays to the project resulting in added costs to the project. As previously stated, the objective of any successful construction schedule is to complete the project in the least amount of time for the least amount of money. The reader should note often these two factors may be counteracting.

The construction industry is an extremely diverse industry ranging from the one-man “handyman-type” home improvement firms to multinational mega corporations with simultaneous projects on all continents throughout the world. For simple construction projects the planning is often a non-formalized collection of intuitive steps rarely documented. On major construction projects the final approved construction schedule may be printed on large sheets of paper and attached to the wall of the office or jobsite trailer to provide a graphic representation of the project’s progress as well as updated and shared electronically.

1.2.2 Assumptions

Construction activities are assumed to be uninterrupted once commenced. The fact that construction activities remain constant is a requirement to preserve the sequencing logic between activities. If an activity is started, stopped, then restarted, it actually represents two activities and should be designated as such in any construction schedule. Construction schedules are assumed to be governed by laws of nature as well as common sense. In other words a construction schedule cannot have negative time values nor can a floor tile be applied to a floor surface that has not been constructed. Finally, sequencing of construction activities is related to construction scheduling. A key component of this research is the sequencing of activities to avoid conflicts that occur due to scheduling.

1.2.3 Theoretical Approaches

Many forms of construction planning exist. From the basic graphic representation such as a bar chart, to the more precise CPM and Linear Scheduling techniques, the common goal of all the procedures is to provide a path or detailed guide for the completion of the required construction activities and for planning and controlling purposes.

Projects are composed of many activities requiring interfacing and shared responsibilities. Using a work breakdown structure (WBS), each of the tasks can be defined by a work package (WP) that clearly defines schedule objectives, individual responsibilities and coordination efforts (Chua and Godinot 2006). As these WPs are developed and assembled, they identify “gray areas” where the definite responsibilities are blurred or vague. Identifying these gray areas and resolving them before they appear in the field eliminate possible rework and project delays. This form of project management is used in the manufacturing industry, but seldom in construction due to the amount of work required for proper creation and monitoring. The recent losses in the economy have resulted in driving down the prices of construction projects while the costs of materials and fuel remain high. The result is a lowering of the profit margins and the conscious effort of contractors to eliminate any potential costs, especially the costs associated with non-revenue generating items such as WBS analysis of projects, from their bids.

1.2.3.1 Graphic Representation as a Bar Chart

A rudimentary form of construction scheduling is a graphic representation of the various activities comprising the construction process. This representation can be a basic sketch or an elaborate diagram. Typically, the graphic sketch should include the construction activities, a duration for each activity, and a time scale that can be hours, weeks, days, months, etc. and finally start and finish dates. The objective of the graphic representation is to present the process information in a meaningful way to individuals who may not be as experienced as the planner. Graphic representations can be boxes with labeled activities and arrows indicating sequence patterns and relationships or bubble diagrams. While easy to read, sketches and bubble diagrams lack the ability to be updated as well as information regarding elapsed time or the relationship between activities. The bar chart, unlike previously discussed graphic schedules, provides graphic relationships from the start of an activity to the finish of a preceding activity as shown in Figure 1.1.

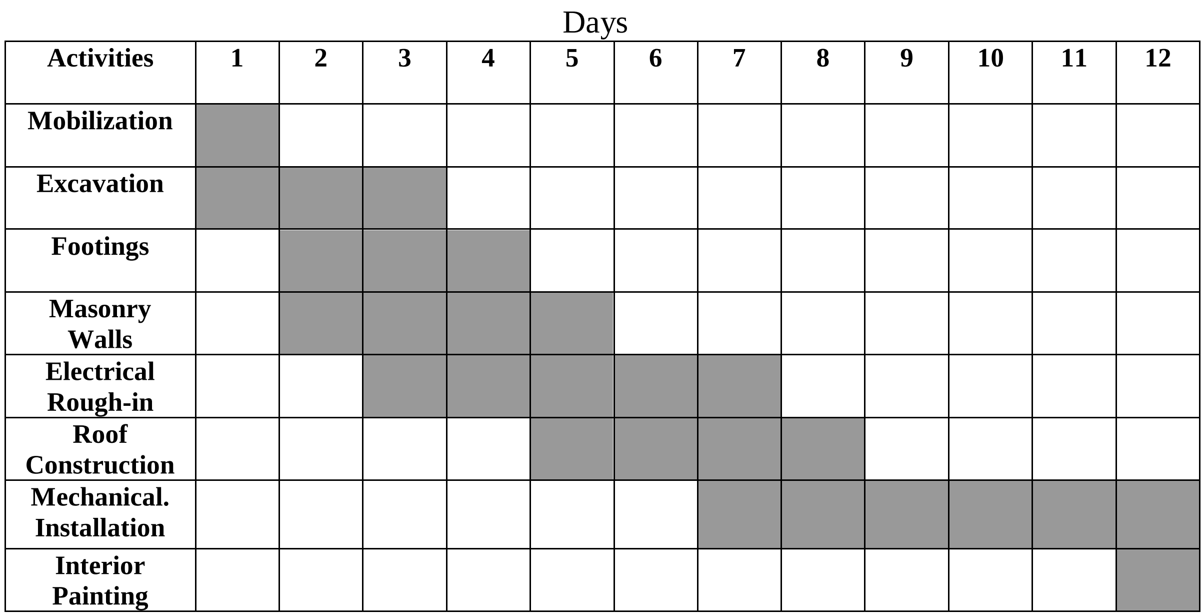

Figure 1.1: Example of a Typical Bar Chart Schedule

In a bar chart, project activities are listed along the vertical axis and the durations listed along the horizontal axis. Each activity is listed on a separate row and the duration of the activity is represented by shading each day. The result is a simple graphic representation of the construction process. This method is an effective management tool for unsophisticated projects, because both experienced and non-experienced construction individuals can identify schedule adherence and future project requirements. For more complex projects, this graphic representation is unable to fully define the project or the resource requirements and lacks the ability for updates without complete regeneration of the schedule. The graphic representation is a record-keeping tool and lacks the ability to function as a true planning tool. Therefore a “thinking” process was developed that took the best qualities of the graphic representation and enhanced those traits with the ability to introduce logic, sequencing, and resource management into the construction scheduling process while at the same time allowing for the calculation of start and finish dates and determination of criticality and float.

1.2.3.2 CPM – Critical Path Method

Since the 1950's, the Critical Path Method (CPM) has contributed significantly to construction planning and control (Lu et al. 2009). In AIA Document A201-1997, a construction industry standard form of agreement between owner and contractor, Section 3.10.1.1 states that a construction schedule "shall be detailed in a precedence-style critical path management (CPM) or primavera-type format satisfactory to the owner…" as a contractual requirement between owner and contractor. The concept of CPM scheduling was developed in Delaware at the DuPont facilities in the twenty seven months from December 1956 to February 1959 (Kelley and Walker 1989). The early objective was to develop a technique that could store and retrieve vast quantities of information associated with project scheduling as a means of improving planning, estimating and scheduling of construction projects. Computers were in their infancy at that time and much of the early work associated with CPM development was completed by mathematicians inventing relevant code.

Today, numerous computer programs have been developed utilizing the CPM technique and are currently employed for all types of construction project scheduling. In a recent survey, 80% of the respondents stated they rely on CPM schedules for making decisions on project execution. In addition, 96% of those same respondents believed having a CPM schedule for their project created an economic benefit for their company. (Galloway 2006). Schedules developed using CPM are routinely used by owners, contractors, and construction managers to insure contractor compliance with project requirements. Milestones established by the schedule are used for all facets of the project including resource purchasing and scheduling, interim payments for work completed as well as legal actions due to delays and project extensions.

The first step in developing a CPM schedule is to identify each of the activities associated with the project. Each activity is given a duration and sequencing logic defined by precedence or restrictions. Using the sequencing logic a graphic representation of the network is developed. Typically the graphic representation is composed of arrows, nodes and descriptions of the activities. Nodes are the circles or identification numbers used to define an activity. In an *i-j* system, an activity is described using the combination of node numbers at the head (*i-node)* and the tail (*j-node)* of the arrow depicting the activity. The most common forms are known as “activity-on-node” or “activity-on-arrow”. In the early forms of CPM the network was expressed as a set of nodes and arrows that resembled vectors in mathematics. The reason for this choice was due to the fact the earliest developers of the CPM method were mathematicians and they were familiar with that graphic expression. An example of "activity-on-arrow" is shown in Figure 1.2.

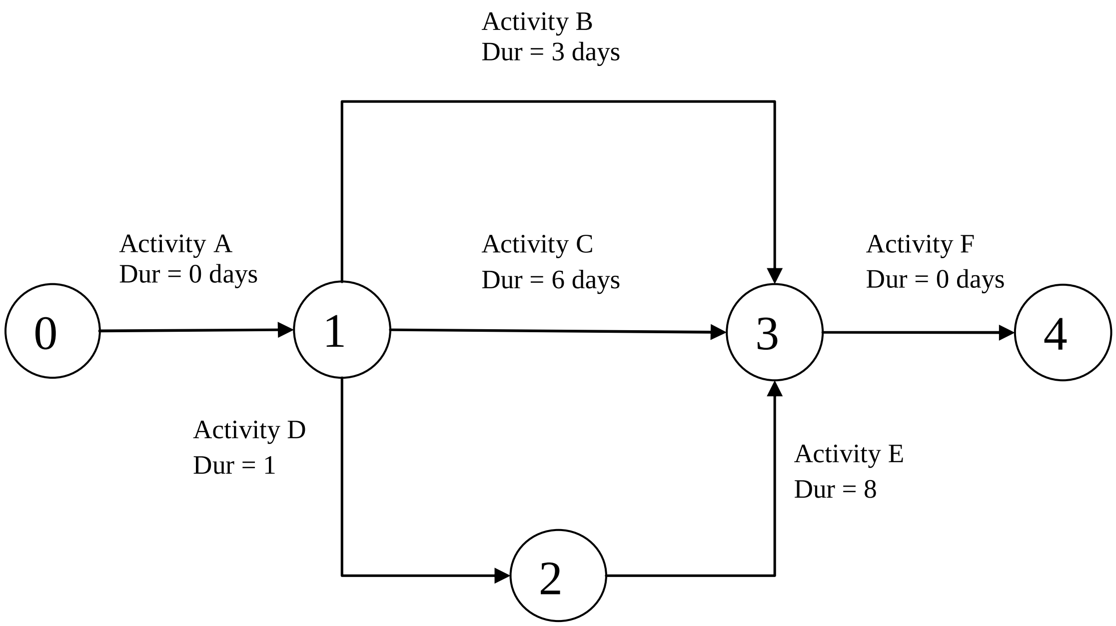

Figure 1.2: Activity-on-Arrow Project Representation

For more complex projects the activity on arrow method becomes cluttered, and often incomprehensible. In response, the industry adopted the activity-on-node approach that is cleaner and much improved over the activity on arrow method. Using the same six activity network diagramed in Figure 1.2, refer to Figure 1.3 and observe the same network defined using the activity-on-node method. The activity description serves as the node and the arrows indicate direction or logic sequence. In addition, more activity sequencing information is now included in the model relating; to the activity early and late start and finishes. In a simple construction schedule, activities are related in a finish-to-start (FS) nature.

In more complicated projects activities could be related to each other in non-FS fashion. Calculating the critical path for a network containing non-FS activities can be difficult and can occasionally lead to improper schedule times due to a misunderstanding of the logic (Lu et al. 2009). Therefore, prior to any scheduling calculations all activities must be defined as equivalent FS activities by introducing “dummy” activities into the network. A dummy activity has no duration and is used as a logic link between activities.

After defining the required activities network, the second step in the process is to identify the early finish (EF) for each activity by completing a series of calculations referred to as the *forward pass*. By definition, the early finish of an activity is the earliest date that activity is expected to be completed given its position in the network and its duration. Initiating at the designated start, the calculations move from left-to-right; for each activity and an early finish (EF) is established by adding the duration to the identified early start (ES) date. The early finish (EF) for an activity is used to establish the early start (ES) for the next activity. This continues through the entire listing of activities until reaching the finish. The summation of all the previous early finish dates is used to establish the early finish of the project.

The final step involves identification of the late start (LS) for each activity through a procedure known as the *backward pass*. The late start date of an activity is the latest point in time that the activity must be started, given its position in the network and the durations of the following activities, if the project is to be completed within the timeframe established by the forward pass calculations. The backward pass begins at the completion of the project schedule, or the finish, and proceeds from right-to-left starting with the last activity. The early finish (EF) established during the forward pass is used to define the late start (LS) to be used for the backward pass. Moving sequentially through each activity, the late finish (LF) for each activity is defined as the smallest value of the late start (LS) for all the preceding activities. Then the late start (LS) for any given activity is the sum of the late finish (LF) minus the activity duration. This procedure is continued until all activities have a late start (LS) and a late finish (LF) defined. Using the early start (ES) and the late finish (LF) for each activity, the *total float or slack* can be calculated for each activity.

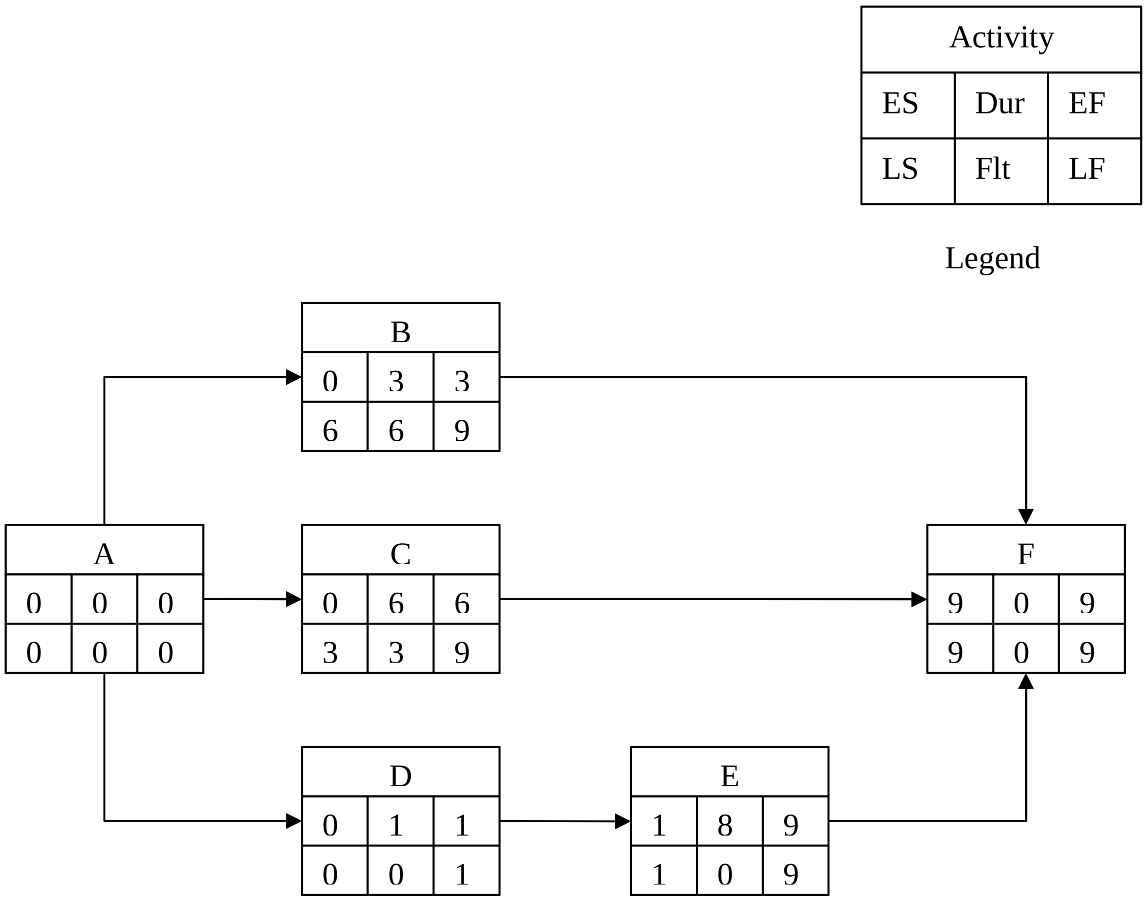

Figure 1.3: Activities-on-Nodes Project Representation

Total Float (TF) is the difference between the amount of time available to accomplish the activity and the time required to accomplish it as defined by Equation 1.1 Free Float (FF), aka Activity Float (AF), differs from the Total Float (TF) identified for each activity and is defined as the difference between the earliest time an activity can start, compared to the latest time that same activity can start, without extending the overall project duration. (Lucko et al. 2007). Free float (FF) can be calculated as the difference between early finish (EF) of one activity and minimum early start (ES) of related next activities in the network, as defined by Equation 1.2.

$$\boldsymbol{Total\ Float\ (TF)\ =\ [LF - EF]}$$ **Equation 1.1**

$$\boldsymbol{Free\ Float\ (FF) = [min\ ES_j] - EF_i\ with\ i\ < j}$$ **Equation 1.2**

At the completion of all computations, the activities with a total float (TF) equal to zero are identified as the *critical path* of completion of the project. The construction schedule is defined as the Critical Path and the duration associated with the Critical Path defines the minimum time length the project can be completed. Any changes to an activity on the Critical Path effect the overall project completion date. Free float (FF) can be used by the project manager to adjust the schedule as a tool for averaging the resources allocated for the project or elimination of time-space conflicts as they appear during construction. Unfortunately, the critical path does not identify potential time-space conflicts because as noted, the process establishes the resulting schedule on a time basis only.

1.2.3.3 Line of Balance

As an alternative to network scheduling such as CPM, linear scheduling techniques, also known as Line of Balance (LOB) scheduling, have been used for years for construction projects repetitive in nature such as pipelines, highways and tunnels

(Arditi et al. 2002). Unlike CPM, the LOB schedule is developed to maintain resource allocation given the repetitive nature of the project and is geared towards producing completed units rather than the earliest finish time based on the various activities and durations.

Any construction project that involves the completion of groups of tasks or units is suitable for this scheduling method. Repetitive projects can be defined as typical or non-typical (El-Rayes and Moselhi 2001). The typical project requires crews to work continuously from one section to the next. Idle crew time is to be avoided and the learning curve for repeated activities introduces a degree of improvement in performance. Examples of this sort of project are housing projects with identical units. Non-typical repetitive activities do not have identical procedures and duration times for similar activities. Although activities are repeated from section to section can differ from one segment to the next. An example of non-traditional repetitive projects would be a highway. Excavation quantities can vary from one portion of the road to another. The added material extends the activity duration and thus any potential learning-curve benefits are lost.

To develop a linear schedule, the first step is to calculate a value for the optimal number of units that can be performed given the crew sizes and available resources. By dividing the scope of the work identified in the construction documents, by the time allowed in the contract, a *minimum productivity* is obtained (Equation 1.3). This is termed the natural rhythm of the project (Arditi et al. 2002) and the subsequent measured outputs of the crew are defined as multiples of the natural rhythm. Discrete activities and non-linear type activities are a problem for linear schedules because they do not adhere to the rules of logic associated with the other activities; yet a failure to complete these activities in a timely fashion can cause delays to the overall project. Often these activities are inserted directly into the schedule.

$$\boldsymbol{Minimum\ Productivity = \frac{Work}{Time}} \qquad \textbf{Equation 1.3}$$

Using the natural rhythm of the project, the project duration is calculated as the quotient of the total number of units required by the contract divided by the natural rhythm. If the calculated duration is less than the contractual time limit then no further action is required. If the calculated duration exceeds the contractual time limit then changes are required for the activity production rates based on resources and financing. Changes to the individual activities modify the natural rhythm of the project and the total duration is computed as before. When the revised natural rhythm provides a completed project within the contract limits then the process is concluded. Once the final schedule is produced the project manager may make minor changes based on actions in the field during construction. Figure 1.4 illustrates a simple linear schedule using the construction activities from Section 1.2.3.2. The advantage of this method is the simplified expression of the activity relationships and durations. At the same time, if these activities were to be repeated for similar sections of various floors the resulting schedule is uncluttered and understandable.

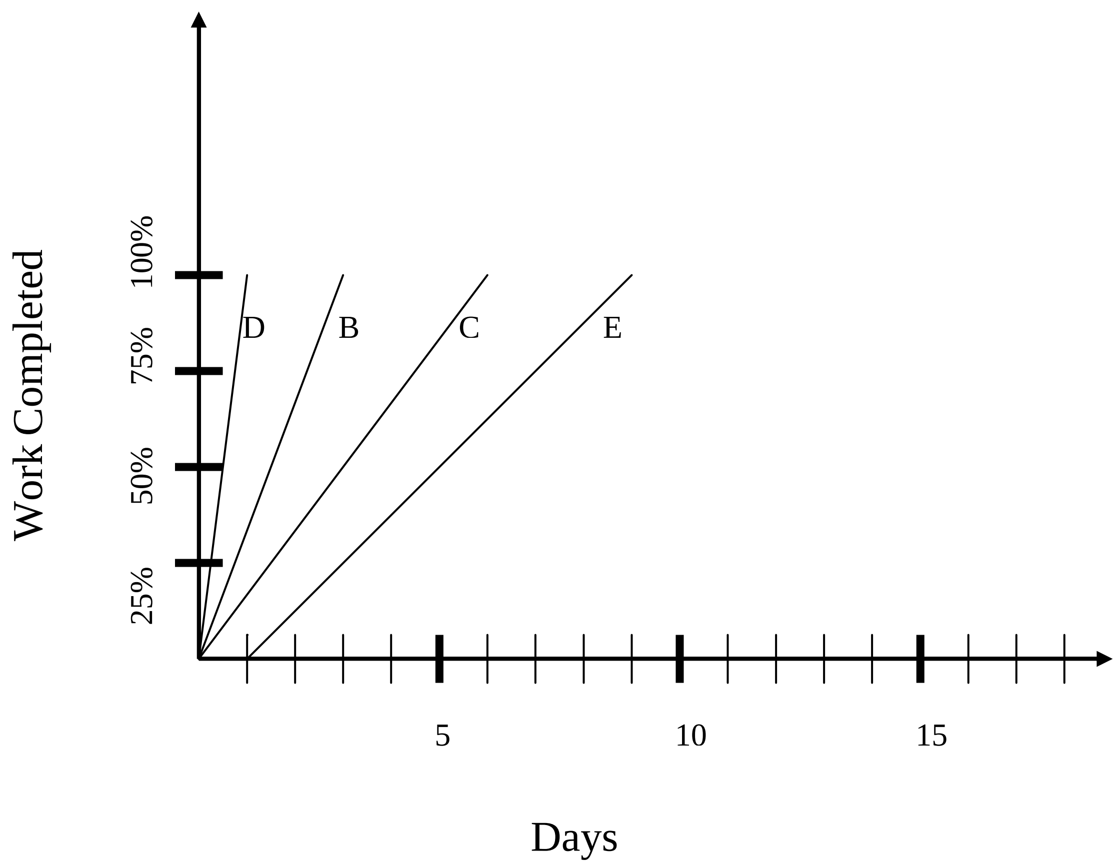

Figure 1.4: LOB Scheduling Diagram

Line of Balance scheduling has been referred to as a visual form of scheduling that lacks the calculating qualities of the network scheduling methods (Fan and Tseng 2006). Therefore the construction industry tends to overlook LOB scheduling for non-repetitive projects. Scholars have presented research that suggests methods of adding the necessary analytical methods to enable float calculation in LOB methods (Lucko 2009) or incorporation of soft logic for resource description in LOB scheduling (Fan and Tseng 2006) as an attempt to seize the advantages of LOB while maintaining the controls of network scheduling. Given the cited research (Lucko 2009; Fan and Tseng 2006) it is possible the U.S. construction industry will consider LOB for non-repetitive projects in the future however currently CPM scheduling is the dominant choice by the U.S. construction professionals for non-repetitive construction projects.

1.3 Construction Site Layout

1.3.1 Planning

Construction site layout planning is similar to designing the schematic and work-flow layout of a manufacturing plant. Both deal with the production and completion of a product. Manufacturing produces the item to be packaged and shipped to the user whereas in construction the completed structure or site is the final product.   Like a manufacturing plant operation, key items to be solved by site planning include access and traffic patterns; material storage and handling; administration activities, equipment placement, workshops and services and welfare sites such as first aid stations. (Mawdesley et al. 2002). Site layout planning is concerned with location of temporary facilities such as cranes, scaffolds, administration and welfare sites like first aid stations.

In addition, material storage and material handling paths must be identified and located such that the resulting material handling costs are minimized. Safety plays an important part in the site layout by determining the safest location of material storage and the elimination of hazardous conditions for the workers (Elbeltagi and Hegazy 2004). Since site layout planning relates the activities to each other spatially, a geometrically space scheduling tool can be used for both site planning and construction scheduling.

1.3.2 Assumptions

A basic assumption crucial for all site planning procedures is the ability to graphically represent any temporary facility or procedure in such a way that allows for location and manipulation on the project site. Typically the facility or procedure is represented as a rectangular shape and the placement is governed by two dimensional orthogonal rules. A coordinate system is required for definition and clarification.

1.3.3 Theoretical Approaches

Construction site planning can be either static or dynamic in nature. The static form of site planning establishes the various temporary facilities and material stockpiles and retains the location and size of these items throughout the entire construction project. The dynamic approach assigns initial size values to all temporary facilities and modifies them throughout the construction project as required. For most cases, the dynamic approach is superior to the static method of representing the activities on an actual job site due to the nature of construction. As the project progresses, materials are used and the resulting storage areas are depleted; the project begins to take shape and occupy initial open spaces on the site; temporary accommodations such as scaffolds and cranes may no longer be present as their portions of the project are completed.

Temporary Accommodations (TA) locations should consider the following factors as the site plan is developed (Elbeltagi and Hegazy 2004):

1. Safety should be considered first and foremost. Does the TA contain hazardous materials? Does the TA pose a physical hazard to personnel?
2. Static resources should be positioned first with mobile resources positioned next.
3. Travel distance and material handling costs associated with the TA and related construction activities should be minimized.
4. Locate TA's with greatest interaction among activities closest to the project site.
5. TA's with greater relocation costs should be located prior to TA's with lesser relocation costs.
6. Look to consolidate and eliminate TA's continually throughout the project.

1.3.4 Scope and Limitations

Site planning differs from construction activity planning in the fact site planning has the ability to revisit previous calculations. In construction activities, once the product is created any potential rework requires demolition of portions previously installed. In site planning, often a trailer or a piece of equipment can be relocated at minimal costs and provide a far superior layout with respect to material handling distances and costs. Spatial conflicts are resolved generally by the on-site staff such as the project superintendent. Site work typically moves at a much slower pace than interior construction activities and therefore the need for a conflict resolution strategy is not as critical for site work as it is for interior construction activities.

1.4 Spatial Characteristics in Construction

1.4.1 Exterior Construction

Construction space on a project is defined by the construction documents. For site activities, the “limit-of-disturbance (LOD)” defines the extreme limits of the project with respect to property lines and soil conservation requirements.

Spatial characteristics in exterior site planning resemble two-dimensional packing problems when the site is viewed from above. The overall mapping of a project site is the purpose of civil engineered site plans. These engineered drawings can be used as the basis for planning the location of the various facilities, offices and equipment required for the completion of the project.

For interior construction, the total available space is composed of *actual available space* and *artificially created available space*. Actual available space is identified as the mathematical solution of the product of the length, width and height of the structure as dictated by the construction documents. Artificially created available space is that work area created by temporary structures such as scaffolding. For the purpose of this research, space is defined as a limited quantity and therefore any resource optimization method must be an allocation type method.

1.4.2 Interior Construction

The true value of space on a construction site is not fully realized until faced with a renovation project within the confines of an existing facility, constrained on all sides, which must remain operational throughout the entire renovation process. Compounding the difficulty of construction work associated with existing structural members and existing mechanical systems is the fact many facilities have no available space for material storage throughout the construction process creating a competition for space where the available space for construction is *less* than the required space for the construction. This study will review the previous works defining space on new construction projects and use this information as a means for applying a similar rationale for renovation projects within existing structures.

1.4.3 New Construction

New construction refers to construction of a totally new structure or process. Plans are developed and the structure is built per the construction documents. Typically this form of construction is the easiest from a designer's point of view. All quantities are known or stated. The strengths of the materials are known based on product information and design mixes submitted for approval. For quality control steel products must have mill certifications submitted and the in-place construction such as cast-in-place concrete and soil compaction are monitored and verified by testing. Space is created with new construction and less complicated to manage than space associated with renovation projects because the manager defines the space based on the construction schedule. The new construction project has fewer unknown conditions than existing renovations and is less apt to be delayed by adverse unforeseen field abnormalities. But experience has shown even the best planned new construction sites experience time-space conflicts between trades.

1.4.4 Renovation

This procedure involves the destruction or revival of an existing structure or process. From a design standpoint, many crucial facts are unknown. Strengths of materials in existing structural members must be verified. Existing foundation conditions cannot be seen and limited demolition techniques are employed to expose the existing conditions. Reusing existing structures can be more expensive than total demolition and rebuilding. Space must be claimed in renovations from existing processes or removal of existing structural elements. When the existing structure is to remain occupied and functional during the renovations, the competition for available space can become heated with clashes between construction workers and the on-site employees. The need for thorough and specific space management is crucial for the project's success.

1.5 Packing Methods

1.5.1 Packing Objectives

The primary objective of any packaging problem is to maximize the number of items that can be packed into the smallest storage volume without exceeding the capacity of the storage volume or the constraints placed upon the packed items. Packing problems differ between industries. Computer programmers use a form of one-dimensional packing theories as they assign bits of information sequentially; newspapers and publishers use two-dimensional packing algorithms to arrange text, photos and advertisement copy on pages; the manufacturing industry uses three-dimensional packing equations to limit shipping costs. Historically, solutions to packing problems have been generated using algorithms defined as either traditional heuristic or meta-heuristic (Wei et al. 2008). Traditional heuristic algorithms are based on a series of steps that guide the user to a solution. An example of a traditional heuristic solution is the bottom-left (BL) method. The first item is placed in the bottom-left corner of the space and the remainder of the items are placed in the available space from that point until the space is filled or there are no more items to be packed. Meta-heuristic algorithms attempt to enhance the traditional heuristic solutions by incorporating genetic algorithms, artificial neural networks or other similar evolutionary techniques to improve the solution. In industry the benefits associated with efficient packing are numerous. The smaller the volume the less materials required to construct the shipping container, the more completely the items fill the storage container the less packing material such as foam rubber or Styrofoam are required to secure the objects within the container and the smaller the shipping container the less costs associated with shipping due to allowing more materials to be packed in a single tractor trailer, sea shipping container, rail car or airplane cargo container. The cost savings associated with the smaller container, as well as the reduced amount of packing material, can mean the difference between a product's success or failure.

These same objectives do not translate to construction projects. In the construction industry, reduced material costs are associated with elimination of rework and waste rather than producing a reduced packing vessel; product size is mandated by the construction documents and the scope of the project verses a mathematical solution to a cardinal bin packing problem. However, the efficient use of space is common to both the packing industry and the construction industry. In both industries, a “best fit” solution will produce a superior product. Construction activities and packaged items cannot share the same space. Therefore existing algorithms from the packing industry developed to identify spatial limitations could apply to the construction scheduling.

1.5.2 Theoretical Approaches

Packing problems can be considered as single dimensional or multi-dimensional in nature. Single dimensional packing problems consist of sorting items into various groups or subsets. Two-dimensional packing problems consider the placement of *n* items into a space defined by *x* and *y* coordinates. Three-dimensional packing uses two-dimensional techniques to sort items in layers. The layers are stacked upon one another and the height of the layers, expressed along the *z* axis, are determined by the height of the individual items to be packed (Lodi et al. 2001). Adding the fourth dimension of time to the 3-D packing procedure produces a 4-D packing problem.

1.6 Terminology and Definitions

For consistency and clarification in this dissertation, the following terms and definitions are presented for use by the reader. These definitions are paraphrased from various literature sources as well as self-defined by the author.

- *3D CAD drawings* – three-dimensional computer-aided design drawings
- *Activity crashing* – used as a term to indicate acceleration of the construction schedule based on the maximum allocation of available resources (Demeulemeester et al. 1998, p1153)
- *Available space* – portion of the calculated project space that remains free from construction or activities.
- *Algorithm* – mathematical equations associated with the step-by-step definition of a process or sequence

- *Conflict resolution* – solving problems or temporal overlapping of construction activities
- *Control Space* – extreme limits of the portion of the project under consideration
- *Critical Path Method* – network process to determine the minimum project duration
- *Free Float* - the difference between early finish (EF) of one activity and early start (ES) of the next activity**;** used by the project manager to adjust the schedule for averaging resource allocations (Lucko and Orozco 2009, p371)
- *Genetic Algorithms* – modeling technique based on natural selection theories from biological studies (Hegazy 1999, p170)
- *Geometric Scheduling* – use of packing techniques for development of a construction schedule
- *Material and Personnel Paths* – space on the construction site that must remain unobstructed to allow movement of materials and individuals
- *Minimum Moment Method* – systemic process for resource leveling
- *Optimization* – seeking the maximum or minimum solution to the equation
- *Optimizing space usage* – using the available space in most efficient fashion space
- *Path* – the clear space required for movement of materials and labor
- *Required space* – space necessary for the completion of a particular activity
- *Resource Allocation* - attempts to reschedule the project to utilize a limited amount of resources

- *Resource Leveling* – attempts to reduce the peaks and valleys associated with a particular commodity such as personnel or bricks while maintain the original construction schedule. This only works if the resource is unlimited.
- *Space* – total volume defined by the physical limits of the site or construction items such as beams, walls, columns, etc.
- *Space Conflict* – defined as more than one space demand claim on a specific available space during the same time period (Guo 2002, p289)
- *Total Float* - difference between the amount of time available to accomplish an activity and the time required to accomplish the activity (Lucko and Orozco 2009, p371)

1.7 Problem Statement

1.7.1 Need for Space Scheduling

Interior and exterior construction projects may differ from one another in size, complexity, and nature, however, they all share similar characteristics concerning sequencing, completion tactics and delays. A similar relationship exists between site construction projects and interior construction projects. Site construction projects can be defined as earthmoving, bridge building, construction of protective dikes and levees, etc. The one theme consistent throughout all site construction work is the fact all the work is new construction type work. Interior construction projects may be new construction work or renovation work. In addition, interior construction projects are confined to the physical limits defined by the structure; thus complicating the project further. The vast majority of new construction projects contain both site and interior elements whereas only the interior construction project can be developed solely as a renovation or reconstruction of an existing structure. Based on construction experience, it is far more difficult to complete a renovation project than a new construction project. Therefore this research is intended to solve the time-space conflicts associated with an interior renovation project because the resulting strategy can be used for new construction projects and site projects.

A literature search returned 21,097 records when the key words “construction scheduling” were entered. Refining the search by adding “space time conflicts” reduced the number of records from 21,097 to 65. Encouraged by these results, the key words “space resource” were entered to further refine the search resulting in a reduction of records from 65 to 21. Finally, the key words “space management” was added to the search and the number of records reduced from 21 to 10. These results suggest a great deal of information is available for construction scheduling; yet very little information exists relative to treating space on a construction site and even less information concerning the management of the space as a resource. Therefore, a logical conclusion to this search exercise is a need exists in the construction industry to develop an effective method for managing activity space on construction sites.

All construction activities, beyond administrative tasks completed at the home office, require space on the job site for their execution and completion. It is reasonable to assume a scheduling process that addresses spatial issues would be extremely effective in reducing wasted time and associated costs. Thabet and Beliveau (1994) proposed a knowledge-based model that identified the space required for each activity and compared the required space with the available space. The *available space* was defined as the total space for a project generated automatically by {x,y,z} coordinates taken from the CAD construction documents and contractor shop drawing submission information. The *required space* for each activity was defined by the user as the shape of the activity as well as all required resources necessary for the installation. This required space had to account for location and coordination of structural members such as columns, beams, footings, etc. with construction processes such as lifting, welding, grinding, painting, placing, etc. Prior to this study the identification and management of space was left to the individuals tasked with completing the project based solely upon the individual's experience.

As an attempt to identify and resolve work space conflicts on a construction project, Guo (2002) considered space to be a resource that had to be managed. Available space on a jobsite was divided in to four subcategories; space within the building, space outside the building envelope, space provided by temporary structures such as platforms and scaffolding, finally space exterior of the jobsite. Space was defined by CAD coordinates for the various activities and locations on the job site. The study proposed a formal procedure to analyze patterns of spatial conflicts. Using MS Project for the construction schedule and AutoCad for the construction drawings, the study identified space conflicts on the project site. Various labor, equipment, material requirements, necessary temporary structures like shoring and scaffolding were all identified for the various activities. Each activity was given a color and the labor, materials et al, were identified by separate patterns and shapes. The patterns and shapes were then layered on the drawings and the conflicts were identified. The strategy developed was to first attempt to resolve the conflicts by adjusting the schedule. If that failed then the next step was to divide the areas in to smaller sections as an attempt to stagger the start times of various portions of the activities to avoid the conflict. Following the successful resolution of the identified spatial conflicts the drawings were reviewed to verify path demands. If necessary, the schedule would be revised due to paths and the entire process repeated.

Winch and North (2006) advanced the ideas of internal space and related required space with construction planning through the idea of “critical space analysis”. Each activity has a space associated with its completion. Spatial loading was a term used to define the percentage of the available space occupied by the activity in consideration. A spatial loading of unity identified the activity as critical because no slack space was available. A spatial loading in excess of unity identified areas of congestion and conflict. They likened the approach to CPM of a project, but space was considered versus time like normal CPM analysis. Unlike previous studies that used CAD drawings to automatically generate the available space, they developed a proprietary software package that required the user to manually define the boundaries of the available space.

Space scheduling is a technique that can be used to identify spatial conflicts existing between various activities and allows for a reworking of the schedule to avoid the conflicts. All construction activities require space for the following four phases: (a) physical space the completed construction activity will permanently occupy; (b) material storage for the components of the activity; (c) path for movement of materials, workers and waste; (d) working space for the completion of the activity. (Riley and Sanvido 1995, p464) The purpose of space scheduling is to manage the available space in such a fashion as to allow for the safe and efficient use of available space to exceed the required space of the activities. Proper scheduling completes the tasks in the least amount of time and in the proper sequence to avoid rework and conflicts. Conflicts between construction activities can lead to detrimental effects on a construction project that range from time delays to the expense of removal and replacement of construction work. Rework can be seen if a drywall work is completed prior to installation of all plumbing, electrical or inspections. Rework can also be seen when a floor is damaged due to work over head and the flooring must be replaced prior to acceptance by the owner. Space scheduling is for the construction manager and allows for the development of a preliminary schedule that can be refined and modified.

Previous time-space studies confined the focused of their research within the construction industry and developed resolution techniques accordingly. This author believes that inspiring change can come to an industry by reviewing other dissimilar industries and attempting to learn from their processes and apply those lessons to the original process; often referred to as thinking creatively or “thinking-out-of-the-box”. A well known hospital greatly improved their productivity by immersing themselves into the Japanese style of management practiced by the Toyota Motor Company of Japan (Taylor 2011). If a hospital can improve its productivity by looking at a car company then it is logical to believe a solution to the time-space conflict resolution on a construction project can have a solution in a completely different industry. What if the construction activities were modeled as three dimensional boxes? Could packing/shipping industry practices lead to a logical solution to construction time-space problems? The remainder of this dissertation answers that question in the affirmative.

To address the problem of time-space conflicts on construction projects consider the packing industry as a guide. The goal of the packing industry is to optimize the number of three-dimensional cartons packed within a minimum volume of a three-dimensional container (Tsai and Li 2006). If each activity can be defined as a three-dimensional rectangular space then it is reasonable to assume that the same methods used for packing boxes into a container would apply to packing the construction activities within a clearly defined work space.

1.7.2 Applying the Scientific Method

The problem identified is the identification and elimination of time-space conflicts on construction projects. Unlike previous studies, the goal of this research is to develop the activity construction sequencing or schedule while identifying potential conflicts. The process involves the review of existing literature then developing a model to test the theory that construction activities can be "packed" into a construction site. The final step is the validation of the model by application to a completed project obtained from industry.

1.8 Research Hypothesis

1.8.1 Hypothesis 1

Defining the construction activities as 3-dimensional rectangular items allows the use of orthogonal packing strategies on the construction scheduling process. The activity space is defined as the physical space occupied by the actual item, such as a wall panel or a fixture, plus the work area required for completion of the activity. Given the space required for a given activity, including the actual size of the completed activity, each activity can be modeled as a rectangular shape “packed” into a controlled volume as small as an existing room or as large as the limits of the structure.

Previous studies utilized a similar concept. Thabet and Beliveau (1994) defined activity space as the product of the physical size of the activity plus the space required for equipment and labor required to install the product. Zouein and Tommelein (2001) modeled various site components on a construction site as 2D geometric shapes. Using the modeled shapes, placement was optimized with algorithms and heuristics, and the site layout was developed. By applying these same concepts to interior activities this research attempts to build on their previous work and develop a similar concept for interior spaces.

Hypothesis - All construction activities can be modeled as three dimensional rectangular shapes. Their individual shape can be defined using the {x, y, and z} coordinates and dimensions specified in the constructions documents.

1.8.2 Hypothesis 2

Network scheduling techniques concentrate on activity durations and dependencies with no formal identification of spatial conflicts. Standard packing processes are concerned with the orientation and location of packed objects rather than the sequence the items are packed. To be useful as a construction scheduling tool, any modified "packing" process must follow a sequence governed by various constraints and interdependent relationships.

Physical relationships affect the sequencing of all construction activities (Echeverry et al 1991). Namely, the activities must be completed in a sequence that follows natural laws such as gravity, obeys logic to eliminate duplicate efforts or avoid rework. Geometric scheduling techniques can identify spatial conflicts associated with required activities while maintaining sequential and logical relationships between activities.

Hypothesis - Modeling construction activities as rectangular shapes and packing them into a control volume identifies potential conflicts that are not identified by CPM scheduling for construction projects.

1.8.3 Hypothesis 3

The word *efficient* is an adjective that is defined as “effective with a minimum of effort, expense, etc.” (Webster 2000). In construction scheduling, *efficient* can be used to describe a construction sequence that eliminates rework of completed tasks and reduces the completion timeframe for the entire project. In the packing industry, the most efficient solution for packing the greatest number of items inside a defined space is called the nesting technique. By placing the largest items first with the smaller items filling the remaining available space a similar strategy will minimize the construction duration time.

For any given construction activity, a required amount of space is necessary for the completion of that activity. A Volume Factor (V_f) as defined by Equation 1.11 where the Activity Volume includes the physical space required for the activity as well as stored materials and the Control Space is defined by the extreme limits of the portion of the project under consideration. Typically the extreme limits refer to the walls, floor and ceiling of the work zone for interior construction. The activities with the largest Volume Factor are completed first with the remainder following.

$$V_f \equiv \frac{Volume\ of\ Activity_i}{Volume\ of\ Control\ Space}$$ **Equation 1.11**

Hypothesis – Allocating activities into a schedule in sequence of largest – to – smallest space usage reduces the construction project durations.

1.9 Research Objectives

1.9.1 Objective 1

Employ established mathematical formula from the packing industry to identify potential spatial conflicts between various construction activities on a project.

1.9.2 Objective 2

Develop a construction scheduling technique that utilizes spatial conflict procedures created by this study and prepares a workable project schedule based upon spatial inputs and sequence constraints.

1.9.3 Objective 3

Verify the developed scheduling technique is technically sound and correct by comparing the resulting schedule to a CPM schedule developed using the same activities and durations.

1.9.4 Objective 4

Establish a method of construction scheduling that can be implemented on existing projects and combines the spatial scheduling technique with existing CPM scheduling software packages such as Microsoft Project.

1.10 Research Scope and Limitations

The research is limited to interior renovation of an existing structure versus new construction or site work because much of the previous research work has been focused on new construction; leaving the renovation market available for new discoveries. At the same time, interior construction activities are completed in a confined space similar to the constraints of a shipping container. The decision to limit the scope and size of the research was an attempt to recreate the shipping environment and eliminate as many unnecessary variables as possible to allow for an accurate comparison of the proposed packing methods to the construction process.

To avoid computing errors and to allow for automation and acceleration of the analysis, the decision to incorporate a computer program was mandated early in the preliminary planning phases of this research. The repetitive nature of the required calculations for space management are ideally suited for spreadsheet analysis (Akinci et al. 2002b). In addition, one of the objectives of this research is to provide a scheduling tool that can be implemented by construction professionals. Therefore this initial study is developed using macro programming with Excel spreadsheets. The decision to use spreadsheet calculations limits the size of the case study projects for this research, however the basic theories remain valid. Future work includes the development of a computer program for practical implementation and wider adoption.

1.11 Chapter Organization

This dissertation is organized as follows:

Chapter 2 is devoted to the existing literature as it relates to the topic. A thorough literature review of over 90 scientific journal articles and publications has been used for the development of this process. Given the large volume of information available on spatial management and packing problems, the use of a diagram, as shown in

Figure 1.5 is a convenient means of organizing the data into a usable form. Known as a *mind map*, this centrally organized diagram has been linked to increases in retention of knowledge in college students (Farrand et al. 2002). Therefore to assist with the development of this research project each of the five headings; Construction Scheduling, Spatial Scheduling, Packing Problems, Resource Allocation, Spatial Characteristics are identified and various papers representing specific topics within these categories are presented in Chapter 2.

Chapter 3 describes the methodology associated with the research and development of the Geometric Information Scheduling technique. Based on the premise that all construction activities can be represented as three dimensional rectangular models, the method uses a series of heuristics and packing techniques to identify an optimal sequencing of activities. After the activity sequence is developed, binary decision variable algorithms are used to identify physical time/space conflicts. The final result is a construction schedule that is free of time/space conflicts and provides the optimal usage of the construction space.

Chapter 4 provides the analysis and verification of the Geometric Scheduling technique developed in Chapter 3 by application to case studies of interior construction and interior renovation projects. Case Study I is a sample new construction project based on numerous similar projects in the commercial industry. Case Study II is an actual completed renovation project for the administrative complex for Baltimore County Public

Schools. The projects were chosen because of their similarities to the initial constraints used to develop the model. Case Study I allowed initial development of the concept and Case Study II provided an opportunity to compare the model results with actual field results. The construction schedule produced by the technique was compared to a network schedule submitted by the contractor to the school system.

Chapter 5 presents the findings and recommendations associated with the process performance and discusses the contributions to the construction industry. The process results are compared with previous time-space research findings with the geometric process substantially reducing the construction schedule of a completed Case Study. As a product of the process the concept of *space float* is identified which could prove extremely useful in future research endeavors.

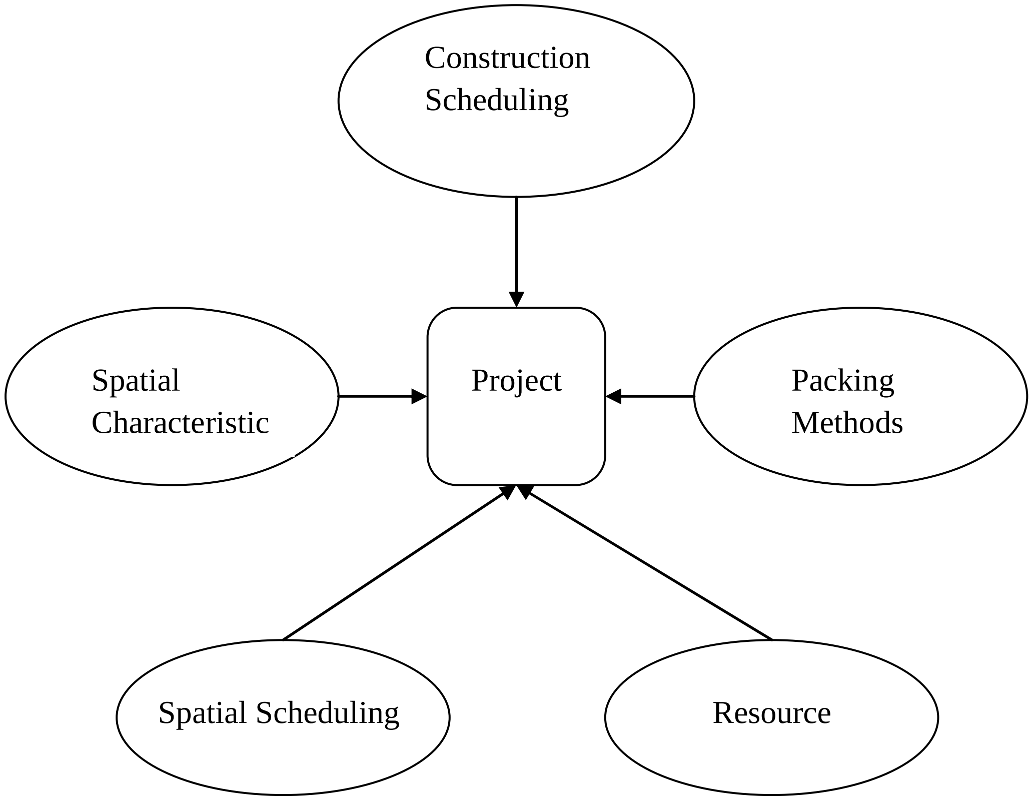

Figure 1.5
Research Organization and Chapter Two Overview

CHAPTER 2

Literature Review

2.1 Introduction

Over the past decade, a vast amount of research has been conducted in the field of construction management. Research and professional organizations such as the Project Management Institute (PMI) have sponsored and published numerous articles relating to the spatial management on construction projects. Much of this research has dealt with attempts to define space on the job site and apply this spatial knowledge to prevent activity conflicts and rework. Advances in Computer Assisted Drafting (CAD) make it possible to generate three dimensional drawings that can be used to visually identify conflicts. Computers are capable of storing vast quantities of information that has lead to the development of Building Information Management (BIM) processes that attempt to centralize project information relating to design and constructability.

2.2 Construction Scheduling

2.2.1 Basic Scheduling Theory

With today's scheduling tools, it is possible to create a schedule with 1,000s of activities, however more is not necessarily better. A construction schedule with an abundance of construction activities listed can be incomprehensible to the individuals tasked with managing the project as well as invite less scrupulous contractors to submit claims against the owner for change orders and revisions claiming the construction schedule dictated ways and means for their work that was contrary to the methods they included in their pricing. One method for limiting the amount of information presented in a schedule is the use of soft logic. Hanks (1999) defined the term "soft logic" as schedule control through summation and collectivization instead of specification. Information is presented in summary form verses itemization of each process. For example, consider a petro chemical plant with related piping and instrumentation. A scheduler using linear scheduling or CPM could identify each segment of piping, for each floor, as a separate item. Using soft logic, the various areas such as north, south, east and west sections of the plant can be scheduled as units with all the piping and instrumentation listed as a single item to be completed.

Consider the activities themselves regardless of the scheduling method chosen. Echeverry et al (1991) defined the process of scheduling construction projects as the orchestration of three main steps; (1) identification and breakdown of individual activities, (2) sequencing of the activities, and (3) allocation of resources to the activities. The construction management professional is responsible for identifying the activity sequencing when developing the schedule. Echeverry et al (1991) focused primarily on mid-rise structures however it was stated that the conclusions from the report could be applied to other facilities. This study used a knowledge-based systems (KBS) approach for generating construction schedules. The KBS process methodology includes acquisition of the knowledge, formalization of the acquired knowledge, then generation of a prototype system. (Echeverry et al. 1991, p120) The process used for this study was to report information obtained from extensive interviews and interactions with five different construction firms. Starting with the premise that an activity can be identified as installing, removing, modifying, or testing a particular component of the construction process, the scheduling process is the act of assembling these components into a finished product. The individual installation activities are governed by a sequence and the factors that govern this sequencing are: physical relationship between activities, trade interaction, path interference between resource movement and completed construction and Building Code regulations. (Echeverry et al. 1991, p120)

In the current construction industry, a majority of non-repetitive projects are scheduled utilizing the critical path method (CPM). Although the CPM method has been used on construction projects since the 1950's and is considered to be the premier scheduling method for construction in the USA, the method has yet to achieve 100% utilization. Galloway (2006) conducted a survey to determine the extent and consistency of CPM usage in the construction industry. The method chosen for the survey was a distribution of an on-line questionnaire sent to owners and contractors. The survey was voluntary so it was not possible to generalize that responses represented the entire construction industry. Nor was it possible to calculate a confidence level associated with the responses. However, the results did provide some useful information. Nearly 50% of all respondents indicated owners prefer CPM schedules because, (1) they are easy to understand, (2) they do not require extensive training for their staff to monitor project status and (3) most projects did not require additional costs associated with the generation of a CPM schedule.

Projects that are repetitive in nature, either vertically, horizontally or in composition are ideally suited for a linear scheduling method. Graphically, the activities are defined by a two-coordinate system; the horizontal axis displays time while the perpendicular axis displays a unit of production. Linear construction consists of a group of operations that involve repetitive units of construction. Highways, high-rises, tunnels, pipelines are excellent examples. Construction proceeds in a linear fashion allowing for cost and time efficiencies. The project manager seeks to balance crew sizes to allow for maximum productivity and also allow for variations in productivity rates. This form of construction scheduling is referred to as Line of Balance scheduling (LOB). Arditti

(2002) claimed the lack of a computer program for LOB scheduling, similar to available software for CPM scheduling, was a problem in the construction industry. His study could not identify any previous systemic attempts to document and treat all problems associated with theory and practice of linear scheduling methods. The purpose of his work was to address LOB issues in such a fashion that computerization of LOB could be developed.

Gehringer (1958) working for the Office of Naval Material stated “Line of Balance is a management tool and not a control system.” He acknowledged the method eliminates the unnecessary activities from consideration and focus on the critical activities when considering project completion. This was the same time in history that saw the development of the CPM method which also identifies the criticality of activities with respect to time. Harmelink (2001) compared linear scheduling methods with network methods such as CPM. Linear methods were adapted to construction from the manufacturing and transportation (rail) industries. Linear schedules typically deal with repetitive projects. The author summarized his comparison of Linear Scheduling Method LSM with CPM scheduling in a tabular form:

Task	CPM	LSM
Critical chain of activities	Key element of the process.	Defines a controlling activity.
Reduction of Uncertainty	Fixed durations for activities	No formal method to allow for uncertainty
Improving Productivity	Resource leveling and resource allocation difficult to retain continuity in repetitive projects.	Easy to understand graphic representation of productivity.
Accurate calculations	Difficult to determine space restrictions.	Space restrictions graphically defined.
Aid in achieving understanding of project objectives.	Computers allow for complex problems.	Very difficult.

Table 2.1
Comparison of Attributes between Critical Path Method (CPM) and Linear Scheduling Method (LSM) (Adapted from Harmelink 2001)

Historically, linear scheduling has been used for major structural work and continues to be used in Europe for construction.(Pollard et al. 1992) The United States at one time incorporated linear scheduling into the management of construction works such as the Empire State Building (Sacks and Partouche 2010) but as noted by previous studies the method of choice is CPM in today's U. S. construction industry. Yet CPM scheduling techniques have three major drawbacks when considering repetitive projects (Vanhoucke 2006, p15):

1. CPM relies on a large number of activities and repetitive projects produce a ladder effect of related activities.
2. CPM is unable to guarantee continuity of work and resources.
3. Activity crashing has adverse effects on future activities.

Networks (CPM) show dependencies between activities but fail to provide information concerning time and space demands as well as production rates. Linear scheduling provides production rate and duration graphically allowing for easy detection of problems and bottlenecks. Compared to network schedules, linear schedules require less time and effort to produce and are adaptable to computer analysis. However, linear scheduling must be able to present a complete analytical analysis that includes accurate calculation of activity float. Lucko (2009) derived calculations for the identification and qualification of numerous activity float times in linear scheduling using singularity functions. Lucko (2009) attempted to bridge the information gap that exists between CPM users in the construction industry and LOB type schedules. The geometric scheduling process developed in this research resembles CPM thinking as it relates activities to one another more than it resembles LOB type scheduling. The process uses the KBS approach proposed by Echeverry and his colleagues and heuristics developed for activity consideration and sequencing.

2.2.2 Specific Scheduling Problems

Consistently throughout the research literature, the major problem with construction scheduling is the ability to accurately model the construction project and the associated logic relationship between activities. Two specific problems that are relevant to the geometric scheduling model developed by this research (a) the ability to accurately represent activity relationships given non-standard finish-to-start relationships, and (b) the effects of resource availability on the construction schedule.

CPM scheduling requires the development of a network diagram to represent activity relationships. (Lu and Lam 2009) Typically this diagram is referred to as an activity-on-node (AON) diagram were the information for each activity is contained on the nodes and arrows indicate sequencing and logic flows. In a simple construction schedule, activities are related in a finish-to-start (FS) nature. In more complicated projects activities can be related to each other in non-FS fashion and the resulting network is referred to as a precedence diagram method (PDM). Calculating the critical path for a network containing non-FS activities can be difficult and can occasionally lead to improper schedule times due to a misunderstanding of the logic. The purpose of this study was to develop a generic process that transforms non-FS activities into equivalent FS activities that can be used for scheduling calculations. To calculate the Critical Path for a schedule containing non-FS relationships, dummy activities are inserted into the schedule prior to calculating the forward and backward pass.

When activities are related in a normal start-to-finish configuration and project floats are calculated without considering the effects of restricted resources, the resource constraint can cause the critical chain of events to be altered. “Once resources are considered in the scheduling process, however, we lose correct float information and, as a result, one or more odd paths become critical.” (Kim and de la Garza 2003, p507). The basic assumption with CPM scheduling is resources are considered unlimited. Rarely on a normal project are all resources available continually, leading to problems with schedule updates and delay calculations when constrained resources are encountered. If the resources for an activity are not available at the start of the activity , the activity must be delayed until a time when the resources are available and the resulting resource dependency is treated as a logical link between activities. (Kim and de la Garza 2003).

Kim and de la Garza (2003) developed a method that combined CPM scheduling and resource constrained scheduling (RCS) to create a resource-constrained critical path method (RCPM) that considers the availability of resources in a realistic fashion, correctly identifies activity floats and critical path based on the resource availability, and provides a stable schedule throughout the project duration. The study identified the concept of “phantom float” that occurs when performing the backward pass on the network of activities. The resource dependencies are typically omitted from the backward pass so the late start time of an activity can be greater than the true value when considering constraints. This difference was defined as the “phantom float” (Kim and de la Garza 2003, p512). because even though the calculations indicated the time was available in reality it did not exist. This phenomenon is critical to identify when considering change orders and contractor claims.

The first step when attempting to resolve a contractor claim for a time extension is to review the activity successor by checking the resource links and determining if an alternative schedule is possible. Critical path activities should be obvious given that any extension in time to critical activities will extend the project completion date. For the remaining activities the resource links can be temporarily removed and the time period in question can be studied to determine if an alternative sequencing of activities is possible. If an alternative schedule is identified the resource links are reviewed to understand if any modifications can be made to the links to facilitate the revised schedule. If attempts to modify the links are unsuccessful then the original schedule and links is restored and some attempt is made to resolve the claim. The RCMP method was tested by the authors (Kim and de la Garza 2003) on several projects and they were able to successfully generate schedules consistent with available computer software results.

2.3 Spatial Characteristics in Construction

Spatial needs for various construction activities should be based on a decomposition of the activity such as material storage, work space required, and final product installation. This fact is true for both exterior site layout and planning as well as interior construction. At the same time, spatial resources are a type of resource required by a group of activities rather than a resource required for a specific activity. A critical requirement in scheduling projects with spatial resources is to ensure uninterrupted usage of resources, for similar activities between different units, because waste comes from crews waiting for the preceding activities to complete their work. (Vanhoucke 2006, p14)

2.3.1 Exterior Construction

Spatial characteristics in exterior construction vary with time and resources are classified as either static or dynamic. An example of a static resource would be a construction office modular building set on masonry foundations or a fuel tank with a spill barrier. Examples of a dynamic resource would be any material stockpile that is used like sand or bricks; dynamic resources could also include large pieces of equipment like a crane or a mobile concrete batch plant. Static resource layout problems consider the shape and location of all temporary facilities as fixed and are solved with heuristics and numerical optimization based on 2-D orthogonal representation (Elbeltagi et al. 2004). Dynamic planning encompasses the idea certain resources change with time such as storage areas that vary in size as the product is consumed by the project.

Elbeltagi and Hegazy (2004) proposed a practical model for the solution of dynamic site layout planning (DSLP) problems and defined their process as follows. If all resources are represented as rectangular shapes with fixed dimensions, site is defined by grid units with the smallest grid unit identified as the least common denominator of all temporary accommodations (TA) to be placed. Static resources are positioned first with dynamic resources positioned next. Dynamic resources are assigned proximity weights identified for each of the temporary facilities using the following rules (Elbeltagi and Hegazy 2004, p537):

1. Resources with larger relocation costs receive higher weights
2. Resources with greater interaction with other resources receive lower weights.
3. Resources with safety related issues receive negative weights.

Starting with initial locations, each of the TA resources is given a proximity weight and the process uses a series of genetic algorithms to calculate travel times between activities. The travel times are used in the objective function to determine the optimal TA locations. Optimal calculated site locations based on travel distance and costs may not be safest; leading to 5 steps required to determine final TA locations on a jobsite paraphrased as follows ((Elbeltagi and Hegazy 2004, pp535-538):

1. Need for the proposed temporary accommodations.
2. Schedule of construction process must be assembled.

3. With activity's requirements of temporary accommodations defined, temporary accommodations treated as resources assigned to activities.
4. Service times for temporary accommodations determined from the construction schedule.
5. Temporary accommodations that serve any time frame must be identified.

2.3.2 Interior Construction

Nearly all construction activities require space for their execution and completion. Thabet and Beliveau (1994) proposed a model that would identify the space required for each process and compared the required space with the available space for interior construction projects. Available space can be generated automatically by using CAD drawings. The required space, defined by the user, ,is coordinated with structural members such as column, beams, footings, etc. with construction processes such as lifting, welding, grinding, painting, etc. The structure is defined as a series of blocks. The blocks are divided into layers and zones with the layers representing time and the zones defining location. Thabet and Beliveau (1994) referred to this process as the generation of "work blocks" presented as a two part system. The first part identifies the required space based on geometric reasoning and construction activity relationships/links. The second part is to identify the available space as defined by the Cartesian coordinates associated with the various construction plans.

If available space is less than the space demand either work cannot proceed or work proceeds at a reduced rate and productivity suffers. Trades compete for space and often project rules prohibit trades from sharing available space. In addition, space can be limited on an urban project. The result is storage of materials competes with available space for construction further complicating the required tasks. Network scheduling logic does not consider work space requirements and logically connected floor activities may be scheduled concurrently but the available space may be insufficient to accommodate both activities.

Guo (2002) stated that space on a construction site should be considered as a resource. For his study, space was categorized by the construction professional as one of the following: exterior space, interior space, inside the structure and finally space provided by temporary construction such as scaffolding or other short-term structures. Then the various categories are given different colors and shapes and located on the construction drawings. Any resulting time-space conflicts are identified visually as overlapping segments on the drawings.

Winch and North (2006) took a different approach in their research of construction space. Rather than focus on the total space defined by the construction documents and the related activities, they concentrated on the execution space required for activity completion as an attempt to define detailed construction-work-space needs to allow construction managers the ability to better schedule projects.. They stated 19 m^2

(205 ft^2) is the minimum space required by a worker for optimal productivity and 50% more man-hours are required when this work space declines to 10.4 m^2 (112 ft^2) as an absolute minimum. (Winch and North 2006, p474) These values for required space appear extremely high based on twenty-five years of experience in the U.S. construction industry.

Akinci et al. (2002b) further developed a formalized approach to identifying and classifying the various types of construction spatial characteristics. For the purposes of their study they identified three categories of space found on any construction site: (Akinci et al.2002b, p296)

1. Macro level Space – defined as the large sized spaces on a site including fabrication areas, storage areas, staging areas, etc. The structure would be considered a macro level space.
2. Micro level Spaces – spaces required for the actual work within the component being constructed. These spaces would include crews, equipment space and even the structural components being installed such as beams and columns.
3. Paths – spaces that must remain clear and open for the transportation of people and products.

The geometric scheduling process is developed primarily for resolution of time-space conflicts located in micro level spaces. During construction micro level spaces can change much quicker than macro level site type spaces and therefore it is critical to avoid conflicts and delays. Unlike micro level and macro level spaces that change in all three dimensions with the passing of time and activity progress, pathways remain constant throughout the process and potential time-space conflicts can be identified during initial planning phases and therefore do not require geometric scheduling techniques.

2.3.3 Activity Characteristics

Thabet and Beliveau (1994) claimed that to acknowledge work-space constraints in scheduling, one first needs to identify and evaluate the different parameters that characterize construction activities. This knowledge is used to create scheduling decisions so that the space model classifies activities into three categories (Thabet and Beliveau 1994, p100):

a. Activities with crews assigned only for that particular activity. Examples of this type of activity include fireproofing, painting and overhead work that would endanger others below.

b. Activities that accumulate their space demand from manpower and equipment. These activities require very little space for material storage and can be scheduled concurrently with trades sharing the work space on a particular floor. An example of this type of activity is electrical wiring.

c. Activities that require large space for storage of materials in the work area prior to progression of work. As work progresses stored materials converted into finished product and the space demand decreases as time increases. Examples of this type of activity include drywall partitions, plumbing, fire protection and ductwork.

To fully describe any particular activity space on a construction site requires eight spatio-temporal identification items: initial insertion points {x,y,z}; dimensions along the x-,y- and z-axes; and the start and end times for each activity. (Akinci et al. 2002b, p297) Akinci et al.(2002b) state current computer drafting and project scheduling software fail to identify all four components (length, width, height and time) and therefore the construction professional is forced to enter the information manually thus creating extra work for himself and the distinct possibility the method will not be used. The goal of geometric scheduling is to provide a system that allows the construction manager to describe the construction activities in a computer-interpretable format such that the process to automatically interprets the information and generates the conflict-free construction schedule.

2.4 Spatial Scheduling

Two problems in construction spatial scheduling; (a) site layout problems associated with temporary facilities and material storage, and (b) space scheduling of activities and construction. Construction planning more difficult than production planning for a factory or similar industrial process because the space is always changing as the work is completed. Factory space is extremely stabile and a great deal of time can be expended planning space with big returns associated with the planning time. Construction site space is dynamic and varies from one day to the next. Therefore very little time is appropriated for space planning because of the little to no return on the investment.

2.4.1 Site Layout Planning

Zouein and Tommelein (1999) state that all resources on a construction project need space and all project sites need a plan. Poor site planning can lead to inefficient material handling costs and possibly resource relocation costs. Site layout problems can be defined as static or dynamic problems. Static problems can be solved using heuristics and numerical optimization. Typically the static resources are modeled as objects with predefined shapes and locations subject to constraints. Dynamic planning includes changing storage areas that may overlap over the course of the project as one resource is consumed and a later resource is stockpile for future incorporation into the project. The purpose of their research was to present a numerical solution to the dynamic site layout problem.

Zouein and Tommelein (1999) utilized a piece-wise numerical solution to solve the site scheduling problems. The user must define the primary time frames the various temporary facilities to be scheduled are required. Hard constraints for each of the activities are defined. These constraints include no overlap, size of the activity must remain within the size of the site termed in-zone by the authors, any minimum required distance based on machine reach or clearance requirements, and finally activity orientation. Once the 2-dimensional relationships are defined by these hard constraints the activities are initially placed within the site boundaries. Linear programming is used to develop a VFL (Value Function of the Layout) for each defined activity location plan. The various VFL values are compared and the lowest value is determined. The site layout with the lowest VFL is recommended as the solution.

The Zouein and Tommelein (1999) method is very similar to resource leveling techniques used in construction planning and therefore is easily utilized by competent field personnel. Static resources are positioned first and relocatable resources are positioned next. Ties between competing plans are resolved with heuristic methods concerning relocation cost of the resource and the interaction with other positioned activities. One drawback to this study is the limited timeframe associated with the calculations. Their method does not have the ability to revise previous calculations so the solution is presented as “the best at the time” which may or may not apply to previous iterations.

Mawdesley et al. (2002) stated that the objective of any site layout plan was to position the temporary facilities in such a fashion as to improve the construction process. Factors that should be considered in site layout management include traffic, materials, buildings, workshops, and welfare facilities. A separate but related topic is the positioning of major pieces of equipment such as cranes and lifts as well as access to a site as defined by entrance locations, e.g. a driveway or construction entrance. Traffic routes define the paths within the site between activities and facilities and traffic routes should never cross if possible. For all sites there are three basic categories of materials (Mawdesley et al. 2002, p419): (a) expensive- must be protected from the weather and theft; (b) dangerous- people need to be protected and sheltered from these; (c) neither-no protection or security required. The key is to handle materials as seldom as possible and avoid double handling of materials. Buildings and welfare facilities should be located in convenient locations but out of the way. Offices need to be in a location with a great view of the site but relatively quiet. Workshops for projects with large equipment are vital to keeping the project moving. These should be located close to the action.

Mawdesley et al. (2002) stated site layout is similar to facility layout for a production plant or factory. As an attempt to optimize temporary facility locations, Mawdesley et al. (2002) used Genetic algorithms (GA) to produce solutions and compared the results to previous iterations with each generation of calculations disposing of the weaker options. Mawdesley et al. (2002) stated the advantages to the GA method to many civil engineering problems are the flexibility and dynamic nature of the method, also the method relies very little on specific knowledge of the problem. As long as the initial parameters are defined properly, the method will provide accurate and reasonable solutions without a thorough understanding of the particular problem. Therefore this method can be applied to a wide range of topics with equal success.

For the site layout problem, Mawdesley et al. (2002) adapted a GA solution by identifying the coordinate system for the site, defining the necessary temporary facilities shape and locations using the coordinate axis system defined for the site, identifying all site access locations (entrances), defining the connections between the various activities temporary facilities (traffic routes). Traffic routes are defined as either linear or Euclidian depending on the degree of accuracy associated with the problem solution. The costs associated with the traffic routes are composed of set-up, removal and travel costs. The site is divided into a grid and the traffic costs are considered uniform within each grid. Finally, a fitness or objective function was used to evaluate the solutions.

Two examples were presented by Mawdesley et al. (2002). The first example was a small example containing two temporary facilities on a site and a temporary facility was to be situated to service both of the existing structures. The objective function was defined and the method converged to a solution within 40 generations of the process; verifying the process works. The second example was much more detailed and realistic. The drawback to the process is that the location program uses location data only and the locations are not related to scheduling. Future work is intended by Mawdesley et al. (2002) to link the location process with approved scheduling techniques.

Elbeltagi et el. (2004) stated the primary concern with any site layout plan should be safety “The U.S. Bureau of Labor Statistics reports an average of one death and 167 injuries per $100 million (U.S.) of annual construction spending. The total cost of these accidents reached $8.9 billion (U.S.) or 6.5% of the $137 billion (U.S.) spent annually on industrial, utility, and commercial construction.” (Elbeltagi et el. 2004, p535) With proper site planning several causes of these accidents can be reduced or eliminated.

Elbeltagi et el. (2004) proposed a site layout process where temporary facilities are defined graphically using the Cartesian coordinate system defined for the site. The facilities are assumed to be rectangular in shape. This allows the shape to be defined by two opposite corner points. Similar to Zouein and Tommelein (1999), this paper identifies all required temporary facilities, schedule of construction processes, activity and process requirements. Once identified, temporary facilities are assigned to the various activities with service times determined from the schedule, and finally the temporary facilities that serve any of the time frames must be identified. This study then graphically represented the site in a grid pattern based on the least common denominator of the temporary facilities to be placed.

2.4.2 Work Space Planning

Work space planning is extremely difficult due to the variations in construction activities as observed in twenty-five years of construction activities. Some activities can be completed in a linear fashion such as studs-electrical-mechanical-drywall-paint while others such as masonry curtain walls generally follow a spiral pattern starting at the base and progressing up and around the structure. Still other activities can be completed randomly. Automated scheduling computer programs and planning techniques tell when an activity will proceed and why due to logic but they fail to tell how the activity will be completed. The existing techniques do not identify the crews to be used for a particular activity or the method chosen. To resolve this situation, Akinci et al. (2002b) proposed a construction method model that defined components, actions and resources (CAR) for the project. The CAR method defines how the activity will be completed defining the crew sizes and methods but it fails to monitor or consider the spatial requirements for the various activities.

Riley and Sanvido (1995) published one of the first identified space studies on construction sites. By considering multi-level construction versus single layer construction, various trades perform the same task from one floor to the next and conflicts can be resolved by moving trades between floors. This study was conducted in three phases. The first phase of the study was data collection and observation. Riley and

Sanvido (1995) conducted interviews with construction workers, visited jobsites over a multi-year period while construction was proceeding and finally reviewed the construction documents of the projects visited. The results of the first phase of the study lead Riley and Sanvido (1995) to the conclusion that different activities require different amounts of space for the actual work as well as the material movement to the activities. These results were then graphically transposed on to the construction drawings. The second phase of the study was to identify activities that followed similar patterns regardless of the jobsite. The article used the example of masons preferring to complete one face of a building at a time before moving on to the next. The third and final phase was to compare the results of the space usage model developed in the first phase with the actual data collected from select test sites.

Akinci et al. (1998) stated that no formal identification process existed prior to their research for identifying time space conflicts or their affects on the construction schedule. However, Thabet and Beliveau (1994) and Riley and Sanvido (1995) were both published earlier and appeared to define space in terms of available and required spaces. Regardless, all three studies agree time-space conflicts are a major cause of lost productivity on construction sites and for the most part they can be eliminated with proper attention prior to work space planning.

2.4.3 Activity Relationships

Critical Path Method (CPM) scheduling of construction projects is the industry standard for producing construction schedules (Koo and Fischer 2000). CPM is limited by showing activities and relationships from one to another yet they often fail to clearly show potential space conflicts. Koo and Fischer (2000) contend that 4D CAD drawings can be generated that quickly identify conflicts and the process is much easier than manually going through the tedious task of reviewing each activity. Large projects can have thousands of scheduled activities and by linking time with 3-dimensional construction drawings produce a visual location of potential conflicts.

Koo and Fischer (2000) used students to review the proposed construction CPM schedules for various projects and citing potential conflicts. The 4D drawings were generated and the result was the identification of numerous conflicts undetected using the standard schedule review. The study project consisted of three identical buildings to be constructed. One of the structures had been completed when the study was initiated. Construction management noted the problems they encountered during the construction of the first building. These notes were not shared with the study participants until the end. The initial review of the construction documents by the students failed to identify any conflicts and the study concluded this may be a result of the lack of experience by the students.

Koo and Fischer (2000) identified the project schedules for the buildings in the study contained approximately 300 activities for each structure. The level of detail for the interior activities was far greater than the exterior. Often subcontractors had to work in the same space during the completion of construction activities. To maintain a continuous work flow the interior spaces were partitioned in to several sections and layers. 4-D drawings identified problems such as “steel erection” noted as 15 days on the schedule because the drawings were much more detailed than the schedule and it was easy to see conflicts between beams and columns, etc. The 4-D drawings made it obvious to view the relationship between components that was lacking with the information given in the schedule. Duct work and associated mechanical, electrical and plumbing work (MEP) was scheduled for construction prior to completion of the upper floor slabs and thus no space for the workers to erect ladders or scaffolds required for the mechanical, electrical, and plumbing (MEP) installation. A similar situation occurred in the main lobby core. Stair installation was shown on the schedule to allow access to the upper floor but the finished lobby floor covering was scheduled at the same time. Workers and materials could not traverse the new floor of stained concrete so the stairs were not accessible. Exterior stairs had to be provided to allow access to the upper floor.

In the same Koo and Fischer (2000) study, the CPM schedule often showed various trades working within the same space. Productivity of the crews suffered as the space available for the workers was cramped and insufficient for efficient completion. 4-

D drawings easily identified cramped spacing problems. The initial schedule had been completed assuming a relative equal amount of space required for similar trades. Actual construction on the first building indicated the initial assumptions were wrong and delays occurred. A problem with 4-D scheduling is the fact the 4-D is excellent for identifying physical constraints but fails to account for availability of resources and often missed conflicts due to non-physical constraints such as lead times on equipment and materials. CPM schedules show what is built and when it is constructed. 4-D goes beyond this concept and shows what is built, when it is built and where it is built. CPM scheduling requires interpretation by the individual workers and managers. It is possible for one individual to interpret a sequence different than another individual. 4-D is graphic and clear and thus eliminates some of the variations due to lack of knowledge and experience.

Koo and Fischer (2000) state 4-D modeling is a very effective tool for constructability reviews but is limited because it requires a great deal of cooperation among the various designers. Due to liability and possible trade secrets many designers are reluctant to freely exchange information. Free exchange of information is vital for this concept to work successfully. A related drawback is the amount of time required to generate the 4-D drawings from the construction documents. The Koo and Fischer (2000) study for a two-story office building took nearly 100 man-hours to complete the schedule and the 4-D drawings. Time is money. In addition, the schedule is developed by the awarded contractor and the drawings are generated by the design professionals.

2.4.4 Activity Conflict Resolution

To resolve time-space conflicts, Thabet and Beliveau (1994) incorporated six decision factors in their model to delay or stagger activity start times. These decision factors are (Thabet and Beliveau 1994, p108):

1. Activity space demand required for each activity that includes space required for manpower and equipment added to material space demands.
2. Activity continuity status relating to the ability of an activity to be split into multiple segments.
3. Maximum number of allowable activity splits.
4. Activity space demand classification (A,B and C). Only activity A requires the entire available space. Activities B and C can share space between trades.
5. Space Capacity Factor (SCF) calculated and related to productivity levels.
6. Identification of minimum productivity rates with respect to schedule completion dates.

Space Capacity Factor defined as:

$$Space\ Capacity\ Factor\ (SCF) = \frac{Space\ Demand\ for\ Activity}{Current\ Space\ Available}$$ **Equation 2.1**

When the calculated SCF ≤ 1.0 productivity for that activity is 100%; for SCF = 1.5 productivity drops to approximately 60% of the optimum value and if the SCF exceeds 2.0, productivity diminishes to less than 10% of optimum values for a typical crew. Using the SCF values for all the activities, the schedule is adjusted as required to reduce activity scores greater than 1.0. Geometric scheduling uses a similar factor to sort the activities prior to conflict comparison.

Akinci et al.(1998) sought a definable solution rather than a generative approach. The authors believed the generative approach can lead to problems in other areas if searching for one solution and producing a schedule that optimizes the usage of space can lead to extended project completion times. They proposed spatial conflicts be solved by adjusting the scheduled but they failed to recognize that reworking the schedule to eliminate time-space conflicts creates unnecessary extra work.

According to Akinci et al.(1998) the following are the major challenges involved with incorporating work space requirements into construction process identified as (Akinci et al. 1998, p6)

1. Representing activity space requirements
2. Recognizing time-space conflicts
3. Predicting the temporal implications of time-space conflict situations.

Many subsequent research efforts by Akinci expanded on the concepts identified in this early work. The purpose of this study was to develop a formal approach used to identify time-space conflicts to be used in further research developing a proactive process for elimination of time space conflicts.

Guo (2002) developed a graphic support system to assists project managers with identification of space conflicts before they developed in the field. AutoCad is used to develop the drawings and Microsoft Project is used to create and maintain the construction schedules. Graphically the available space is divided into four categories: (1) exterior space, (2) interior space, (3) inside the structure and finally (4) space provided by temporary construction such as scaffolding or other short-term structures. The interior space was further divided into stories and zones. As the various subcontractors identified the space they needed to complete their contract, the information was translated onto CAD drawings for different areas and different times. The resulting conflicts were identified visually with the size and type of conflict noted for the resolution strategies. A series of criteria were developed to assist the construction professional with conflict resolution on the site and the research proposed seven rules to apply to the conflict as a means of identification of the first to last conflicts to be resolved. (Guo 2002, p290) The rules are paraphrased as follows:

Rule 1 – Logical sequence. If conflicting activities have a logical sequence regarding the construction process, the space demand needs to follow the activity logic and the subsequent activity starts must be delayed.

Rule 2 – Critical Path. Activities on the critical path of a CPM network project have priority over non-critical activities.

Rule 3 – Space Divisibility. If the space can be divided into smaller areas then attempt to schedule conflicting areas in a non-conflicted sequence to resolve the situation.

Rule 4 – Location Change. This applies primarily to material storage and temporary structures and/or equipment. Attempt to resolve the conflict by moving one or more of the temporary items.

Rule 5 – Space Size Modification. If the conflicting work areas can be reduced in size to resolve the conflict then consider scheduling crews in the modified spaces. The problem with this solution is the smaller area will reduce productivity of the crews.

Rule 6 – Start time modification. If the conflicting activities can have their start times staggered to resolve the conflict then consider the effects to the overall schedule. Will the delayed activity ultimately delay the entire project?

Rule 7 – Length of Occupancy. Modification of the duration of the occupancy by conflicting activities could resolve the conflict. The reduced duration could be a result of increased crew sizes which leads to increases in labor costs.

In summary, Guo (2002) identified spatial conflicts on a construction project and presented a method of resolving the identified conflicts. The method is logical and sound but requires direct data input from the user for every activity and subcontractor. To resolve time-space construction conflicts, Guo (2002) suggested three resolution strategies to eliminate space conflicts: 1. adjust the space demands without altering the schedule; 2. adjust the schedule to eliminate space conflicts such as adjusting the start-finish times of activities to avoid conflicts; 3. a hybrid system that incorporates both of the other two strategies. Once the strategy is chosen the study develops a series of criteria that can be utilized to eliminate the conflict. The critical point made in the study is that once the conflict between competing activities is identified the process must be repeated throughout the project to insure no further space conflicts are created by future work. Rather than identifying the conflicts visually/graphically the geometric scheduling technique uses a mathematical solution based on packing algorithms.

Winch and North (2006) introduced the concept of Spatial Loading as a means of resolving time-space conflicts between activities. They claim their Spatial Loading factor (Equation 2.2) is analogous to critical path in the network CPM calculations. Spatial Loading = 1.0 defines a critical space. Critical spaces are to have preference over non-critical spaces if the construction schedule is to be maintained.

$$Spatial\ Loading = \frac{Required\ Space}{Available\ Space}$$ **Equation 2.2**

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Winch and North (2006) state the identification of discrete spaces is trivial and can be accomplished with Visual Basic applications to CAD drawings. Space scheduling resolution techniques should do the following (Winch and North 2006, p476):

1. Decision support system and NOT a decision-making system
2. Should integrate with existing applications and methods

3. Must be quick and intuitive.

Unlike previous studies (Akinci et al.1998; Thabet and Beliveau 1994; Akinci et al. 2002b; Guo 2002), Winch and North (2006) claim tasks should be allocated to available spaces rather than spaces allocated to the tasks. They believe the concept of assigning space to the individual tasks is intuitively flawed. Logic would seem to indicate the opposite is true. For any given project, space is limited to a finite value defined by the outer limits of the construction. Space is limited and must be considered a restricted resource. For the ability to assign tasks to available space one must assume the space is limitless.

As the construction activities are completed, various conflicts due to temporary structures, such as scaffolding, will change with time and as the activities are completed the conflicts disappear. Akinci, Kunz et al.(2002b) attempted to formalize the identification of time-space conflicts and to categorize them based on the severity of the conflicts to the project schedule. The methodology is similar to geometric scheduling except for the actual conflict resolution. Geometric scheduling uses packing methods and heuristics to resolve conflicts whereas Akinci et al.(2002b) categorized and prioritized the conflicts for resolution and suggest minor time-space conflicts may be overlooked by the construction manager if the cost to resolve the conflict exceeds the cost associated with the potential delay.

2.5 Packing Methods

There are many different types of packing problems however the same basic principles apply to each of the applications. Packing problems can be 3-dimensional such as the automotive industry packing parts and vehicles into shipping containers; or packing problems may be 2-dimensional such as the newspaper and printing industry packing algorithms to "load" the pages of their publications with the various articles and advertisements. Three-dimensional packing is found in the cartage and manufacturing industries. Packing software available typically concentrates on the individual item to be packed or the pallet. Often, a pallet calculator is written in the specification of the project.

Maximum cardinality bin packing (CBP) is the term used to define a type of packing problem that seeks to maximize the number of items n that can be packed into a given number of bins m without exceeding the bin capacities or splitting items. (Labbé et al. 2002, p490) CBP is one-dimensional used for packing and sorting information such as on-line retail, computer data storage and health care records. The formula for the CBP method is: (Labbé et al. 2002, p490):

$$maximize\ z = \sum_{i=1}^{n} \sum_{k=1}^{m} x_{ik}$$ **Equation 2.3**

Subject to $$\sum_{i=1}^{n} w_i x_{ik} \leq c, \qquad k \in \{1, \dots, m\},$$ **Equation 2.4**

$\sum_{k=1}^{m} x_{ik} \leq 1 \qquad i \in \{1, \dots, n\},$ **Equation 2.5**

$x_{ik} = 0 \; or \; 1, \qquad i \in \{1, \dots, n\},$ **Equation 2.6**

$k \in \{1, \dots, m\}.$ **Equation 2.7**

where $z = maximum\ number\ of\ items\ packed\ into\ bin\ k$

$x_{ik} = 1\ if\ and\ only\ if\ item\ i\ is\ assigned\ to\ bin\ k, else\ 0$

$c = bin\ capacity$ $\qquad n = number\ of\ items$ $\qquad m = number\ of\ bins$

and $w_i = weights\ of\ items\ (i = 1, \dots, n)$

If a solution to equation 2.3 has an optimal value equal to z^*, then an optimal solution or upper bound for the CBP is obtained by selecting the first z^*smallest items and is defined as: (Labbé et al. 2002, p491)

$$\overline{U}_o = \max_{i \leq k \leq n}\left\{k : \sum_{i=1}^{k} w_i \leq mc\right\}$$ **Equation 2.8**

Labbé et al. (2002) presented a heuristic method for solution of the CBP problem based on heuristics from packing procedures. The method starts by sorting items by non-decreasing weights of the items; then an upper bound is computed using Equation 2.8. If the number of items n exceeds the upper bound computed $\overline{U}$, then remove the $n - U$ largest items and set $n = U$. The final step is to apply one of the following packing procedures. If any application yields a solution of value $\overline{U}$, then this is the optimal solution because all remaining *n* items can be packed by definition.(Labbé et al. 2002, p493)

a) Consider the items in turn; place the first item in the lowest numbered bin that the item will fit, then the next item in the next bin it can fit and continue until all items are placed.
b) Consider the items in turn; place the first item into largest capacity bin, then the next item into the next largest bin and continue until all items are placed.
c) Consider the items in reverse order. Place the largest item into the lowest numbered bin that it will fit. If *m* bins can accept all the items then the solution is obtained, otherwise discard the largest item and recalculate.

For geometric scheduling, CBP algorithms serve as a model for sequential logic for packing items within the control volume however 2-D and 3-D packing methods are required for solutions of any substance. Tsai and Li (2006) claim existing packing methods may only find local optimal solutions. At the same time, the current methods employ an excessive amount of binary variables thus causing considerable delays in the computations. Tsai and Li (2006) introduced the basic packing formulas and concept in an extremely comprehensive fashion that was easy to understand. The basic formulas presented (Tsai and Li 2006, p688-690) are the source of the non-overlapping portion of the geometric scheduling process.

Wei et al. (2008) stated packing formulas are heuristic algorithms, based on various strategies, that can be classified as either traditional heuristic or meta-heuristic. Traditional heuristic applications use the given information to guide the process, i.e. top-down, left-to-right, etc. Meta-heuristic equations use processes such as genetic algorithms to define, refine and improve the process until a solution is achieved.

Wei et al. (2008) investigates the 2-D packing problem, also known as the knapsack problem, and suggests a rectangular packing strategy that allows the target pieces to be rotated 90 degrees and no guillotine constraint is stipulated. The process for the packing solution begins with an initial least-wasted strategy. The first rectangle is packed into the sheet with its bottom-left corner placed at the origin. The next largest rectangle is packed into the sheet in such a position that no edges overlap the initial rectangle or extend beyond the limits of the sheet. The remaining rectangles are packed around the first two until the sheet is full. (Wei et al. 2008, p1609)

Rectangles can be rotated but they cannot overlap or be cut. The area to receive the rectangles is called the envelope and it is defined as the space within the original sheet boundaries minus any placed rectangles. To determine if a rectangle can be packed in the envelope the dimensions of the rectangle are checked against the available space remaining in the envelope. If any rectangle will not fit within a certain area then the area is called a bad area. Bad areas are removed from the envelope and the boundary dimensions are revised. Wei et al. (2008) referred to this process as "smoothing" the envelope and introduced the concept of a goodness number (GN) as a means of aiming the search toward a solution. If a rectangle's base equals the available width and the side equals the available height of the envelope, the pack is given a GN=2. If only the base or the height meet this criteria then the pack is given a GN=1 and if neither criteria is met the pack is given a GN=0. Wei et al. (2008) select the pack with the greatest GN value if all other packing criteria are equal. Goal of the 2D packing problem is to identify a packing sequence that maximizes the total area of rectangles packed into a sheet or filling rate.

Castillo et al. (2007) considered the problem of solving circle packing problems as they relate to industry. Circle packing problems are much more difficult to optimize than rectangular packing problems because they cannot be solved with purely analytical methods. For that reason the authors speculate that circular pack problems have received limited attention in research literature. The authors limited the scope of this paper to introduction of various circle packing problems in industry and presentation of exact and heuristic strategies for their solutions. Typically the generic form of circular packing problems attempts to maximize the number of non-overlapping circles contained within the minimum sized container. The container can be circular as well as rectangular and the circles can be uniform or arbitrary sized radii. Specific applications were shown as container packing, fiber optic cables within a conduit and circle cutting of plate stock to minimize waste. Solution strategies differed however the conclusion the authors stated was in general, the most successful packing resolutions followed three basic rules: (1) pack the circles from largest to smallest, (2) pack larger circles in the corners, and (3) pack equal sized circles together. (Castillo et al.2007, p792)

Nesting techniques seek to minimize the volume of the carton by maximizing the packing density without overlap of the packed items. Goodman et al.(1994, p27) defined the nesting process as consisting of the following activities: (a) sorting of the items to be packed by size, (b) placing the first rectangle at a corner of the receiving space, (c) place the biggest rectangles before the smaller rectangles, (d) repeat item (c) until all the rectangles have been packed. Solving the nesting problem mathematically is extremely difficult (Fischetti and Luzzi 2008). Therefore heuristics are typically used by industry for packing containers and related activities. The Volume Factor (V_f) used in geometric scheduling was developed specifically to identify the larger activities mandated by nesting techniques.

2.6 Resource Management

Resources on a project can be materials consumed by the construction, skilled workers, a specialized piece of equipment such as a large crane or concrete pump, rental equipment or temporary facilities. This study considers space as one of the resources to be managed and optimized as a product of this process. The two most common forms of resource management currently used in the industry are resource leveling and resource allocation. R*esource leveling* attempts to reduce the peaks and valleys associated with a particular commodity such as personnel or bricks by adjusting start times of related activities within identified float times. The project schedule is maintained as the construction manager works to maintain optimal resource levels. *Resource allocation* attempts to reschedule the project to utilize a limited amount of resources. Resource levels may be set at a maximum cap due to finances or staffing. Any costs associated with an extended schedule are intended to be nullified by the material savings associated with the optimal resource levels. On the other hand, if space is considered the resource as in this study, by definition, any resource management must be of the allocation form due to the finite amount of space as defined by the construction documents.

2.6.1 Resource Leveling

Resource leveling assumes an unlimited supply of resources is available to the construction project and the schedule remains constant while the resource levels are adjusted to maintain the schedule.

Harris (1990) identified the need for resource management on a project and presented a resource leveling method based on heuristics. The procedure presented in the literature was to develop an initial histogram for the project by first considering only the critical activities or activities with total float less than or equal to the activity duration as identified by a network schedule. The goal was to produce rectangular plots that corresponded to the resource requirements for the activities. This initial histogram was considered the baseline for the project and the non-critical events were added after the initial values. Shared resources were identified and the process consisted of attempting to minimize the resulting moments when the time (duration) was multiplied by the resource value for each activity. To facilitate the development of the histogram, the following rules were presented to guide the decision making process (Harris 1990, p332):

1. Activities are considered to be time continuous.
2. Resources applied to each of the activities are to remain constant throughout the duration of the activity.
3. The duration of the individual activities are to remain constant.
4. The network logic is assumed fixed.
5. The project's completion date is to remain fixed.

Hegazy (1999) attempted to improve the resource leveling and resource allocation heuristics by incorporating genetic algorithms into the solution. Heuristic rules are simple to understand and easy to incorporate into the solution but they perform with varied degrees of success with an apparent lack of standard guidelines to direct the construction professionals toward the wisest choice between schedule duration or resource levels. Of all the heuristic methods available for resource management associated with the construction schedule, the minimum moment method is perhaps the best known. Once the schedule is constructed a histogram is prepared with the days as the horizontal axis and resource units as the vertical axis. The moment M_x calculated for each activity is defined by Equation 2.9 to minimize the resource fluctuation.

$$M_x = \sum_{j=1}^{n}\left[\left(1 \times Resource\ Demand_j\right) \times \frac{1}{2} Resource\ Demand_j\right]$$ **Equation 2.9**

where $n = working\ day\ number\ of\ the\ project's finish\ date$

The calculated minimum moment M_x about the horizontal axis does not consider the resource utilization period. This becomes critical if the resource considered is a piece of rental equipment such as a crane. To manage the resource utilization period the moment about the vertical axis (resource amount) M_y must be calculated as defined by Equation 2.10.

$$M_y = \sum_{j=1}^{n}\left[\left(1 \times Resource\ Demand_j\right) \times j\right]$$ **Equation 2.10**

Once the moment calculations are defined, the project manager has four options based on the particular scheduling objectives: (1) minimize M_x alone if the focus is to reduce daily resource fluctuations, (2) minimize M_y alone if the focus is to reduce resource utilization periods, (3) minimize M_y if the focus is to release a resource at the earliest possible date, (4) minimize both moments when the focus is to reduce all aspects associated with the project resources. (Hegazy 1990, p170). The goal is to achieve a uniform distribution of the resources over time by minimizing the resulting moment values. One method used for reducing the computed moments is to reduce the extreme values of the resources by schedule manipulation. Start times for activities are staggered based on available slack time and float generated through the schedule process.

2.6.2 Resource Allocation

Resource allocation attempts to utilize a specific or limited amount of resources and adjusts the schedule, as required, to avoid resource shortages. Perhaps the best example of a limited resource on any construction project is funding.

Demeulemeester et al. (1998) considered the discrete time/cost trade-off problem based on a CPM network. They suggested for every activity there is a specific cost based on a given duration. These costs are bounded on the low side by the normal duration of activities (most efficient resource allocation) and on the high side based upon the crash duration (maximum allocation of resources). Ultimately, the cost of the project is subject to the supply and availability associated with the limited, non-renewable resources. Three types of objective functions were presented as viable solutions to optimize the time/cost problem: Type 1 – limit placed on the total availability of a single non-renewable resource and project completed in the shortest time frame based on resource restrictions (schedule completion date allowed to slide); Type 2 – completion date is set and the resources are considered unlimited and renewable with the goal to complete the project with the least amount of required resources; Type 3 – complete time/cost information calculated for the entire project. (Demeulemeester et al. 1998, p1153)

A series of costs and related durations are identified and the solution is presented as the pairing, cost and related duration, for which no other solution can be found that is equal or less than the identified solution. To accomplish this, Demeulemeester et al. (1998) presented a branch-and-bound algorithm that identified the lower bounds associated with the project costs and durations. This procedure is superior to the minimum-moment method of resource leveling because it converges to an exact solution quickly due to an iterative approach.

CHAPTER 3

Research Methodology

3.1 Introduction

Research work for this study is organized into three segments. The first segment is an introduction of construction scheduling techniques and an identification of the problems associated with time-space conflicts on project sites. The information is presented through knowledge gained in twenty-five years of construction experience and a comprehensive literature review of related studies pertaining to the latest scholarly works (Chapters 1 and 2).

The second segment is the development of a model that identifies potential time-space conflicts, between construction activities, while producing a project schedule (Chapter 3). The third and final segment is the validation of the model by analysis on a completed construction project data and comparison to anticipated results generated by the model (Chapter 4 and 5). As previously stated, the purpose of this research is the development and implementation of a generic process that can identify potential time-space activity conflicts while creating the construction schedule.

The model uses packing principles as the basis for its form and function. Each construction activity is defined geometrically as rectangular prisms with dimensions equal to the physical size of the activity plus a working clearance as shown in Figure 3.1. The working clearance is set by the user and must include any necessary machinery, scaffolding or similar temporary structures that may be required due to the method of installation chosen by the individual. Construction methods and constraints determine the sequence of the activities while modified packing algorithms accomplish the task of fitting the shapes into the defined workspace by mathematically comparing shape coordinates and identifying potential conflicts between activities. Previous time-space studies (Akinci et al. 2002a; Guo 2002; Winch and North 2006) required the construction schedule be completed prior to application of their respective solution methods. This research is designed to identify all time-space conflicts based on the geometric shapes and sequential logic associated with the activities. From an efficiency perspective, reworking the schedule to resolve the conflicts is far less desirable than producing a conflict-free schedule initially.

Tsai and Li (2006) identified a collection of equations that mathematically define a method for packing cartons into a container. These equations form the basis of the geometric scheduling method presented in this research. Packing solutions for discrete items differs from scheduling construction activities in the following ways: carton sizes remain constant while construction activities vary in size with time; construction activities cannot be rotated to fit within the available space as a carton can; relationships between activities are governed by physical demands and constraints whereas cartons' single restriction is two items cannot share the same space; and finally sequencing of construction activities are guided by logic, laws of physics and specific site requirements such as access and physical locations of the activities. Thus the final derived packing/scheduling algorithms must account for changing activity shapes while maintaining site defined spacing and sequencing restrictions.

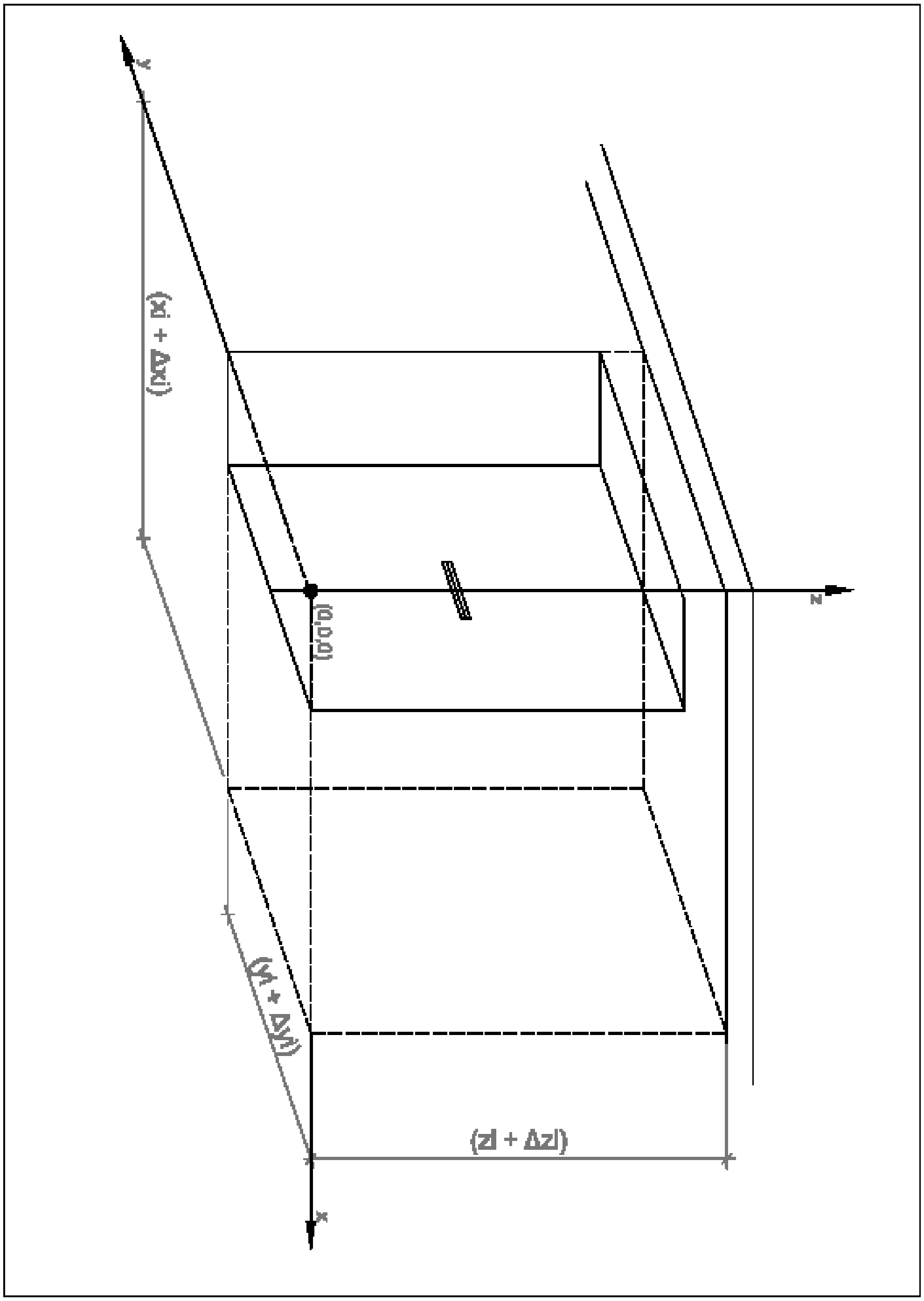


Figure 3.1 Construction Activity Modeled as a Rectangular Prisms

3.2 General Requirements

Packing algorithms are designed to place cartons inside a confined space and must be modified to reflect the challenges associated with construction activity scheduling. Physical conflicts can be identified by binary decision modifiers working within existing industry algorithms. However, logic and activity dependencies require sequencing knowledge not common in packing processes therefore dependencies must be defined by the user prior to activity comparisons for time-space conflicts. In addition, the process must remain applicable to the construction industry while maintaining a user-friendly approach that encourages the method's use by construction managers. Finally, the process must be comprehensive and complete so as to provide a meaningful contribution to the industry as well as a consequential solution to time-space conflict resolution on even the most sophisticated construction projects.

3.2.1 Specific Objectives

Consider two boxes as shown in Figure 3.2 shown at the end of this section on page 99. The two boxes can be used to represent the 3D graphical representations of two construction activities Activity i and Activity k where $i \neq k$. To avoid packing the boxes in the same space, the following mathematical relationships must all be true (Tsai and Li 2006):

$$x_i + P_i \cdot l_{xi} + Q_i \cdot w_{xi} + R_i \cdot h_{xi} \le x_k + (1 - A_{ik}) \cdot M$$ **Equation 3.1**

$$x_k + P_k \cdot l_{xk} + Q_k \cdot w_{xk} + R_k \cdot h_{xk} \le x_i + (1 - B_{ik}) \cdot M$$ **Equation 3.2**

$$y_i + P_i \cdot l_{yi} + Q_i \cdot w_{yi} + R_i \cdot h_{yi} \le y_k + (1 - C_{ik}) \cdot M$$ **Equation 3.3**

$$y_k + P_k \cdot l_{yk} + Q_k \cdot w_{yk} + R_k \cdot h_{yk} \le y_i + (1 - D_{ik}) \cdot M$$ **Equation 3.4**

$$z_i + P_i \cdot l_{zi} + Q_i \cdot w_{zi} + R_i \cdot h_{zi} \le z_k + (1 - E_{ik}) \cdot M$$ **Equation 3.5**

$$z_k + P_k \cdot l_{zk} + Q_k \cdot w_{zk} + R_k \cdot h_{zk} \le z_i + (1 - F_{ik}) \cdot M$$ **Equation 3.6**

Where *M* is defined as a generic multiplier:

$$M = X \cdot Y \cdot Z = Total\ Volume\ of\ Control\ Space$$ **Equation 3.7**

The purpose of the generic multiplier is to provide an extremely large value to insure a positive result for the comparisons when the activities are located in such a fashion that they will not conflict due to locations. The total volume is also used by the model to create the Volume Factor (V_f) defined by Equation 1.11 and used in the heuristics for the activity sorts.

3.2.2 Definitions and Terminology

Six (6) 0-1 binary decision factors are required to define potential space conflicts for adjacent activities in the x, y and z directions. If the resulting multiplier equals zero then the initial activity extreme limit must be less than or equal to the starting dimension of the next activity or a false statement identifies a space conflict. The multipliers are defined as:

A_{ik} = 1 if activity space *i* is on the left of activity *k*, otherwise A_{ik} = 0.

B_{ik} = 1 if activity space *i* is on the right of activity *k*, otherwise B_{ik} = 0.

C_{ik} = 1 if activity space *i* is directly in front activity *k*, otherwise C_{ik} = 0.

D_{ik} = 1 if activity space *i* is directly behind activity *k*, otherwise D_{ik} = 0.

E_{ik} = 1 if activity space *i* is below activity *k*, otherwise E_{ik} = 0.

F_{ik} = 1 if activity space *i* is above activity *k*, otherwise F_{ik} = 0.

Using standard nomenclature from the packing industry, numerous variables are required to define the orientation of the individual cartons:

(x_i, y_i, z_i): Continuous variables for location using the coordinates of the front-left-bottom corner of the activity space *i* (x_i, y_i and z_i are integers if the given dimensions of the activities are integers).

(l_{xi}, l_{yi}, l_{zi}): Binary variables indicating whether the length of the activity space *i* is parallel to the X-axis, Y-axis or Z-axis. For example, the value of l_{xi} is equal to 1 if the length of the activity space *i* is parallel to the X-axis; otherwise, it is equal to 0. It is clear that $l_{xi} + l_{yi} + l_{zi} = 1$.

(w_{xi}, w_{yi}, w_{zi}): Binary variables indicating whether the width of the activity space *i* is parallel to the X-axis, Y-axis or Z-axis. For example, the value of w_{xi} is equal to 1 if the width of the activity space *i* is parallel to the X-axis; otherwise, it is equal to 0. It is clear that $w_{xi} + w_{yi} + w_{zi} = 1$.

(h_{xi}, h_{yi}, h_{zi}): Binary variables indicating whether the height of the activity space *i* is parallel to the X-axis, Y-axis or Z-axis. For example, the value of h_{xi} is equal to 1 if the height of the activity space *i* is parallel to the X-axis; otherwise, it is equal to 0. It is clear that $h_{xi} + h_{yi} + h_{zi} = 1$.

Given construction activities cannot be rotated to fit within the space, the binary variables *l*,*w* and *h* are not required. Therefore these variables can be eliminated from the packing algorithm by declaring the following:

Let P = dimension of the rectangular prism along the x-axis

Q = " " " " " " y-axis

R = " " " " " " z-axis.

The preceding mathematical relationships are reduced to:

$$x_i + P_i \leq x_k + (1 - A_{ik}) \cdot M$$ **Equation 3.8**

$$x_k + P_k \leq x_i + (1 - B_{ik}) \cdot M$$ **Equation 3.9**

$$y_i + Q_i \leq y_k + (1 - C_{ik}) \cdot M$$ **Equation 3.10**

$$y_k + Q_k \leq y_i + (1 - D_{ik}) \cdot M$$ **Equation 3.11**

$$z_i + R_i \leq z_k + (1 - E_{ik}) \cdot M$$ **Equation 3.12**

$$z_k + R_k \leq z_i + (1 - F_{ik}) \cdot M$$ **Equation 3.13**

The modified equations produces a static representation of the activities in question and can serve as a preliminary scheduling tool to quickly identify potential conflicts when the variables P, Q and R represent the total spatial requirement for each activity.

The total value for the spatial requirement must include a safe working space for the installation of the activity as well as the physical size of any lift or similar equipment required by the activity. Since these dimensions vary from site to site and activity to activity these values must be user defined. Previous studies claimed worker space on a job should range from 111 sf (10.4 m^2) (Winch and North 2006) to 300 sf (28 m^2) (Riley and Sanvido 1995) per worker. Assuming the worker space as a square, those values equate to an average clear space of 15 ft (4.6 m) on all sides. Experience on hundreds of construction sites dictates that amount of space to be impractical on a normal construction site. A more reasonable number would be 3 ft (.9 m) to 5 ft (1.5 m). For the model development, a default value of 3 ft (.9 m) will be added to activity dimensions to allow for installation (actual values should be used whenever possible).

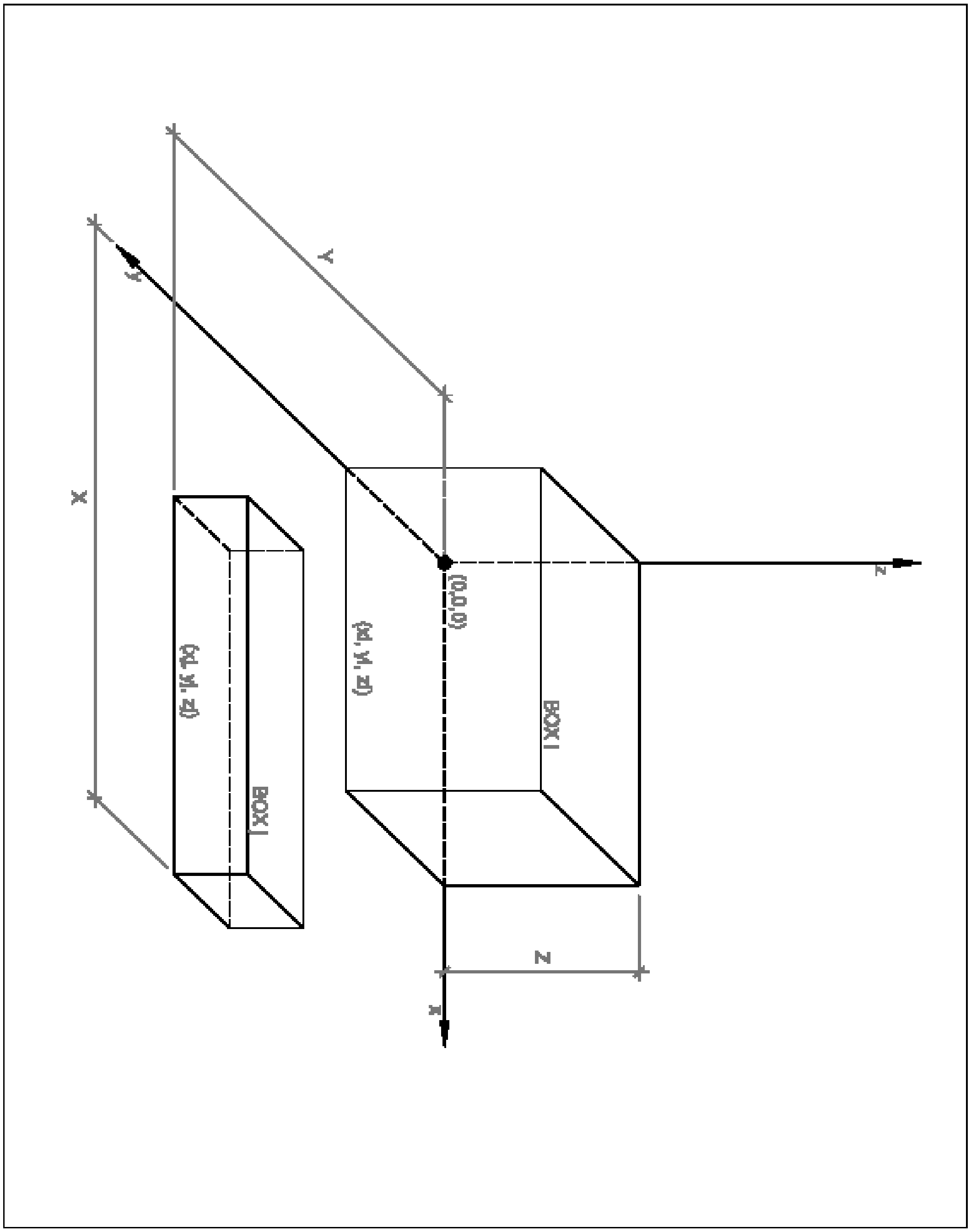


Figure 3.2: Graphic Representation of Adjacent Boxes

3.2.3 Spatial Relationships

The primary concept guiding this research is to model each construction activity as a rectangular prism and then mathematically relate pairs of activities to identify potential conflicts. Packing algorithms can be used to perform this function but the results are extremely limited and not suited as a scheduling tool. By incorporating the effects of the activity duration the initial algorithm can be improved to allow for changing shapes. This ability to allow for the changing required spaces associated with the activities is a key element in effectively modeling the activities and allows for changing the rate of completion of activities associated with schedule crashing and increasing crew sizes.

Consider a mathematical function that defines the rectangular model for each activity. The origin for each rectangle is set as the lower left-hand corner for each shape to avoid the introduction of negative numbers into the calculations. By setting the origin of each shape as the lower left-hand corner all changes are considered positive when they flow to the right and up from this location. At the same time, for simplicity, assume construction activities are continuous once started and are completed in an orderly fashion. Thus if length, width and height of each activity are defined by their initial positions and dimensions as detailed in Figure 3.2, the change in initial values can be defined by the following equations:

$P = x_i + \Delta x_i$ **Equation 3.14**

$Q = y_i + \Delta y_i$ **Equation 3.15**

$R = z_i + \Delta z_i$ **Equation 3.16**

where $\Delta x_i = \frac{dx_i}{dt}$, $\Delta y_i = \frac{dy_i}{dt}$, $\Delta z_i = \frac{dz_i}{dt}$

The Δ function is defined as the rate of change for the given dimension with respect to time. Time is defined as the duration value for each activity. In practice, two of the three dimensional constraints will remain constant with change only occurring in the third. In other words the width and height of the activity being produced will remain constant while the length varies with time. For the constant activities, $dt = 1.0$ and the Δ function is the entire length, width or height of the particular activity. For a variable activity dimension, the Δ function is the total length, width or height divided by the duration; the resulting value is used to progress in a step-wise pattern positively away from the identified activity local origin.

Substituting the Δ function into the identities shown in Equations 3.14 - 3.16, and rewriting the mathematical relationships previously identified as Equations 3.8 -3.13, leaves the following equations that identify potential time-space conflicts between activities while accounting for the variable shape associated with completed activities.

$$x_i + \frac{dx_i}{dt} \leq x_k + (1 - A_{ik}) \cdot M$$ **Equation 3.17**

$$x_k + \frac{dx_k}{dt} \leq x_i + (1 - B_{ik}) \cdot M$$ **Equation 3.18**

$$y_i + \frac{dy_i}{dt} \leq y_k + (1 - C_{ik}) \cdot M$$ **Equation 3.19**

$$y_k + \frac{dy_k}{dt} \leq y_i + (1 - D_{ik}) \cdot M$$ **Equation 3.20**

$$z_i + \frac{dz_i}{dt} \leq z_k + (1 - E_{ik}) \cdot M$$ **Equation 3.21**

$$z_k + \frac{dz_k}{dt} \leq z_i + (1 - F_{ik}) \cdot M$$ **Equation 3.22**

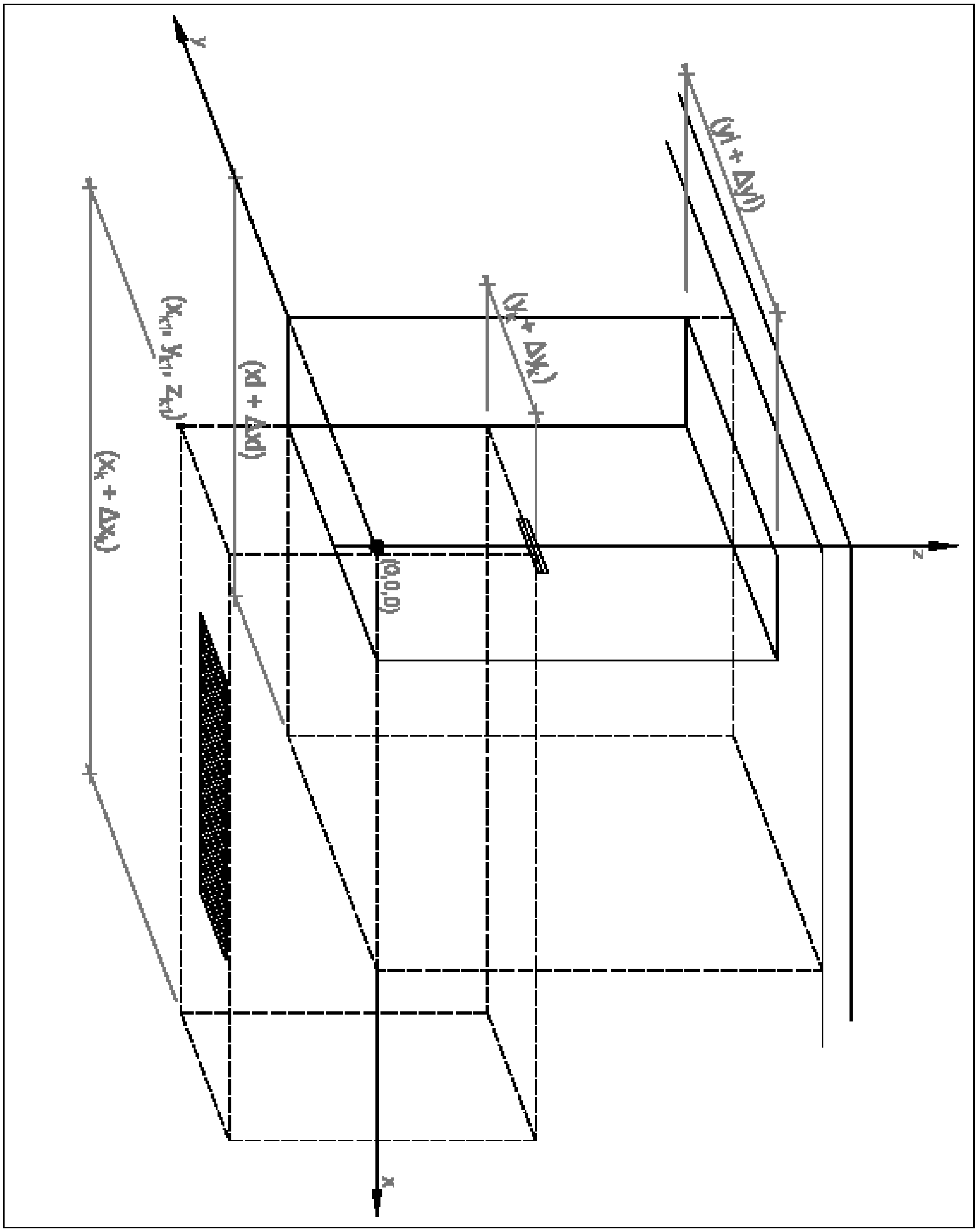


Figure 3.3 Graphic Representation of Adjacent Activities

3.2.4 Sequencing

Standard packing algorithms are independent of sequencing requirements. A meaningful implementation of the packing algorithms for construction scheduling must include direction defined by the relationship of activities to each other. A method was sought that could universally relate any given activity to a subsequent activity.

Echeverry et al. (1991) studied numerous construction schedules from a variety of projects. They concluded all construction activities are related and these relationships can be defined by one or more common characteristics that can be summarized as follows (Echeverry et al.1991 p121):

1. Supported by – one activity is directly supported by another activity
2. Covered by – a single activity or component is covered by another
3. Embedded within for structural function– an activity is embedded within a subsequent activity to form a combined structural member
4. Embedded within for a noncontributing for structural function – an activity is embedded within another for aesthetic purposes
5. Relative distance to support – one or more activities are supported by a structural member and the closest activities must be completed before subsequent items

6. Relative distance to access – to install activities within a confined site with limited access the items must be installed in a pattern that allows subsequent activity's access
7. Weather protected – activities that would be damaged by exposure to the weather must be installed after the area is made weather-tight.

All construction projects and activities must obey the laws of Physics, therefore any activity supporting others must come first. Of these relationships, Items 1, 3, 4 and 5 can be simplified and combined into a single item that relates one activity to another through the physical dependency of support. The second most important constraint to consider, governing a construction activity's sequence, is its relevance to Local Building Code requirements. Consider sprinkler head locations within a structure. For example, in the event a sprinkler head is located in the same location as the HVAC duct, the duct is modified to accommodate the sprinkler head location mandated by Local Code requirements. Missing from the initial listing is any reference to Building Codes and thus will be added for consideration by this research. Item 6 relates to activity access and is defined by site specific constraints as opposed to generic activity relationships so it will not be a factor in this research. Item 7 can identify any number of activities such as drywall, painting, interior finishes, etc. It can also identify activities not specifically defined by the other Items. Finally, consider the concept of *flexible* and *inflexible* activities. Inflexible activities are any activities that are supported by others, provide support to others or are governed by Local Building Codes. Flexible activities are any activities not identified as inflexible. Inflexible activities must be scheduled before flexible activities. However, temporary actions can make an inflexible activity into a flexible activity, such as scaffolding for beam support or weather protection for delayed window deliver. So for scheduling reasons, if the additional costs, associated with the modification such as scaffolding or temporary weather protection, are less than the benefits associated with a revised schedule then the temporary measures can be used by the construction manager to alter an activity's status from inflexible to flexible.

Using these definitions, all activities can be classified and given a numeric ranking that allows for a simple sorting. This numerical ranking is identified as the "Sequence Identifier (SI)" as defined in Table 3.1.

Mark	Description
S1	One activity supported by another.
S2	Location of an activity governed by Local Building Code
S3	One activity covered, encased or embedded in another.
S4	Activities to be protected from weather.

Table 3.1 Identification of SI Criteria

Items that are required to support other items must be completed first and are given SI=1, items required by Code are given SI=2, etc. The user defines these classifications based on his or her knowledge of the industry and experience. The model sorts the activities and completes the activities in numeric sequence. All activities identified as a SI=1 are completed before SI=2, which are completed before SI=3, and finally SI=4.

3.2.5 Constraints

How the activities are sequenced within the control space or construction zone is subject to constraints. Constraints are defined as rules relating physical locations and logical sequencing of activities and they can be defined as:

1. One activity cannot be completed over the top of another activity
2. Two activities cannot occupy the same space
3. Access – one activity cannot block the access of a subsequent activity
4. Space required for one activity cannot overlap the space required for another activity.
5. Dependency of an activity on another

All spatial requirements, except the access constraint, are satisfied by the spatial relationship equations with binary decision variables. The access constraint is resolved by expressing the required access area as an individual activity with a constant duration similar to the use of dummy variables in CPM scheduling. Unlike the actual project activities, the dummy access activity can be modified and relocated as required to allow completion of other activities. The final constraint, dependency logic, is treated the same as it would using any other scheduling method such as CPM or LOB.

3.3 Optimization

Optimization of space management is one of the primary objectives of this research. Two theories exist in the current literature for space management. One group of scholars (Winch and North 1999) attempts to assign space to the individual tasks similar to resource leveling. This first method assumes an unlimited supply of the resource to be leveled (space) is applied to the various tasks utilizing a weighted process and activity floats. A second group of scholars (Akinci et al. 2002a; Guo 2002; Thabet and Beliveau 1994) suggests the amount of space is a finite quantity and assigns tasks to the available space similar to resource allocation methods for other resources. Both of these forms of management require the completion of a project schedule to identify any free float associated with affected activities and suggest potential potential time/space conflict solutions. This research assumes space is a limited resource and each activity is assigned to the available space as the schedule is developed.

The optimization process has been defined as seeking the maximum or minimum solution to the equation put forth. In construction management, typically three approaches can be considered when attempting to optimize a process:

(1) The first approach is an exact mathematical approach utilizing linear programming. If the process is continuous an exact solution can be attempted.

Unfortunately, construction projects are seldom continuous and meeting the continuity requirement is extremely difficult.

(2) The second form of optimization involves evolutionary algorithms that attempt to model the construction activities and compensate for the lack of continuity. Evolutionary algorithms, also referred to as genetic algorithms, are equations that first identify a potential solution then compare the known solution to others in search of the optimal solution as defined by the user. The method is called genetic or evolutionary because it resembles the natural selection process and genetics in reproduction. (Hegazy 1999,170). Recent years have seen an increase in the use of genetic algorithms to optimize construction processes.

(3) The third accepted practice for optimizing a process is to use heuristics (rules) to develop a ranking and sequencing of the construction activities that seek to identify an optimal solution. Heuristics are simple to understand and easily adaptable to computer programming. (Hegazy 1999, 167) Using packing principals as the guide assigns tasks to available spaces at various times using heuristics to guide the optimal solution calculations. 3-D nesting techniques, as a form of heuristic evaluation, are used to optimize the geometric information scheduling process. Prior to packing the activities, physical constraints and relationships between activities must be identified. Obviously a surface cannot be painted or finished prior the construction of the structural components

supporting the exposed product. The heuristics used by the method are shown in Table 3.2.

Heuristics used by the Method
1. Activity constraints must be identified through Sequence Indicator (SI) factors; soft logic is used to combine similar activities to reduce the number of required calculations. Activity predecessor relationships must be identified
2. Nesting techniques set the activities with the largest Volume Factor (V_f) first then attempt to insert the remaining smaller activities into the control volume without overlapping, overhead or exceeding the limits of the work area.
3. Work proceeds in a top-down fashion when considering tie-breakers between activities.

Table 3.2 Geometric Information Scheduling Heuristics

3.4 Algorithm Development

Identification and elimination of potential time-space conflicts between construction activities is similar to problems observed in the packing industry when considering the packing of individual boxes within a shipping container. A review of current industry packing methods revealed an assortment of various methods and algorithms that could potentially solve the time-space conflicts and the intent of this research is to identify an existing algorithm found in literature or libraries to modify rather than develop an entirely new equation.

The model is based on a temporal-space algorithm derived from the packing industry (Tsai and Li 2006). Initial geometric values for the work space and the individual activities are fed into the model manually from the data contained on the construction documents. An origin for the work space is defined as the lower left-hand corner of the space to insure all values remain positive. The individual activities are defined as rectangular prisms that are composed of the actual physical size of the product to be installed as well as the required work space associated with the installation chosen and necessary safety considerations. Activities are compared based on technical relationships, sequencing requirements and location. As the model identifies spatial conflicts between the activities those pairings are eliminated from consideration leaving a listing of possible activities that can be completed for any given time-frame. The schedule produced is a summary of the non-conflicting activities for each of the days.

3.4.1 Algorithm Inputs

The algorithm, central to the model development, requires geometric information concerning the work space and the individual activities. The individual activities are to be represented by three-dimensional rectangular shapes approximating the initial shape of the item to be constructed as well as a clearance space required to allow installation.

To manage the activities within the workspace, the user must define the space as well as the individual activities. Akinci et al. (2002b, p297) stated eight (8) separate pieces of information, including the location of the object relative to a fixed reference, the dimensions of the shape and the start and finish times associated with the activity are required for the identification of any activity when attempting to generically model the construction. The model requires these spatial cooridnates as data input from the user. The model also requires a definition of the work space and individual activity relationships and constraints.

3.5 Process Flow

Using the information supplied by the user, the model identifies potential spatial conflicts and prepares the schedule following the process flow defined in Figure 3.4 on page 108. The process flow is structured using a parallel approach (Thabet and Beliveau 1997). That is all activities are considered available to be completed for any given time and the process identifies and eliminates the conflicting activities while the remaining activities are completed on parallel pathes. The first five steps involve user input data for the project. The remaining steps take the information and produce a potential conflict-free schedule. The following remarks identify the various steps involved with the model:

Step 1 Identify the the global coordinates and origin for the given space. For each application, be it a room, a structure, a floor, etc. the origin will always be defined as the lower left hand corner of the space. Once the origin is defined then the various activity shapes are expressed in terms of the origin.

Step 2 Define the spatial volume (M) as the product of the global coordinates defining the perimeter and height of the portion of the project under consideration.

Step 3 Define P,Q and R for each activity as a rectangular space that mirrors the item being installed. For example, if a chalkboard is to be installed on a classroom wall, the activity space would be defined as the dimensions of the chalkboard plus the user defined space required to allow for worker access during installation. Spatial definitions are given by cartesian coordinates of the lower left hand corner of each activity shape {x,y, and z}.

Step 4 SI factors for each activity defined by the user and assigned to the activity.

Step 5 Identify predecessor activities, if applicable, to the individual activities.

Step 6 Volume Factors (V_f) for the individual activities are calculated by the model from the spatial information supplied by the user.

Step 7 The rate of change for the spatial dimensions is calculated by the model based on the durations supplied by the user.

Step 8 The model performs an initial sort to identify any activities without predecessors requirements. These activities will be completed before subsequent activities can start.

Step 9 The first two activities are identified based on the lowest SI factors, largest V_f values and physical constraints produced by the data sorts. These activities are compared by the spatial algorithm to determine if a conflict exists. If no conflict is detected the pair is saved and the process repeated. If a conflict is detected then the pair is discarded and the process repeated. The process continues until all possible pairings of activities has been completed.

Step 10 From the possible pairings identified in Step 9, the comparison process is repeated to identify any potential conflicts between subsequent activities. The final product is a listing of all activities that can be completed on that particular day with no conflicts.

Step 11 The program subtracts one day from the schedule and physical sizes for the non-completed activities are recalcualted. Activities started in the previous day continue while activities completed are removed from the process. Steps 8 – 11 are repeated until the list of activities is exhausted.

Step 12 The final schedule is presented as a result of the process.

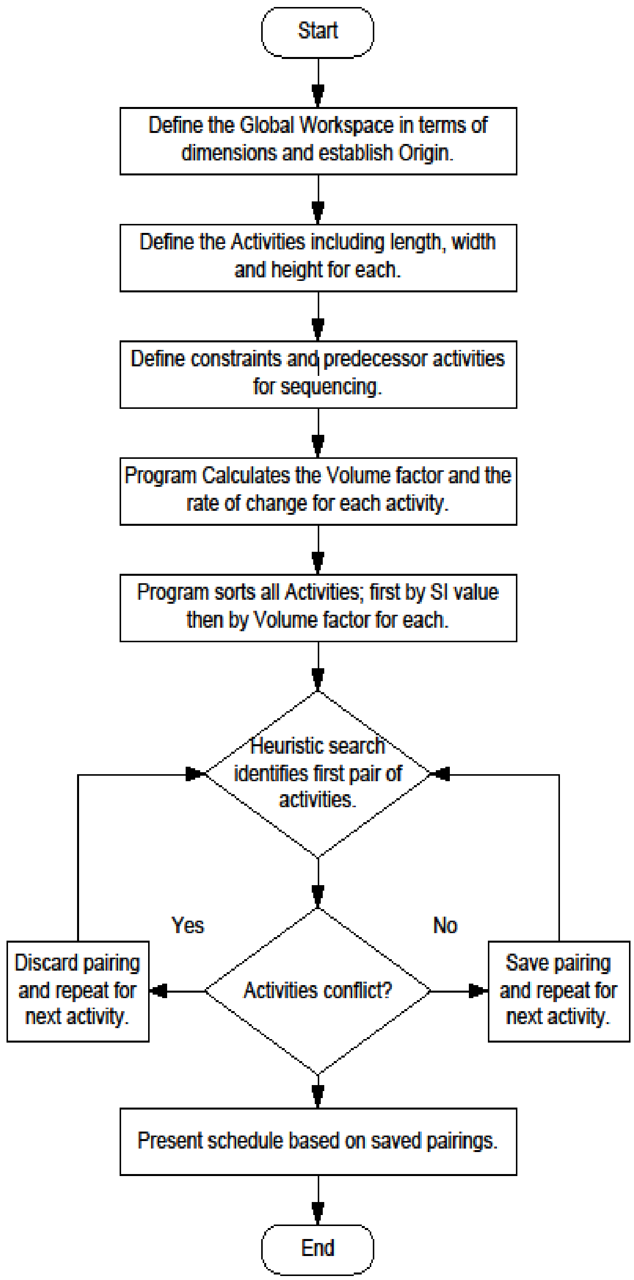


Figure 3.4: Process Flow Diagram

3.6 Performance Testing

The final step in development of any model is to test the theories on actual construction projects. The first tests were conducted on hypothetical situations with sufficient activities to allow for a rich and complete analysis. Following these initial tests, the model was applied to an actual construction project and the resulting schedule was compared to the CPM schedule submitted by the contractor to the owner.

3.6.1 Parameters

The parameters used for this performance testing consist of physical attributes of the construction space, as well as activity characteristics. The control space (see Section 1.6) was limited to a volume ≤ 10,000 ft^3 (283 m^3) with no more than fifty (50) individual activities. Durations of the activities typically varied from 1-5 days and the predecessor activities was limited to one (1) per activity to simplify the logic associated with the activity sorts. The construction costs associated with the case studies ranged from $500,000.00 - $1,000,000.00 (U.S.) and the projects were located in suburban sections of Baltimore County, MD.

3.6.2 Result Ranges

The test result ranges included the total number of potential time-space conflicts identified and the total number of days reduced from any pre-existing project schedule developed using network techniques.

3.7 Computer Implementation

3.7.1 Spreadsheet Analysis

To avoid human errors associated with data manipulation, a standard Excel spreadsheet with macros was designed to perform the mathematical calculations associated with the scheduling process. The initial template is filled with the activities information and macros are used to sort the activities based on the activity sequence, logic and location heuristics. With the initial sort completed, a second macro compares the first two ordered pairs, if the result is no conflict, the macro saves the identity of the non-conflicting pair of activities and continues. The next step is to compare the first item with the third item. If no conflict exists then the second item is compared to the third item. If a conflict is detected between the second and third activities then the pairing is discarded and continues. When the first day calculations are complete, all non-conflicting activities with the first activity are identified as the first day of the schedule. The process continues until all activity comparisons have been completed.

3.7.2 Linkage with Scheduling Software

The original data can be manually entered into the program or automatically read from a schedule created using Microsoft Project. Microsoft Project was chosen because it is widely used in the construction industry and it readily shares data with Excel spreadsheets. Figure 3.5 summarizes the basic concept used by the program. Automatic entering of activity data is preferable to manual methods because manual input introduces potential errors into the process, is extremely time consuming for larger projects and given the herculean effort required to enter the data manually nearly guarantees the program and the process will not be utilized by the construction professional.

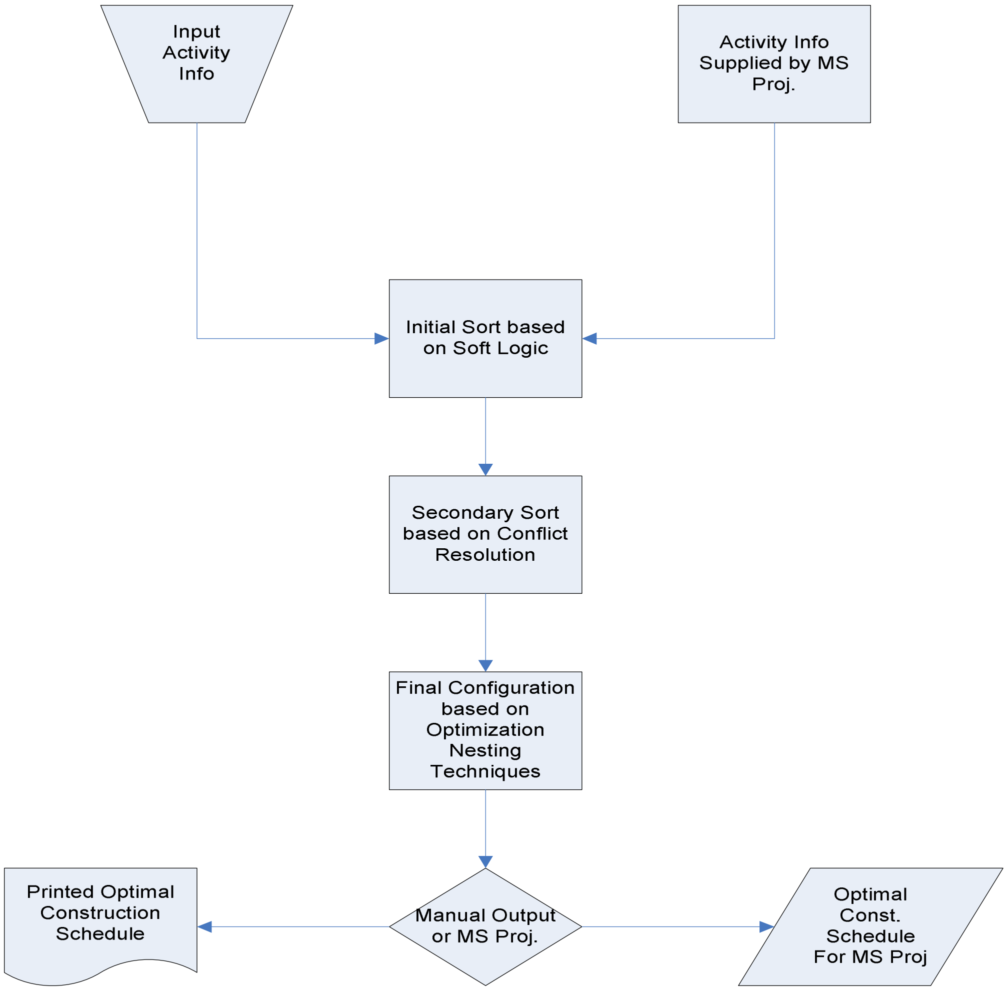


Figure 3.5: Integration of the Model with Existing Scheduling Software

Once the optimal sequencing of activities is generated the information can be used in a variety of ways. The sequencing of activities can be entered into a standard construction scheduling program, such as Microsoft Project, and the schedule for submission to the owner prepared. The proposed project schedule, created by a standard scheduling method, can be reviewed with potential conflicts identified and resolved prior to construction. The optimal sequencing results can also be used for subcontractor scheduling. The more accessible the information is to the user the more likely the information will be used on the project site.

3.8 Conclusions

One final note concerning time-space conflicts regards the severity of the conflict and the effects on the final schedule. Conflicts will manifest on construction sites even with the best pre-construction planning. The resolution of the conflicts is the responsibility of the construction management team. The construction manager is provided the information via this method and he or she is solely responsible for how that information is integrated into the construction project. No attempt is made by this model to rank or qualify the identified conflicts.

The creation of the geometric information scheduling model required three major modifications to packing principles for adaptation to the construction scheduling industry. First, the packing industry is not concerned with the orientation of each package as long as ultimately the pieces fit within the defined boundaries. Obviously, the orientation of the construction activities is set therefore we eliminated the need for binary multipliers to identify the {x, y, z} orientation of the activities. Second, construction activities vary in size during the completion of the activity and packing boxes remain constant throughout the entire process. To accommodate the changing construction activity sizes the model introduces the concept of the Δ factor based on the rate of change given by an activity's duration. The third major difference concerned sequencing. As stated, the packing industry is concerned about sequencing to the extent that items placed within the defined space cannot block the access of subsequent items. Construction activities are extremely dependent upon sequencing as defined by the relationship activities have with one another. Complicating the issue of sequencing is the requirements placed by Codes and industry standards. For example, the location of sprinkler heads is dictated by Code and not subject to change in the field. If a given head location is competing with an HVAC duct for the same space, the duct work must be modified to allow for the sprinkler head to be placed as shown.

The packing process is analogous to creating a resource-constrained critical path (RCP) form of scheduling when the space is considered the resource. Therefore many of the attributes used developing an RCP schedule apply to this method.

Chapter 4

Analysis and Verification

4.1 Introduction

A representative test case was created to demonstrate the capabilities of the process. The test case was based on a generic interior new construction project that contained a sufficient number of construction activities to allow for a meaningful exercise. The knowledge gained from the test case was used to improve the process for subsequent test cases and projects. The metrics used as verification of the process include adherence to the stated research hypotheses and comparison of the completed time-space scheduling with a construction schedule prepared using CPM and Microsoft Project.

The first step in validation of the process is to re-state the hypotheses introduced in Section 1.7:

1.) ***All construction activities can be modeled as three dimensional rectangular shapes. Their individual shape can be defined using the {x, y, and z} coordinates and dimensions specified in the constructions documents.***

2.) ***Modeling construction activities as rectangular shapes and packing them into a control volume identifies potential conflicts that are not identified by CPM scheduling for construction projects.***

3.) ***Allocating activities into a schedule in sequence of largest – to – smallest space usage reduces the construction project durations.***

These hypotheses will be examined at the conclusion of this section with the study results compared to the desired objectives for validation.

4.2 Case Study I

Case Study I is a fabricated construction project created to test the process. The project is a tenant fit-out. The term tenant fit-out, as used in this instance, refers to the lease-holder responsible for all space improvements. This building is a newly constructed, multi-level steel framed structure located in the Baltimore-Washington corridor. The foundations have been poured and the structural steel and metal deck has been erected. The concrete infill for the metal deck is poured, cured, and serves as a work surface as well as a convenient staging site for materials and equipment. The HVAC system has a plenum return system therefore only supply ducts are required in the final construction. Typical floor-to-floor height of the structural steel is 15'-0" with a finished ceiling space of 10'-0". Figure 4.1 is a partial framing plan for the beams and columns and Figure 4.2 identifies architecturally the walls, doors, lighting and the suspended ceiling. Partition walls extend 1'-0" beyond the ceiling height leaving substantial space for coordination of supply ducts, piping and wiring in the space above the ceiling. Electrical power is encased in conduit and supported from the underside of the steel beams of the floor overhead.

The construction activities associated with this work are listed in Table 4.1. Predecessors have been identified based on conventional construction procedures. The V_f and the SI factors have been included in the chart for completeness. Drywall and finishes can only be accomplished after the interior work space is made water-tight and the interior environment is established. Table 4.1 identifies the flexible and inflexible activities to assist with the initial sorting and sequencing (Echeverry et al. p 122). The sequencing must account for the dependent nature of the inflexible activities while the flexible activity initiations are fluid and can be scheduled at convenient times.

Inflexible Activities	**Flexible Activities**
Conduit, HVAC and Plumbing	Doors, Drywall, Paint
Stud Walls, Curtain Walls	Ceiling Grid, Diffusers, Ceiling Tiles
Insulation	Towel Warmer, Marble Tub
Glazing	Spot lights, Perimeter Lighting
	Floor Mural
	Chair Rail, Theater Seating
	Lockers

Table 4.1 – Case Study I: Flexible vs. Inflexible Activities

The first step of the process is to define the work space including a set origin and the global boundaries as shown in Figure 4.2. The second step involves defining the individual activities utilizing the local x, y and z coordinate system. For each of the activities, the local coordinate system follows the framing coordinates based on the structural steel dimensions and the column spacing of 20’-0” o/c and floor-to-floor height of each level at 15’-0”. The lower left-hand corner of the defined space is identified as the origin and the spatial reasoning formulas are derived with the positive values of the activities extending to the right and up respectively. Table 4.2 contains the spatial coordinate information for all of the construction activities considered for this test project.

A rectangular shape is modeled for each activity. by taking the physical size of the activity, be it an area to receive piping, ductwork, etc. with a “work space” defined as 3’0” clear space to allow for workers. For example, if the activity is the installation of an electrical panel, the corresponding rectangular shape would be defined by the dimensions of the panel with 3’-0” clear space at the front and sides to allow for installation. If the item to be installed is located on a wall, the rectangular space would extend from the floor to ceiling to avoid overhead and underfoot conflicts. Table 4.3 contains all the spatial information for the activities including all associated work space.

Once the physical attributes of the activities are defined, the next step is to sort the activities based on the sequencing (SI), the size (V_f) and the construction logic. The initial pass identifies Activity 1 – Conduit and Activity 3B Plumbing Rough-in as the first two activities to be completed per the process decision variables. A spatial conflict is identified between Conduit and Plumbing Rough-in therefore one of the activities can proceed and the other must wait. Tie-breakers are based on the heuristics listed in Table 3.2 however in this case, the two activities are of the same size and height above the floor, the selection of Conduit ultimately is a random selection. Conduit is compared to all other activities free of any predecessor requirements. Conduit and Curtain Wall A are identified as the only non-conflicting activities to be completed on Day 1. The complete analysis for Case Study I is included as Appendix A with all the activity comparisons used to develop the completed schedule. Results from the spread sheet calculations were entered into a Microsoft Project file and the schedule was generated and is shown in Figure 4.4. The sequencing results were also used to create the network diagram in Figure 4.5.

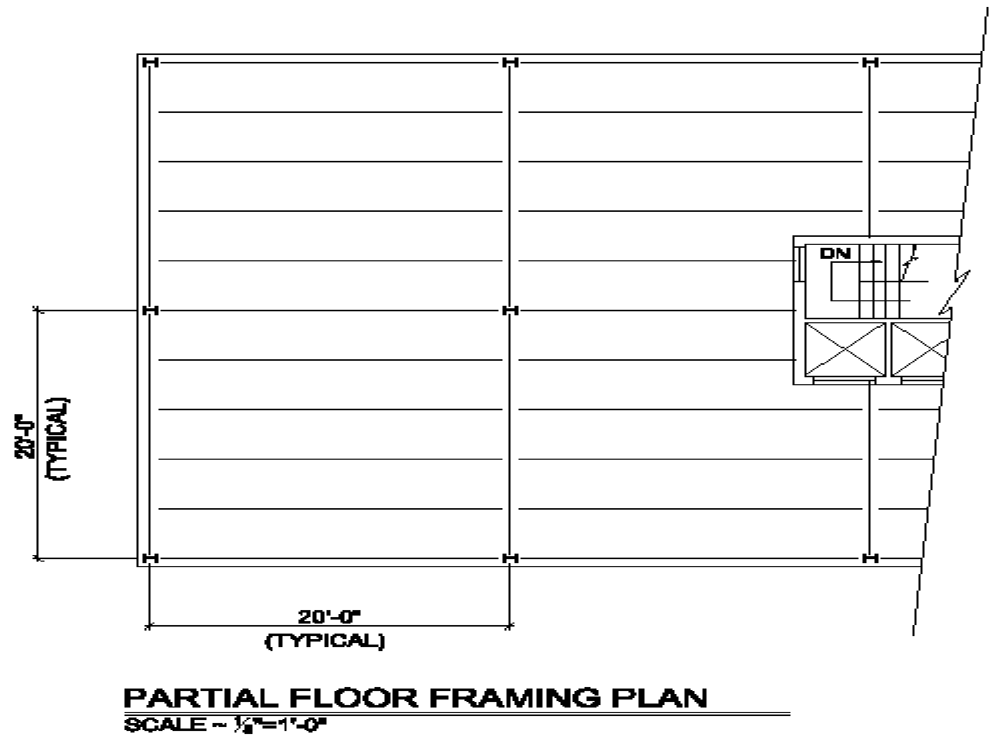


Figure 4.1: Case Study I: Partial Framing Plan

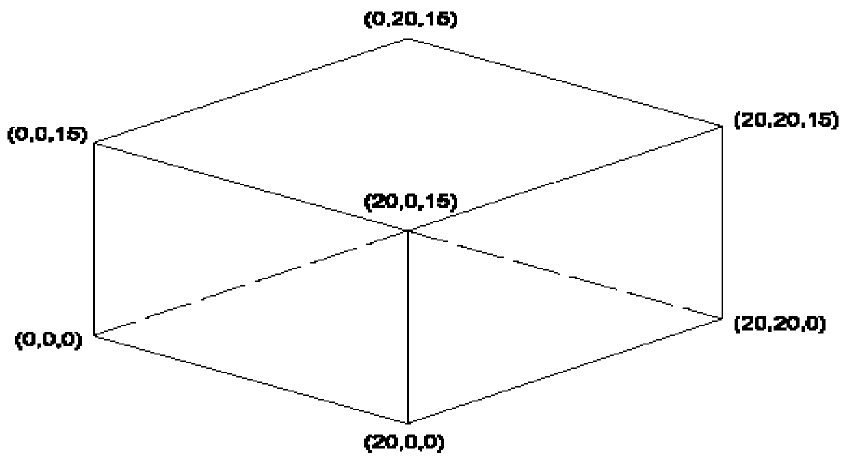


Figure 4.2: Case Study I: Global Boundaries

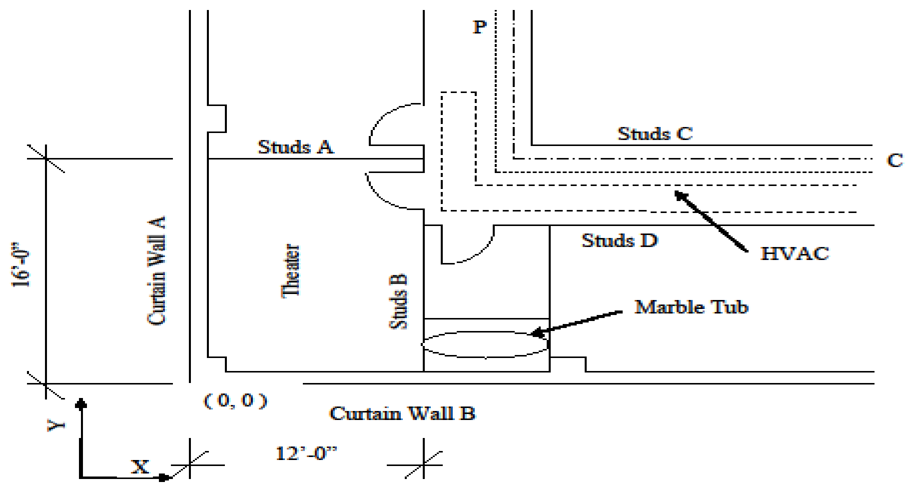


Figure 4.3: Case Study I: Architectural Layout

Activity	Description	Duration	Predecessor	V_f	SI
1	Conduit	1		0.02	1
2	HVAC	2		0.05	3
3B	Plumbing Rough'n	1		0.02	1
4A	Stud A	1		0.13	3
4B	Stud B	1		0.25	3
4C	Studs C	1		0.05	3
4D	Studs D	1		0.07	3
5	Doors	1		0.16	4
6A	Drywall A	1	25A	0.13	4
6B	Drywall B	1	25B	0.08	4
6C	Drywall C	1	25C	0.05	4
6D	Drywall D	1	25D	0.07	4
7	Paint	1	6A-6D,26	0.73	4
8	Ceiling grid	1	7	0.20	4
9	Diffusers	2	8	0.20	4
10	Ceiling Tiles	1	8	0.20	4
11	Floor Tiles	1		0.19	4
12	Towel Warmer	1	6B	0.00	4
13	Marble Tub	1		0.05	4
14	Spot Lights	1	8	0.07	4
15	Perimeter Light	1	8	0.02	4
16	Floor Mural	3	13	0.05	4
17	V Fans	1		0.01	4
18	Chair Rail	1	6A-6D	0.17	4
19A	Cur Wall A	2		0.20	1
19B	Cur Wall B	2		0.20	1
20	Glazing	2	19A,19B	0.04	3
21	Shades	1	20	0.02	4
22	Proj Scrn	1		0.02	4
23	Theater seats	1	11	0.10	4
24	Sound	1		0.10	4
25A	Insulation A	1	4A	0.09	3
25B	Insulation B	1	4B	0.11	3
25C	Insulation C	1	4C	0.05	3
25D	Insulation D	1	4D	0.07	3
26	Lockers	1	4D	0.05	4
27	Projector	1		0.01	4

Table 4.2: Case Study I: List of Construction Activities

Activity	Description	Duration	x_i	y_i	z_i	P_i	Q_i	R_i
1	Conduit	1	13	14	14	7	6	3
2	HVAC	2	10	11	12	10	9	3
3B	Plumbing Rough'n	1	12	2	14	3	12	3
4A	Stud A	1	0	16	0	12	6	11
4B	Stud B	1	12	0	0	9	15	11
4C	Studs C	1	15	15	0	5	5	11
4D	Studs D	1	17	0	0	3	12	11
5	Doors	1	9	9	0	11	11	8
6A	Drywall A	1	0	16	0	12	6	11
6B	Drywall B	1	12	0	0	3	15	11
6C	Drywall C	1	15	15	0	5	5	11
6D	Drywall D	1	17	0	0	3	12	11
7	Paint	1	0	0	0	20	20	11
8	Ceiling grid	1	0	0	10	20	20	3
9	Diffusers	2	0	0	10	20	20	3
10	Ceiling Tiles	1	0	0	10	20	20	3
11	Floor Tiles	1	0	0	0	12	16	6
12	Towel Warmer	1	12	6	4	2	1	1
13	Marble Tub	1	12	0	0	9	4	8
14	Spot Lights	1	2	2	11	9	15	3
15	Perimeter Lights	1	12	3	11	8	6	3
16	Floor Mural	3	12	4	0	9	6	6
17	V Fans	1	14	4	11	4	4	3
18	Chair Rail	1	0	2	4	12	14	6
19A	Cur Wall A	2	0	0	0	4	20	15
19B	Cur Wall B	2	0	0	0	20	4	15
20	Glazing	2	0	9	4	4	11	6
21	Shades	1	1	9	10	4	11	3
22	Proj Scrn	1	0	0	11	12	4	3
23	Theater S	1	1	6	0	10	10	6
24	Sound	1	0	0	8	12	16	3
25A	Insulation A	1	0	16	0	12	4	11
25B	Insulation B	1	12	0	0	4	15	11
25C	Insulation C	1	15	15	0	5	5	11
25D	Insulation D	1	17	0	0	3	12	11
26	Lockers	1	14	6	0	6	6	8
27	Projector	1	4	9	11	4	4	3

Table 4.3: Case Study I: Spatial Coordinates of Activities

4.2.1 Case Study I Results

Some activities are easily converted to rectangular models while others require breaking into components. One possible representation of the walls shown in Figure 4.3.is to consider a rectangular shape that fully encompasses all walls. This creates a large void and would not accurately represent the relationships between activities. The conflict resolution calculations are based on spatial coordinates and do not allow overlapping. Therefore any activity scheduled to be completed within the rectangle formed by the walls acting as the right and back sides (as viewed from the origin) would not be completed until the wall construction was finished. To resolve this, break the wall construction activities into multiple components reflecting the various walls and related trades such as studs, insulation, drywall and painting. Painting is defined as one activity within the control volume of this example problem because the paint is to be sprayed Had the example used painting with rollers then the painting activity would be broken down into the various walls just like studs and insulation.

The Test Project identified numerous positive results further evidence of the effectiveness of the process:

a. Conflict comparisons calculations reduced dramatically because of sequencing and activity dependencies. Given 36 activities associated with the construction, the process calculations only required 91 comparisons.

b. Equivalent comparisons between activities, or ties, are broken by heuristics with largest then highest activity due to nesting techniques and avoidance of rework because of inherent damage due to working in the space directly over another.

c. Spatial 1-0 multipliers C and D should only be equal to 1 if the comparing activity is directly in front of or behind the other activity. Failure to make this distinction will lead to false negative results and lengthen the completed schedule.

d. Process result identifies certain days when only one or two activities could be completed within the defined construction space.

e. The project has an estimated duration of nineteen (19) days. No contractor supplied schedule available for comparison.

ID		Task Name	Duration	Start
1		Conduit	1 day	Wed 3/9/11
2		HVAC	2 days	Thu 3/10/11
3		Plumbing Rough'n	1 day	Thu 3/10/11
4		Stud A	1 day	Wed 3/16/11
5		Stud B	1 day	Mon 3/14/11
6		Studs C	1 day	Thu 3/10/11
7		Studs D	1 day	Mon 3/14/11
8		Doors	1 day	Mon 4/4/11
9		Drywall A	1 day	Mon 3/21/11
10		Drywall B	1 day	Thu 3/17/11
11		Drywall C	1 day	Mon 3/14/11
12		Drywall D	1 day	Fri 3/18/11
13		Paint	1 day	Tue 3/22/11
14		Ceiling grid	1 day	Wed 3/23/11
15		Diffusers	2 days	Fri 3/25/11
16		Ceiling Tiles	1 day	Tue 3/29/11
17		Floor Tiles	1 day	Thu 3/31/11
18		Towel Warmer	1 day	Fri 3/18/11
19		Marble Tub	1 day	Fri 3/25/11
20		Spot Lights	1 day	Thu 3/24/11
21		Perimeter Lights	1 day	Thu 3/24/11
22		Floor Mural	3 days	Wed 3/30/11
23		V Fans	1 day	Wed 3/16/11
24		Chair Rail	1 day	Fri 4/1/11
25		Cur Wall A	2 days	Wed 3/9/11
26		Cur Wall B	2 days	Thu 3/10/11
27		Glazing	2 days	Fri 3/11/11
28		Shades	1 day	Mon 3/28/11
29		Proj Scrn	1 day	Wed 3/16/11
30		Theater S	1 day	Mon 4/4/11
31		Sound	1 day	Wed 3/30/11
32		Insulation A	1 day	Thu 3/17/11
33		Insulation B	1 day	Wed 3/16/11
34		Insulation C	1 day	Fri 3/11/11
35		Insulation D	1 day	Wed 3/16/11
36		Lockers	1 day	Mon 3/21/11
37		Projector	1 day	Wed 3/16/11
38		Sprinkler	2 days	Mon 3/14/11

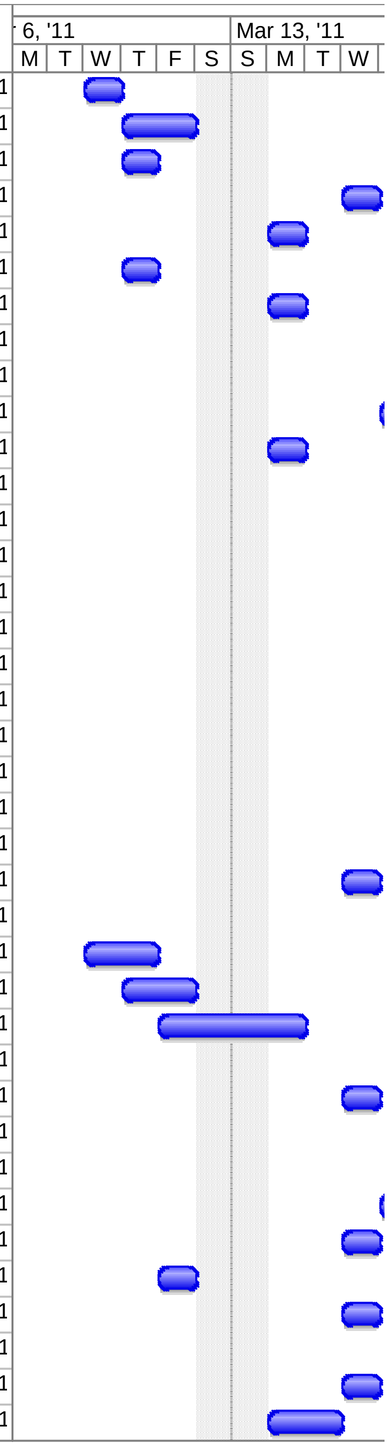


Figure 4.4: Case Study I: Completed Schedule

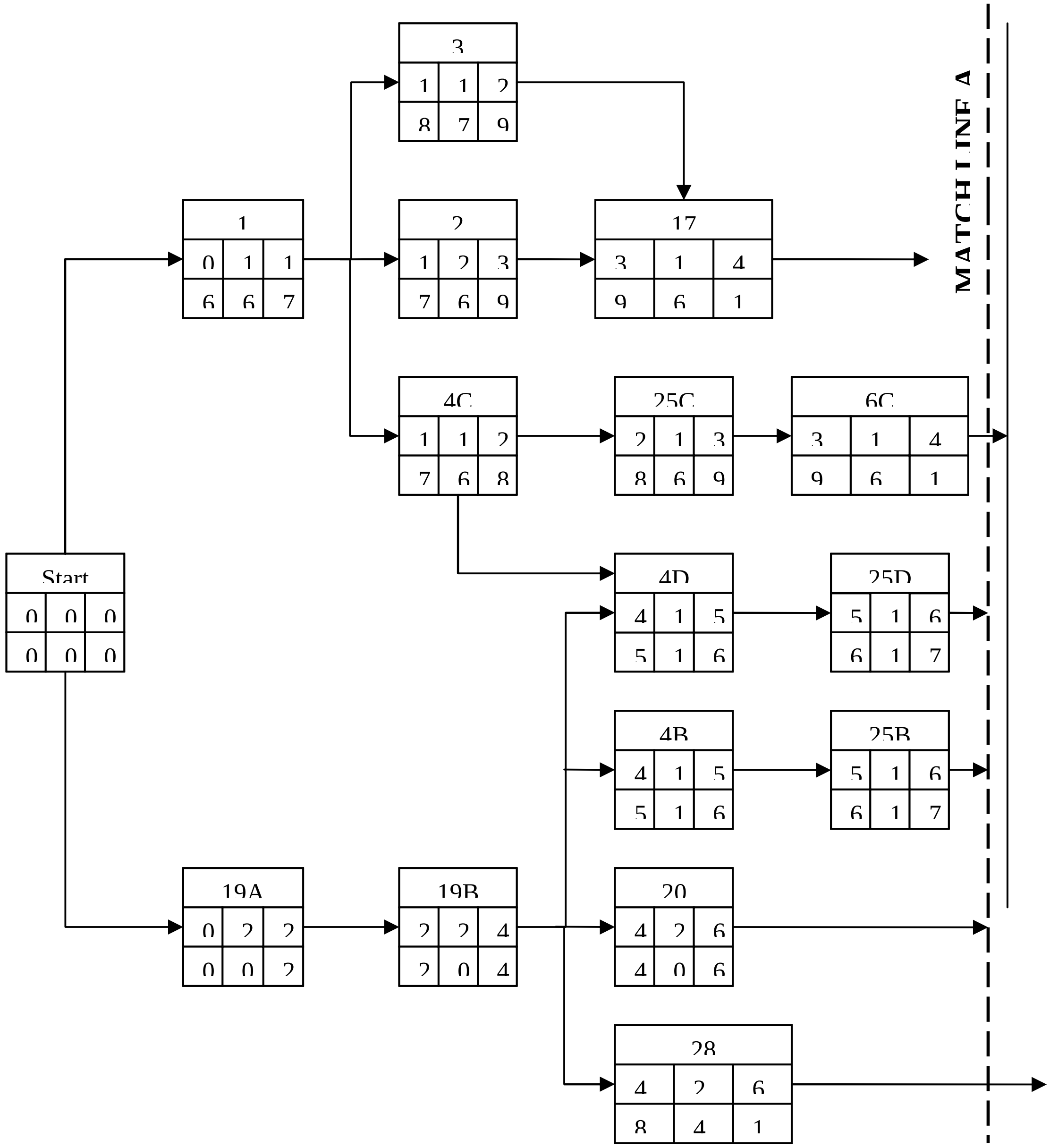


Figure 4.5: Case Study I: Network Diagram

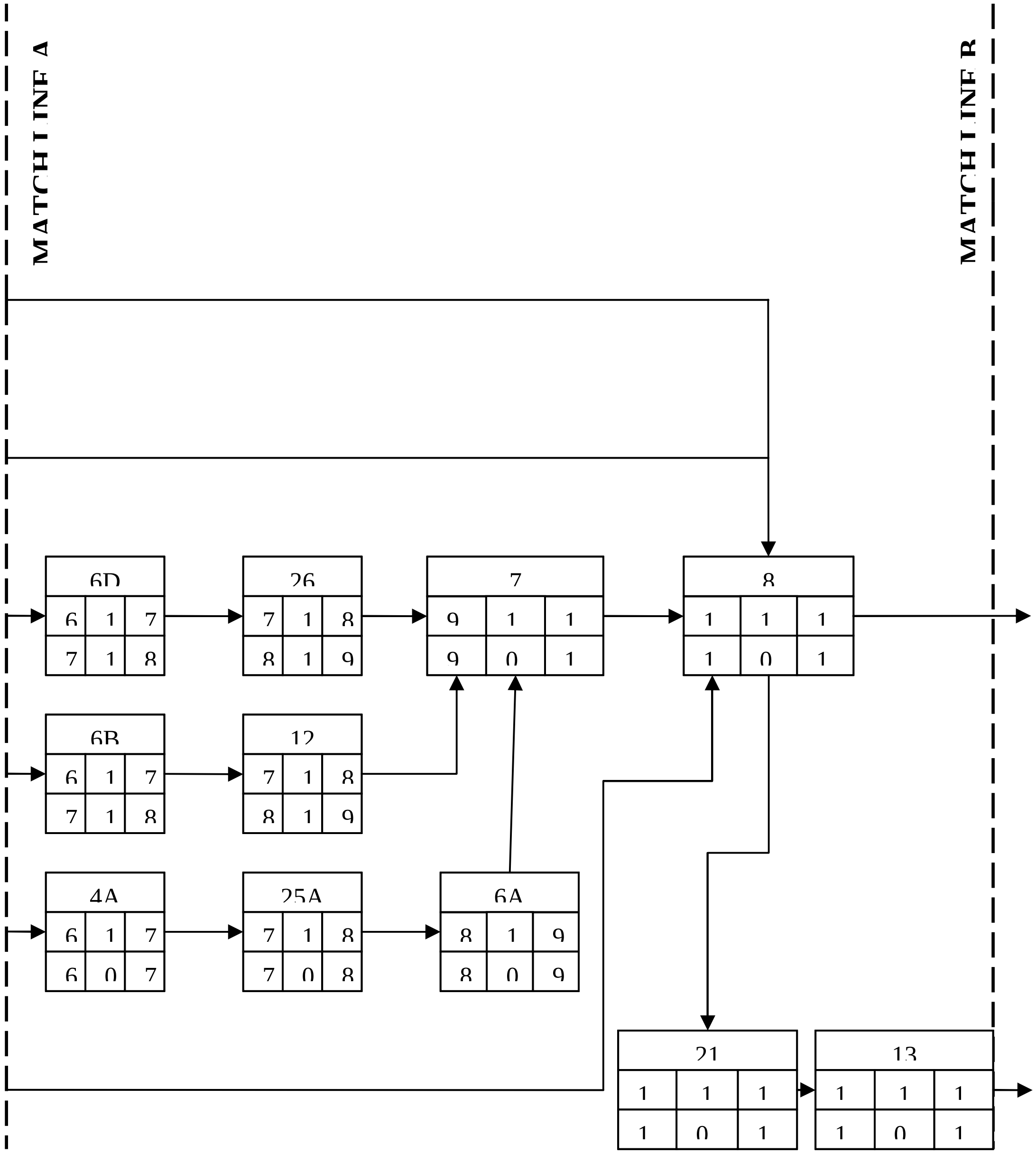


Figure 4.5: Case Study I: Network Diagram (Continued)

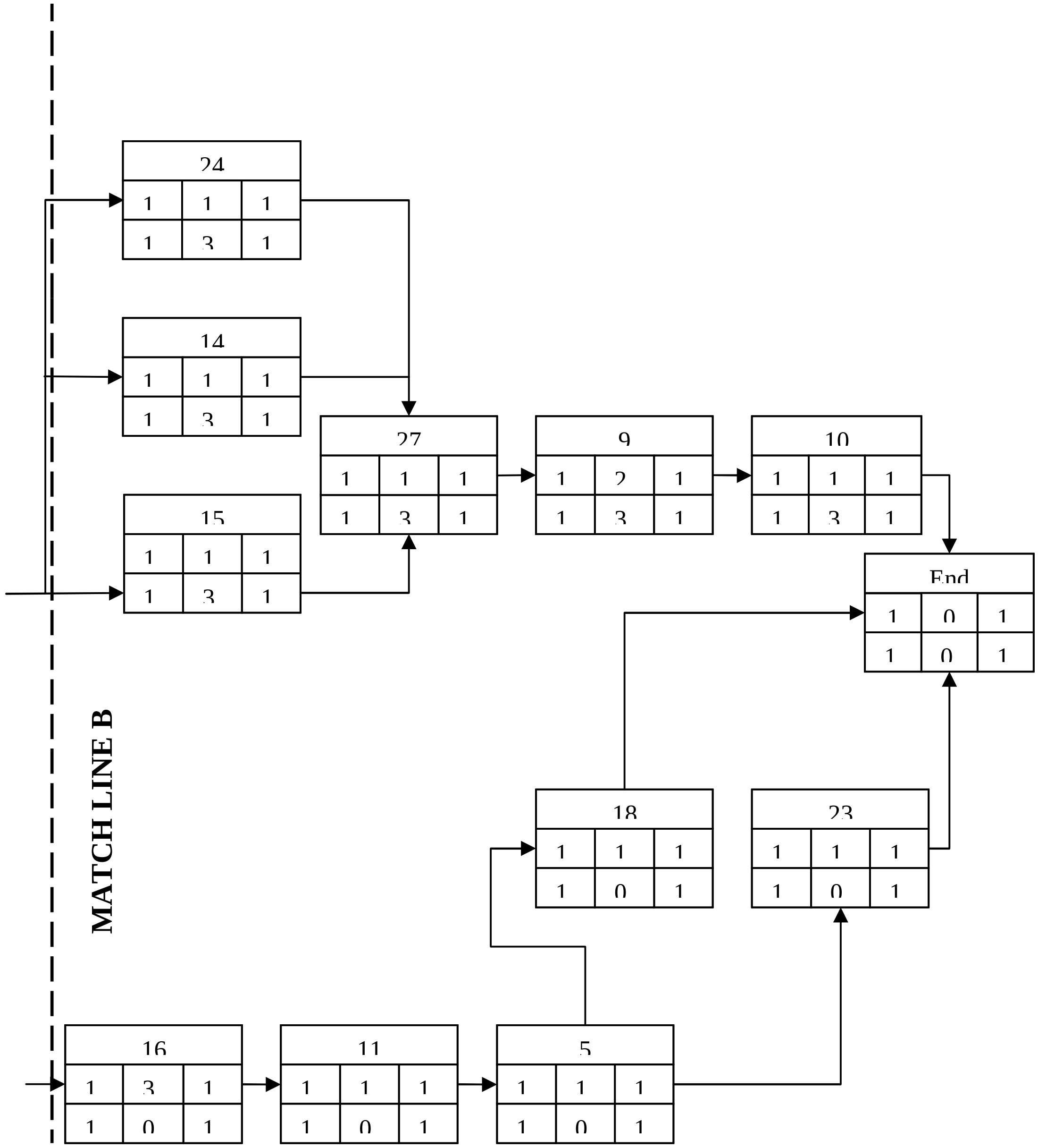


Figure 4.5: Case Study I: Network Diagram (Continued)

4.2.2 Case Study I Validation and Recommendations

The results of Case Study I validate the process is technically correct and acceptable as a means of identifying potential time-space conflicts for a sequence of construction activities. Using the {x, y, z} components for the individual activities the process successfully identified and modeled the proposed activities and validated Hypothesis 1. The analysis of the activities in Case Study I also identified four days that only one activity could be completed without a time-space conflict between activities. Those four days would not have been identified on a CPM network schedule for the same activities therefore validating Hypothesis 2. Finally, the results for Case Study I provided a very efficient and effective schedule for the required activities. The resulting network analysis, using the data from the geometric information scheduling provided an efficient CPM schedule and validates Hypothesis 3. The estimated project schedule using the industry standard of staggering the various trades results in a schedule of 26 days required for the completion of the project. The geometric scheduling process provides a 24% reduction on the staggered trades schedule.

4.3 Case Study II

The second test for the process involved review of a completed construction project provided by the Baltimore County Public School System. The project was a renovation/replacement of the HVAC system and Baltimore County Building Code required fire alarm upgrades for the central administrative office building. The scope of the project included smoke damper installations in new and existing ductwork, partition installations on various floors, installation of new smoke/fire alarms, construction of a new entrance canopy with adjacent stairs to the basement and installation of a sump pump system in the basement. The contractor submitted a Schedule of Values listing the project cost at $468,100.00 (U.S.) with a construction time of 85 days. The construction documents allowed for 120 days for completion.

The contractor's submitted network schedule identified the critical path as the procurement and installation of the steel frames and metal doors for the various modified openings. The majority of time was anticipated to be involved with the purchase and shipping of the doors and frames which is beyond the control of the project manager (aside from submission and return of all submittals in a timely fashion). To test the process, the congested work space in the basement of the main administrative building was chosen. The work in this area consisted of the activities listed in Table 4.4 and 4.5 and as detailed in Figure 4.6.

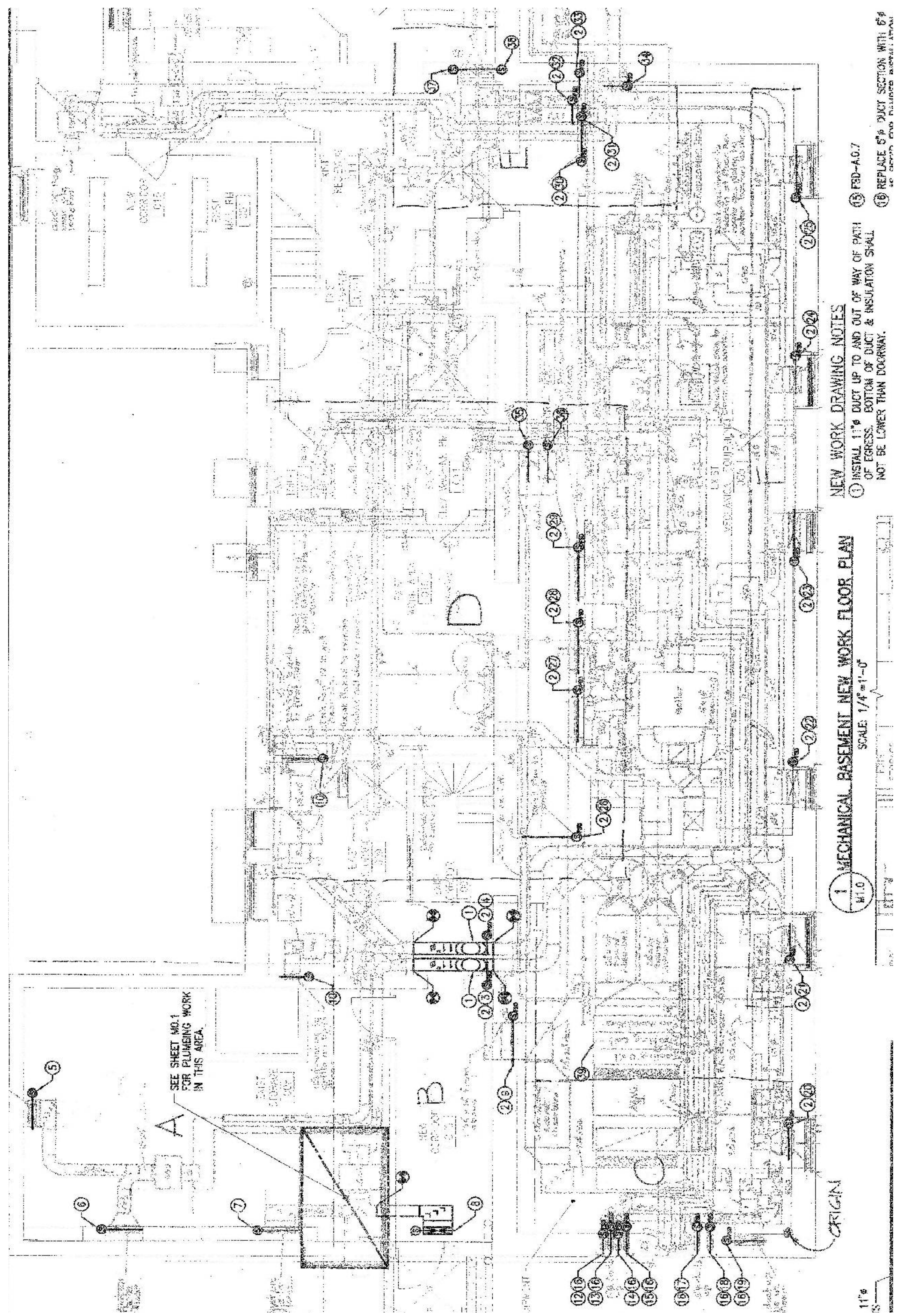


Figure 4.6 Case Study II: Construction Documents

The activity information in Table 4.5 indicates the dimensional quantities required for the geometrical scheduling procedure. The installation procedure requires one crew to install the dampers in the ducts and a separate crew to install the conduit. Electricians are required to install all wiring and electrical components and carpenters finish the labor pool required for this portion of the project. For the initial scheduling trial it is assumed all trades are limited to one crew only.

Activity	Description	Duration	Predecessor	V_f	SI
7	Smoke Dampers D	2		0.05	2
13	Smoke Conduit D	2		0.05	2
19	Smoke Wiring D	1	13	0.05	2
4	Smoke Dampers A	2		0.02	2
10	Smoke Conduit A	2		0.02	2
16	Smoke Wiring A	1	10	0.02	2
5	Smoke Dampers B	1	22	0.02	2
11	Smoke Conduit B	2	5	0.02	2
17	Smoke Wiring B	1	11	0.02	2
9	Smoke Dampers F	2		0.01	2
15	Smoke Conduit F	2		0.01	2
21	Smoke Wiring F	1	15	0.01	2
8	Smoke Dampers E	2		0.01	2
14	Smoke Conduit E	2		0.01	2
20	Smoke Wiring E	1	14	0.01	2
6	Smoke Dampers C	2		0.01	2
12	Smoke Conduit C	2		0.01	2
18	Smoke Wiring C	1	12	0.01	2
2	Stud Wall A	3	1	0.03	3
3	Stud Wall B	2		0.02	3
22	Duct Installation	3		0.02	3
1	Sump Installation	2		0.01	3
23	Signage	1		0.17	4

Table 4.4: Case Study II: List of Construction Activities

The activity information in Table 4.4 lists all the major activities in the control space and has been sorted by Sequence Indicator (S_i) and Volume Factor (V_f) to indicate the highest to lowest ranking for each of the activities. Using the spatial coordinate information shown in Table 4.5, the first step in the geometrical scheduling technique compares Smoke Dampers D with Smoke Conduit A given their respective sizes and the crew limitation allowing only one damper and one conduit installation at a time.

Activity	Description	Duration	x_i	y_i	z_i	P_i	Q_i	Ri
7	Smoke Dampers D	2	26	12	6	36	24	2
13	Smoke Conduit D	2	26	12	6	36	24	2
19	Smoke Wiring D	1	26	12	6	36	24	2
4	Smoke Dampers A	2	0	31	6	19	21	2
10	Smoke Conduit A	2	0	31	6	19	21	2
16	Smoke Wiring A	1	0	31	6	19	21	2
5	Smoke Dampers B	1	0	18	6	25	14	2
11	Smoke Conduit B	2	0	18	6	25	14	2
17	Smoke Wiring B	1	0	18	6	25	14	2
9	Smoke Dampers F	2	17	0	6	70	3	2
15	Smoke Conduit F	2	17	0	6	70	3	2
21	Smoke Wiring F	1	17	0	6	70	3	2
8	Smoke Dampers E	2	76	8	6	12	19	2
14	Smoke Conduit E	2	76	8	6	12	19	2
20	Smoke Wiring E	1	76	8	6	12	19	2
6	Smoke Dampers C	2	0	0	6	11	18	2
12	Smoke Conduit C	2	0	0	6	11	18	2
18	Smoke Wiring C	1	0	0	6	11	18	2
2	Stud Wall A	3	0	23	0	21	7	8
3	Stud Wall B	2	66	24	0	8	11	8
22	Duct Installation	3	0	18	6	25	14	2
1	Sump Installation	2	0	27	0	8	6	8
23	Signage	1	0	20	4	87	17	4

Table 4.5: Case Study II: Spatial Coordinates of Activities

No wiring can be installed unless the conduit in the area is installed first. Therefore Activities 1, 2, 3, 22 and 23 are the only remaining potential activities eligible for completion. The comparison algorithm identifies the remaining conflict-free activities for the first day as Activities 1 and 3. Thus work in this area starts with Activities 1,3,7 and 10. The complete analysis for Case Study II is included in Appendix B with all the activity comparisons used to develop the completed schedule. The results of the geometric scheduling are organized in a network schedule shown in Figure 4.7 and are listed in Microsoft Project Form in Figure 4.8. For comparison, Figure 4.8 also includes the portion of the original contractor schedule submitted for the project..

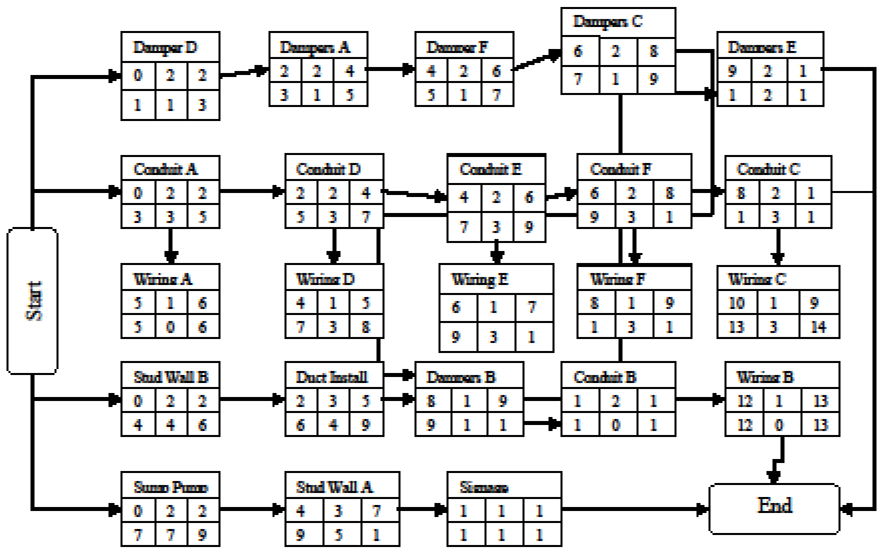
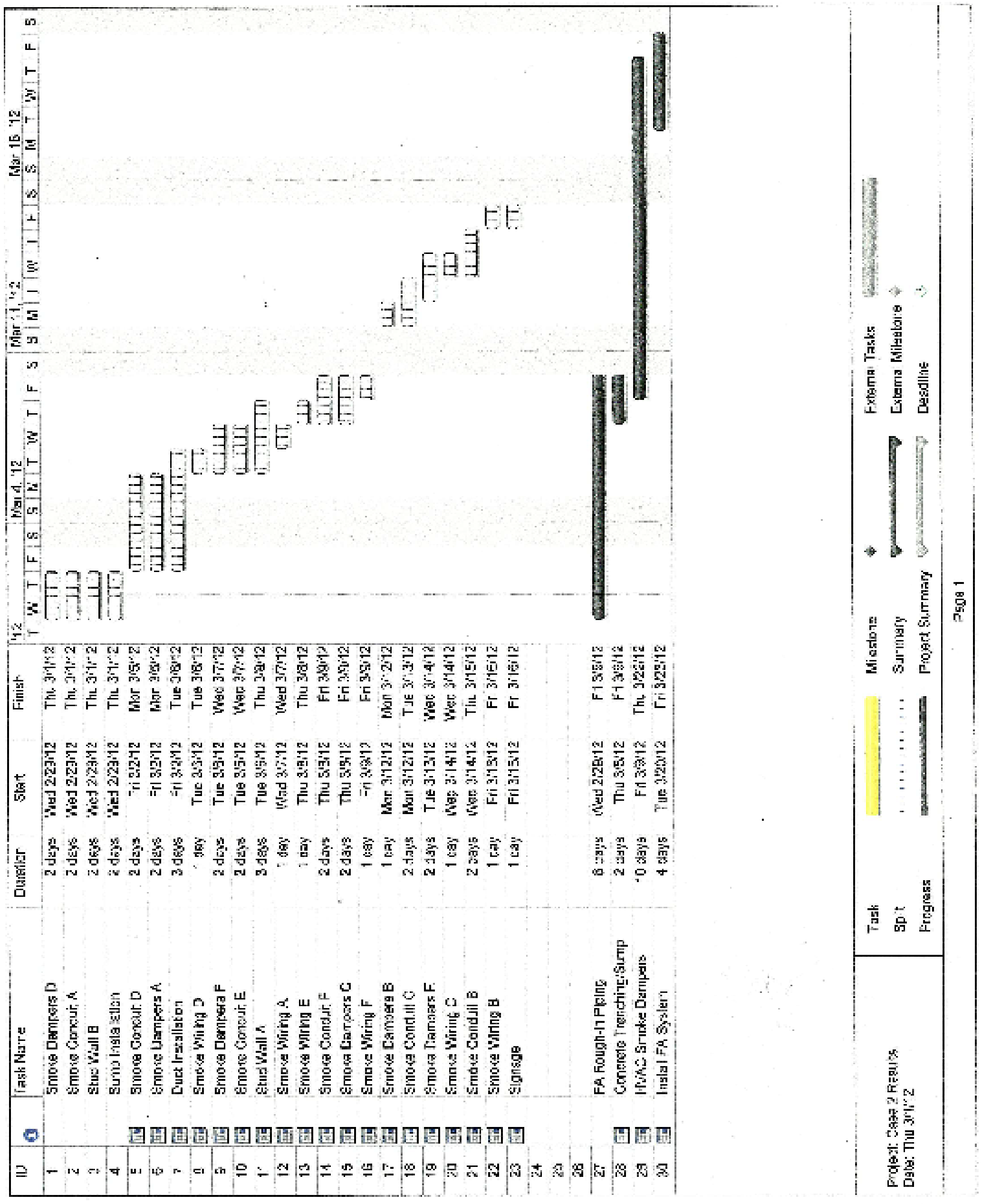


Figure 4.7 Case Study II: Network Diagram



ID		Task Name	Duration	Start	Finish
1		Smoke Dampers D	2 days	Wed 2/29/12	Thu 3/1/12
2		Smoke Conduit A	2 days	Wed 2/29/12	Thu 3/1/12
3		Stud Wall B	2 days	Wed 2/29/12	Thu 3/1/12
4		Sump Installation	2 days	Wed 2/29/12	Thu 3/1/12
5		Smoke Conduit D	2 days	Fri 3/2/12	Mon 3/5/12
6		Smoke Dampers A	2 days	Fri 3/2/12	Mon 3/5/12
7		Duct Installation	3 days	Fri 3/2/12	Tue 3/6/12
8		Smoke Wiring D	1 day	Tue 3/6/12	Tue 3/6/12
9		Smoke Dampers F	2 days	Tue 3/6/12	Wed 3/7/12
10		Smoke Conduit E	2 days	Tue 3/6/12	Wed 3/7/12
11		Stud Wall A	3 days	Tue 3/6/12	Thu 3/8/12
12		Smoke Wiring A	1 day	Wed 3/7/12	Wed 3/7/12
13		Smoke Wiring E	1 day	Thu 3/8/12	Thu 3/8/12
14		Smoke Conduit F	2 days	Thu 3/8/12	Fri 3/9/12
15		Smoke Dampers C	2 days	Thu 3/8/12	Fri 3/9/12
16		Smoke Wiring F	1 day	Fri 3/9/12	Fri 3/9/12
17		Smoke Dampers B	1 day	Mon 3/12/12	Mon 3/12/12
18		Smoke Conduit C	2 days	Mon 3/12/12	Tue 3/13/12
19		Smoke Dampers E	2 days	Tue 3/13/12	Wed 3/14/12
20		Smoke Wiring C	1 day	Wed 3/14/12	Wed 3/14/12
21		Smoke Conduit B	2 days	Wed 3/14/12	Thu 3/15/12
22		Smoke Wiring B	1 day	Fri 3/16/12	Fri 3/16/12
23		Signage	1 day	Fri 3/16/12	Fri 3/16/12
24					
25					
26					
27		FA Rough-In Piping	8 days	Wed 2/29/12	Fri 3/9/12
28		Concrete Trenching/Sump	2 days	Thu 3/8/12	Fri 3/9/12
29		HVAC Smoke Dampers	10 days	Fri 3/9/12	Thu 3/22/12
30		Install FA System	4 days	Tue 3/20/12	Fri 3/23/12

Figure 4.8: Case Study II: Schedule Comparison

4.3.1 Case Study II Results

Using the geometric scheduling technique, a total of thirteen (13) working days is required to complete this portion of the project. Figure 4.8 is the graphic representation of the completed geometric scheduling process and the schedule submitted by the contractor for the same work. The geometric scheduling removed five days from the contractor's completion schedule resulting in a 31.6 % reduction in the project schedule.

Akinci et al. (1998) performed a similar time-space analysis of the construction of the Haas School of Business building in Berkeley, CA. Their study identified potential time-space conflicts by reviewing the construction documents and interviewing the construction personnel who performed the work. Akinci et al. (1998) ranked the identified conflicts and concentrated on schedule manipulation to resolve conflicts between activities identified on the critical path of the project completion. The result was an identification of a 27% increase in the initial construction schedule as a result of the identified conflicts and subsequent reduction in productivity as a result of the conflicts. In other words, if the conflicts had been resolved prior to construction the effect would have been a 27% reduction in the actual project duration. The results obtained by the analysis of Case Study II indicate the geometric information scheduling technique is a more efficient method than Akinci et al. (1998) that we believe is due to the more efficient use of space by incorporating packing techniques into the scheduling process.

Finally, the geometric scheduling identified fifteen potential time-space conflicts. Intuitively, the contractor attempted to avoided worker conflicts by scheduling the duct work and conduit work separately. However, the results show that using the geometric scheduling technique allows all trades the ability to work in the same area with a much more efficient project schedule.

4.3.2 Case Study II Verification and Recommendations

This case study involved construction activities with locations mandated by Code requirements. By definition, none of the activities could be considered flexible with respect to location however flexibility was incorporated into the process by assuming the conduit and associated wiring could be completed without the actual damper installation; provided the pulled wires were coiled with sufficient slack to allow for proper connection to the dampers. The waste associated with extra lengths of wiring was considered minimal with respect to the time savings allowed by scheduling of parallel activities.

The results of Case Study II validate the process is technically correct and acceptable as a means of identifying potential time-space conflicts for a sequence of construction activities. Using the {x, y, z} components for the individual activities the process successfully identified and modeled the proposed activities and validated Hypothesis 1. The analysis of the activities in Case Study II also identified one day that only one activity could be completed without a time-space conflict between activities.

That day would not have been identified on a CPM network schedule for the same activities therefore validating Hypothesis 2. Finally, by producing a construction schedule that is five days shorter than the CPM schedule submitted by the contractor validates Hypothesis 3.

4.4 Conclusions

Geometric information scheduling was shown to be effective when applied to an actual construction projects. In both Case Study I and Case Study II, the use of the construction space was shown to be efficient resulting in time savings to the project. These time savings not only eliminated potential time-space conflicts but also reduced the project completion times. The case studies also verified the initial hypotheses concerning the modeling and sequencing of construction activities. When applied properly, the geometric scheduling techniques can be used to produce initial schedules as well as review existing network schedules prior to construction.

CHAPTER 5

Contributions and Recommendations

5.1 Introduction

The purpose of this research was to identify a systemic procedure for elimination of time-space conflicts on construction sites. Once a method was chosen then the research efforts turned to verification of the assumptions and comparison with network scheduling results. The comparison was extremely favorable. For Case Study II the use of the geometric information scheduling eliminated five (5) days from the contractor's submitted schedule. These research efforts proved that the more efficient use of the construction space leads to a shorter construction schedule and faster project completion.

In the process of developing the geometric process, the research identified a concept that existed when the directional flow of the activity is reversed. This new concept is termed Space Float and further defined in Section 5.3.

5.2 Research Hypothesis

Managing time-space conflicts on a construction site is typically left to the construction superintendent or project manager. Often, his or her effectiveness is a result of previous experience or intuitive knowledge gained from years of experience. The goal of this research was to develop a process that would identify time-space conflicts prior to their appearance on construction projects.

This research has succeeded in providing a mathematical method for identification of time-space conflicts that typically is done intuitively by the responsible construction professional.

5.3 Research Results

Reviewing the results from Case Study II, it was proven that using geometric scheduling can produce a more efficient construction schedule than a network schedule based on staggered start times for various trades. The research also identified a concept as yet undefined in the construction industry. The term is called *space float* and is defined as the available space within the control space that can be utilized provided the direction of the activity is reversed. An example of this phenomenon was identified in

Case Study II on the final day considering the installation of signage and the smoke wiring installation for area B.

On day 13 of the activity comparisons for Case Study II, Wiring of the Smoke Dampers B and Signage each have a one day duration and their respective work zones overlap. Thus the process defines these two activities as conflicted and therefore fails the comparison. However, if the signage at the far end of the work zone is completed first (farthest away from origin) rather than last, the two activities do not initially conflict. For these two activities, the Signage has a ½ day of space float when considering the conflict with Smoke Dampers B. For this instance, the space float is less than one complete day and normally would not alter the sequencing of the activities. As previously described, the limited scope of the sign installation and damper wiring allowed for the judgment call that both activities could be completed on the final day with no detrimental effect to the project.

Figure 5.1 is a graphic description of the *space float* concept. The space identified between the early finish (EF) of the preceding activity compared to the reversed early start (ES) of the following activity. Duration that an activity can start earlier or finish later simply gained by changing the direction of the work flow relative to a competitor activity in the same space.

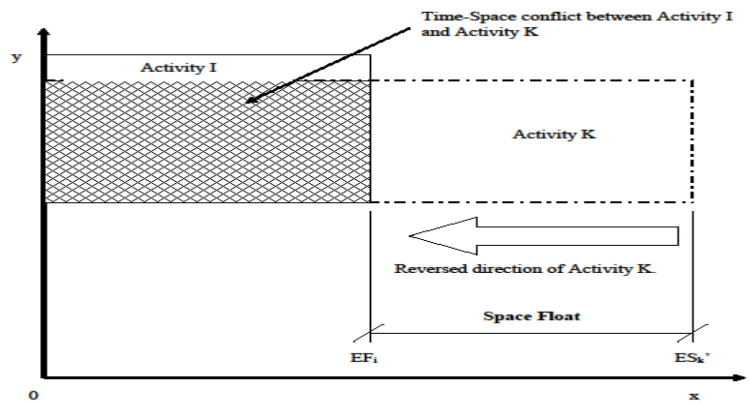


Figure 5.1: Graphic Description of Space Float

The formal definition of the space float concept can be written as:

> *Space Float* equals the numeric duration an activity can start earlier or finish later simply gained by changing the direction of its workflow relative to the completion of the activity in the same space.

5.4 Research Implementation

Implementation of the concepts presented in this research can be done with little effort by the construction professional. The spreadsheet templates are easy to comprehend and user friendly. Obviously, a project with a 1000 activities would be impossible to calculate all the possible pairings to identify conflicts. So for this product to be effective, the user must identify smaller segments of the project (just as we did for Case Study II and limiting the scope to the Basement) and apply the technique. Future research will include use of the geometric scheduling concepts for site planning.

5.5 Contribution to the Body of Knowledge

The primary contribution of this research to the construction industry is that it identifies an effective systemic process for elimination of time-space conflicts on a construction project without the need for the development of a detailed construction schedule. Typically, elimination of time-space conflicts is an intuitive process based on the knowledge and experience of the construction professional. The conservative approach is to schedule the various trades at different times to avoid any potential conflicts. Yet, the results of this research indicate that method is not the most efficient use of the construction space; costing projects time and money. With this process the potential conflicts can be eliminated prior to finalizing the construction schedule and therefore eliminating subsequent schedule redrafts and modifications.

5.6 Future Research

Current CAD systems can provide complete graphical information for construction projects through Open Database Connectivity (ODBC) (Mallasi and Dawood 2003). This information can be channeled directly to the spreadsheet templates developed by this research for use in time-space conflict detection between construction activities. The geometrically derived schedule can be compared to the network derived schedule during the contract negotiation period between general contractor and owner or construction manager.

Future research will take the concept of space float and study its effect on construction scheduling. Can space float be used to mitigate claims for delays? Does the concept help owners or contractors? How can this information be used to increase productivity?

Appendix A: Case Study I: Spreadsheet Analysis

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	V_f	SI	Predecessor
1	Conduit	1	13	14	14	7	6	3	7	6	3	0.02	1	
2	HVAC	2	10	11	12	10	9	3	5	4.5	1.5	0.05	3	
3B	Plumbing Rough'n	1	12	2	14	3	12	3	3	12	3	0.02	1	
4A	Stud A	1	0	16	0	12	6	11	12	6	11	0.13	3	
4B	Stud B	1	12	0	0	9	15	11	9	15	11	0.25	3	
4C	Studs C	1	15	15	0	5	5	11	5	5	11	0.05	3	
4D	Studs D	1	17	0	0	3	12	11	3	12	11	0.07	3	
5	Doors	1	9	9	0	11	11	8	11	11	8	0.16	4	
6A	Drywall A	1	0	16	0	12	6	11	12	6	11	0.13	4	25A
6B	Drywall B	1	12	0	0	3	15	11	3	15	11	0.08	4	25B
6C	Drywall C	1	15	15	0	5	5	11	5	5	11	0.05	4	25C
6D	Drywall D	1	17	0	0	3	12	11	3	12	11	0.07	4	25D
7	Paint	1	0	0	0	20	20	11	20	20	11	0.73	4	6A-6D,26
8	Ceiling grid	1	0	0	10	20	20	3	20	20	3	0.20	4	7
9	Diffusers	2	0	0	10	20	20	3	10	10	1.5	0.20	4	8
10	Ceiling Tiles	1	0	0	10	20	20	3	20	20	3	0.20	4	8
11	Floor Tiles	1	0	0	0	12	16	6	12	16	6	0.19	4	
12	Towel Warmer	1	12	6	4	2	1	1	2	1	1	0.00	4	6B
13	Marble Tub	1	12	0	0	9	4	8	9	4	8	0.05	4	
14	Spot Lights	1	2	2	11	9	15	3	9	15	3	0.07	4	8
15	Perimeter Lights	1	12	3	11	8	6	3	8	6	3	0.02	4	8
16	Floor Mural	3	12	4	0	9	6	6	3	2	2	0.05	4	13
17	V Fans	1	14	4	11	4	4	3	4	4	3	0.01	4	
18	Chair Rail	1	0	2	4	12	14	6	12	14	6	0.17	4	6A-6D
19A	Cur Wall A	2	0	0	0	4	20	15	2	10	7.5	0.20	1	
19B	Cur Wall B	2	0	0	0	20	4	15	10	2	7.5	0.20	1	
20	Glazing	2	0	9	4	4	11	6	2	5.5	3	0.04	3	19A,19B
21	Shades	1	1	9	10	4	11	3	4	11	3	0.02	4	20
22	Proj Scrn	1	0	0	11	12	4	3	12	4	3	0.02	4	
23	Theater S	1	1	6	0	10	10	6	10	10	6	0.10	4	11
24	Sound	1	0	0	8	12	16	3	12	16	3	0.10	4	
25A	Insulation A	1	0	16	0	12	4	11	12	4	11	0.09	3	4A
25B	Insulation B	1	12	0	0	4	15	11	4	15	11	0.11	3	4B
25C	Insulation C	1	15	15	0	5	5	11	5	5	11	0.05	3	4C
25D	Insulation D	1	17	0	0	3	12	11	3	12	11	0.07	3	4D
26	Lockers	1	14	6	0	6	6	8	6	6	8	0.05	4	4D
27	Projector	1	4	9	11	4	4	3	4	4	3	0.01	4	

Activity	SI	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f
1	1	Conduit	1	13	14	14	7	6	3	7	6	3	0.02
3B	1	Plumbing Rough'n	1	12	2	14	3	12	3	3	12	3	0.02
19A	1	Cur Wall A	2	0	0	0	4	20	15	2	10	7.5	0.20
19B	1	Cur Wall B	2	0	0	0	20	4	15	10	2	7.5	0.20
3	2	Sprinkler	2	2	2	14	18	18	3	9	9	1.5	0.16
4A	3	Stud A	1	0	16	0	12	6	11	12	6	11	0.13
4B	3	Stud B	1	12	0	0	9	15	11	9	15	11	0.25
4C	3	Studs C	1	15	15	0	5	5	11	5	5	11	0.05
4D	3	Studs D	1	17	0	0	3	12	11	3	12	11	0.07
20	3	Glazing	2	0	9	4	4	11	6	2	5.5	3	0.04
2	3	HVAC	2	10	11	12	10	9	3	5	4.5	1.5	0.05
25A	3	Insulation A	1	0	16	0	12	4	11	12	4	11	0.09
25B	3	Insulation B	1	12	0	0	4	15	11	4	15	11	0.11
25C	3	Insulation C	1	15	15	0	5	5	11	5	5	11	0.05
25D	3	Insulation D	1	17	0	0	3	12	11	3	12	11	0.07
6A	4	Drywall A	1	0	16	0	12	6	11	12	6	11	0.13
6B	4	Drywall B	1	12	0	0	3	15	11	3	15	11	0.08
6C	4	Drywall C	1	15	15	0	5	5	11	5	5	11	0.05
6D	4	Drywall D	1	17	0	0	3	12	11	3	12	11	0.07
7	4	Paint	1	0	0	0	20	20	11	20	20	11	0.73
8	4	Ceiling	1	0	0	10	20	20	3	20	20	3	0.20
9	4	Diffusers	2	0	0	10	20	20	3	10	10	1.5	0.20
10	4	Ceiling Tiles	1	0	0	10	20	20	3	20	20	3	0.20
11	4	Floor Tiles	1	0	0	0	12	16	6	12	16	6	0.19
12	4	Towel Warmer	1	12	6	4	2	1	1	2	1	1	0.00
13	4	Marble Tub	1	12	0	0	9	4	8	9	4	8	0.05
14	4	Spot Lights	1	2	2	11	9	15	3	9	15	3	0.07
15	4	Perimeter Lights	1	12	3	11	8	6	3	8	6	3	0.02
16	4	Floor Mural	3	12	0	0	9	12	6	3	4	2	0.11
17	4	V Fans	1	14	4	11	4	4	3	4	4	3	0.01
18	4	Chair Rail	1	0	2	4	12	14	6	12	14	6	0.17
5	4	Doors	1	9	9	0	11	11	8	11	11	8	0.16
26	4	Lockers	1	14	6	0	6	6	8	6	6	8	0.05
27	4	Projector	1	4	9	11	4	4	3	4	4	3	0.01
21	4	Shades	1	1	9	10	4	11	3	4	11	3	0.02
22	4	Proj Scrn	1	0	0	11	12	4	3	12	4	3	0.02
23	4	Theater S	1	1	6	0	10	10	6	10	10	6	0.10
24	4	Sound	1	0	0	8	12	16	3	12	16	3	0.10

Day 1 -

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f
1	Conduit	1	13	14	14	7	6	3	7	6	3	0.02
3B	Plumbing Rough'n	1	12	2	14	3	12	3	3	12	3	0.02

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
0	1	0	0	0	0

"$x_i + Dx_i$ = 20 "< or = 6012 "$x_k + (1-A_{ik})*M$ pass

"$x_k + Dx_k$ = 15 "< or = 13 "$x_i + (1-B_{ik})*M$ fail

"$y_i + Dy_i$ = 20 "< or = 6000 "yk + (1-Cik)*M pass

"$y_k + Dy_k$ = 14 "< or = 6014 "yi + (1-Dik)*M pass

"$z_i + Dz_i$ = 17 "< or = 6014 "zk + (1-Eik)*M pass

"$z_k + Dz_k$ = 17 "< or = 6014 "zi + (1-Fik)*M pass

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f
1	Conduit	1	13	14	14	7	6	3	7	6	3	0.02
19A	Cur Wall A	2	0	0	0	4	20	15	2	10	7.5	0.20

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
0	1	0	0	0	0

"$x_i + Dx_i$ = 20 "< or = 6000 "$x_k + (1-A_{ik})*M$ pass

"$x_k + Dx_k$ = 2 "< or = 13 "$x_i + (1-B_{ik})*M$ pass

"$y_i + Dy_i$ = 20 "< or = 6000 "yk + (1-Cik)*M pass

"$y_k + Dy_k$ = 10 "< or = 6014 "yi + (1-Dik)*M pass

"$z_i + Dz_i$ = 17 "< or = 6000 "zk + (1-Eik)*M pass

"$z_k + Dz_k$ = 7.5 "< or = 6014 "zi + (1-Fik)*M pass

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f
1	Conduit	1	13	14	14	7	6	3	7	6	3	0.02
19B	Cur Wall B	2	0	0	0	20	4	15	10	2	7.5	0.20

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
0	0	0	1	0	0

"$x_i + Dx_i$ = 20 "< or = 6000 "$x_k + (1-A_{ik})*M$ pass

"$x_k + Dx_k$ = 10 "< or = 6013 "$x_i + (1-B_{ik})*M$ pass

"$y_i + Dy_i$ = 20 "< or = 6000 "yk + (1-Cik)*M pass

"$y_k + Dy_k$ = 2 "< or = 14 "yi + (1-Dik)*M pass

"z_i + Dz_i = 17 "< or = 6000 "zk + (1-Eik)*M pass
"z_k + Dz_k = 7.5 "< or = 6014 "zi + (1-Fik)*M pass

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f
1	Conduit	1	13	14	14	7	6	3	7	6	3	0.02
3	Sprinkler	2	2	2	14	18	18	3	9	9	1.5	0.16

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
0	0	1	0	0	0

"x_i + Dx_i = 20 "< or = 6002 "x_k + (1-A_{ik})*M pass
"x_k + Dx_k = 11 "< or = 6013 "x_i + (1-B_{ik})*M pass
"y_i + Dy_i = 20 "< or = 2 "yk + (1-Cik)*M fail
"y_k + Dy_k = 11 "< or = 6014 "yi + (1-Dik)*M pass
"z_i + Dz_i = 17 "< or = 6014 "zk + (1-Eik)*M pass
"z_k + Dz_k = 15.5 "< or = 6014 "zi + (1-Fik)*M pass

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f
1	Conduit	1	13	14	14	7	6	3	7	6	3	0.02
4A	Stud A	1	0	16	0	12	6	11	12	6	11	0.13

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
0	1	0	0	0	0

"x_i + Dx_i = 20 "< or = 6000 "x_k + (1-A_{ik})*M pass
"x_k + Dx_k = 12 "< or = 13 "x_i + (1-B_{ik})*M pass
"y_i + Dy_i = 20 "< or = 6000 "yk + (1-Cik)*M pass
"y_k + Dy_k = 22 "< or = 6014 "yi + (1-Dik)*M pass
"z_i + Dz_i = 17 "< or = 6000 "zk + (1-Eik)*M pass
"z_k + Dz_k = 11 "< or = 6014 "zi + (1-Fik)*M pass

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f
1	Conduit	1	13	14	14	7	6	3	7	6	3	0.02
4B	Stud B	1	12	0	0	9	15	11	9	15	11	0.25

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
0	1	0	0	0	0

"x_i + Dx_i = 20 "< or = 6012 "x_k + (1-A_{ik})*M pass
"x_k + Dx_k = 21 "< or = 13 "x_i + (1-B_{ik})*M fail
"y_i + Dy_i = 20 "< or = 6000 "yk + (1-Cik)*M pass

"y_k + Dy_k = 15 "< or = 6014 "yi + (1-Dik)*M pass
"z_i + Dz_i = 17 "< or = 6000 "zk + (1-Eik)*M pass
"z_k + Dz_k = 11 "< or = 6014 "zi + (1-Fik)*M pass

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f
1	Conduit	1	13	14	14	7	6	3	7	6	3	0.02
4C	Studs C	1	15	15	0	5	5	11	5	5	11	0.05

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
0	0	1	0	0	0

"x_i + Dx_i = 20 "< or = 6015 "x_k + (1-A_{ik})*M pass
"x_k + Dx_k = 20 "< or = 6013 "x_i + (1-B_{ik})*M pass
"y_i + Dy_i = 20 "< or = 0 "yk + (1-Cik)*M fail
"y_k + Dy_k = 20 "< or = 6014 "yi + (1-Dik)*M pass
"z_i + Dz_i = 17 "< or = 6000 "zk + (1-Eik)*M pass
"z_k + Dz_k = 11 "< or = 6014 "zi + (1-Fik)*M pass

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f
1	Conduit	1	13	14	14	7	6	3	7	6	3	0.02
4D	Studs D	1	17	0	0	3	12	11	3	12	11	0.07

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
0	0	1	0	0	0

"x_i + Dx_i = 20 "< or = 6017 "x_k + (1-A_{ik})*M pass
"x_k + Dx_k = 20 "< or = 6013 "x_i + (1-B_{ik})*M pass
"y_i + Dy_i = 20 "< or = 0 "yk + (1-Cik)*M fail
"y_k + Dy_k = 12 "< or = 6014 "yi + (1-Dik)*M pass
"z_i + Dz_i = 17 "< or = 6000 "zk + (1-Eik)*M pass
"z_k + Dz_k = 11 "< or = 6014 "zi + (1-Fik)*M pass

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f
19A	Cur Wall A	2	0	0	0	4	20	15	2	10	7.5	0.20
4A	Stud A	1	0	16	0	12	6	11	12	6	11	0.13

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
1	0	0	0	0	0

"x_i + Dx_i = 2 "< or = 0 "x_k + (1-A_{ik})*M fail

"x_k + Dx_k = 12 "< or = 6000 "x_i + (1-B_{ik})*M pass

"y_i + Dy_i = 10 "< or = 6000 "yk + (1-Cik)*M pass

"y_k + Dy_k = 22 "< or = 6000 "yi + (1-Dik)*M pass

"z_i + Dz_i = 7.5 "< or = 6000 "zk + (1-Eik)*M pass

"z_k + Dz_k = 11 "< or = 6000 "zi + (1-Fik)*M pass

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f
19B	Cur Wall B	2	0	0	0	20	4	15	10	2	7.5	0.20
4A	Stud A	1	0	16	0	12	6	11	12	6	11	0.13

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
0	0	1	0	0	0

"x_i + Dx_i = 10 "< or = 6000 "x_k + (1-A_{ik})*M pass

"x_k + Dx_k = 12 "< or = 6000 "x_i + (1-B_{ik})*M pass

"y_i + Dy_i = 2 "< or = 16 "yk + (1-Cik)*M pass

"y_k + Dy_k = 22 "< or = 6000 "yi + (1-Dik)*M pass

"z_i + Dz_i = 7.5 "< or = 6000 "zk + (1-Eik)*M pass

"z_k + Dz_k = 11 "< or = 6000 "zi + (1-Fik)*M pass

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f
19A	Cur Wall A	2	0	0	0	4	20	15	2	10	7.5	0.20
19B	Cur Wall B	2	0	0	0	20	4	15	10	2	7.5	0.20

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
1	0	0	1	0	0

"x_i + Dx_i = 2 "< or = 0 "x_k + (1-A_{ik})*M fail

"x_k + Dx_k = 10 "< or = 6000 "x_i + (1-B_{ik})*M pass

"y_i + Dy_i = 10 "< or = 6000 "yk + (1-Cik)*M pass

"y_k + Dy_k = 2 "< or = 0 "yi + (1-Dik)*M fail

"z_i + Dz_i = 7.5 "< or = 6000 "zk + (1-Eik)*M pass

"z_k + Dz_k = 7.5 "< or = 6000 "zi + (1-Fik)*M pass

START/COMPLETE CONDUIT, START CURTAIN WALL A

DAY 2

Activity	Description		x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
19A	Cur Wall A	1	0	10	0	4	10	15	4	10	15	0.10	1
19B	Cur Wall B	2	0	0	0	20	4	15	10	2	7.5	0.20	1

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
0	0	0	1	0	0

"x_i + Dx_i = 4 "< or = 6000 "x_k + (1-A_{ik})*M pass

"x_k + Dx_k = 10 "< or = 6000 "x_i + (1-B_{ik})*M pass

"y_i + Dy_i = 20 "< or = 6000 "yk + (1-Cik)*M pass

"y_k + Dy_k = 2 "< or = 10 "yi + (1-Dik)*M pass

"z_i + Dz_i = 15 "< or = 6000 "zk + (1-Eik)*M pass

"z_k + Dz_k = 7.5 "< or = 6000 "zi + (1-Fik)*M pass

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
19A	Cur Wall A	1	0	10	0	4	10	15	4	10	15	0.10	1
3B	Plumbing Rough'n	1	12	2	14	3	12	3	3	12	3	0.02	1

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
1	0	0	0	0	0

"x_i + Dx_i = 4 "< or = 12 "x_k + (1-A_{ik})*M pass

"x_k + Dx_k = 15 "< or = 6000 "x_i + (1-B_{ik})*M pass

"y_i + Dy_i = 20 "< or = 6002 "yk + (1-Cik)*M pass

"y_k + Dy_k = 14 "< or = 6010 "yi + (1-Dik)*M pass

"z_i + Dz_i = 15 "< or = 6014 "zk + (1-Eik)*M pass

"z_k + □z_k = 17 "< or = 6000 "zi + (1-Fik)*M pass

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
19B	Cur Wall B	2	0	0	0	20	4	15	10	2	7.5	0.20	1
3B	Plumbing Rough'n	1	12	2	14	3	12	3	3	12	3	0.02	1

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
0	0	1	0	0	0

"x_i + Dx_i = 10 "< or = 6012 "x_k + (1-A_{ik})*M pass

"x_k + Dx_k = 15 "< or = 6000 "x_i + (1-B_{ik})*M pass

"y_i + Dy_i = 2 "< or = 2 "yk + (1-Cik)*M pass

"y_k + Dy_k = 14 "< or = 6000 "yi + (1-Dik)*M pass

"z_i + Dz_i = 7.5 "< or = 6014 "zk + (1-Eik)*M pass

"z_k + Dz_k = 17 "< or = 6000 "zi + (1-Fik)*M pass

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
19A	Cur Wall A	1	0	10	0	4	10	15	4	10	15	0.10	1
3	Sprinkler	2	2	2	14	18	18	3	9	9	1.5	0.16	2

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
1	0	0	0	0	0

"x_i + Dx_i = 4 "< or = 2 "x_k + (1-A_{ik})*M fail

"x_k + Dx_k = 11 "< or = 6000 "x_i + (1-B_{ik})*M pass

"y_i + Dy_i = 20 "< or = 6002 "yk + (1-Cik)*M pass

"y_k + Dy_k = 11 "< or = 6010 "yi + (1-Dik)*M pass

"z_i + Dz_i = 15 "< or = 6014 "zk + (1-Eik)*M pass

"z_k + Dz_k = 15.5 "< or = 6000 "zi + (1-Fik)*M pass

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
19A	Cur Wall A	1	0	10	0	4	10	15	4	10	15	0.10	1
4C	Studs C	1	15	15	0	5	5	11	5	5	11	0.05	3

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
1	0	0	0	0	0

"x_i + Dx_i = 4 "< or = 15 "x_k + (1-A_{ik})*M pass

"x_k + Dx_k = 20 "< or = 6000 "x_i + (1-B_{ik})*M pass

"y_i + Dy_i = 20 "< or = 6015 "yk + (1-Cik)*M pass

"y_k + Dy_k = 20 "< or = 6010 "yi + (1-Dik)*M pass

"z_i + Dz_i = 15 "< or = 6000 "zk + (1-Eik)*M pass

"z_k + Dz_k = 11 "< or = 6000 "zi + (1-Fik)*M pass

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
19A	Cur Wall A	1	0	10	0	4	10	15	4	10	15	0.10	1
4D	Studs D	1	17	0	0	3	12	11	3	12	11	0.07	3

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
1	0	0	0	0	0

"x_i + Dx_i = 4 "< or = 17 "x_k + (1-A_{ik})*M pass

"x_k + Dx_k = 20 "< or = 6000 "x_i + (1-B_{ik})*M pass

"y_i + Dy_i = 20 "< or = 6000 "yk + (1-Cik)*M pass

"$y_k + Dy_k$ = 12 "< or = 6010 "yi + (1-Dik)*M pass
"$z_i + Dz_i$ = 15 "< or = 6000 "zk + (1-Eik)*M pass
"$z_k + Dz_k$ = 11 "< or = 6000 "zi + (1-Fik)*M pass

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
19B	Cur Wall B	2	0	0	0	20	4	15	10	2	7.5	0.20	1
4C	Studs C	1	15	15	0	5	5	11	5	5	11	0.05	3

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
0	0	1	0	0	0

"$x_i + Dx_i$ = 10 "< or = 6015 "$x_k + (1-A_{ik})$*M pass
"$x_k + Dx_k$ = 20 "< or = 6000 "$x_i + (1-B_{ik})$*M pass
"$y_i + Dy_i$ = 2 "< or = 15 "yk + (1-Cik)*M pass
"$y_k + Dy_k$ = 20 "< or = 6000 "yi + (1-Dik)*M pass
"$z_i + Dz_i$ = 7.5 "< or = 6000 "zk + (1-Eik)*M pass
"$z_k + Dz_k$ = 11 "< or = 6000 "zi + (1-Fik)*M pass

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
19B	Cur Wall B	2	0	0	0	20	4	15	10	2	7.5	0.20	1
4D	Studs D	1	17	0	0	3	12	11	3	12	11	0.07	3

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
0	0	1	0	0	0

"$x_i + Dx_i$ = 10 "< or = 6017 "$x_k + (1-A_{ik})$*M pass
"$x_k + Dx_k$ = 20 "< or = 6000 "$x_i + (1-B_{ik})$*M pass
"$y_i + Dy_i$ = 2 "< or = 0 "yk + (1-Cik)*M fail
"$y_k + Dy_k$ = 12 "< or = 6000 "yi + (1-Dik)*M pass
"$z_i + Dz_i$ = 7.5 "< or = 6000 "zk + (1-Eik)*M pass
"$z_k + Dz_k$ = 11 "< or = 6000 "zi + (1-Fik)*M pass

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
19A	Cur Wall A	1	0	10	0	4	10	15	4	10	15	0.10	1
2	HVAC	2	10	11	12	10	9	3	5	4.5	1.5	0.05	3

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
1	0	0	0	0	0

"x_i + Dx_i = 4 "< or = 10 "x_k + (1-A_{ik})*M pass

"x_k + Dx_k = 15 "< or = 6000 "x_i + (1-B_{ik})*M pass

"y_i + Dy_i = 20 "< or = 6011 "yk + (1-Cik)*M pass

"y_k + Dy_k = 15.5 "< or = 6010 "yi + (1-Dik)*M pass

"z_i + Dz_i = 15 "< or = 6012 "zk + (1-Eik)*M pass

"z_k + Dz_k = 13.5 "< or = 6000 "zi + (1-Fik)*M pass

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
19B	Cur Wall B	2	0	0	0	20	4	15	10	2	7.5	0.20	1
2	HVAC	2	10	11	12	10	9	3	5	4.5	1.5	0.05	3

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
1	0	0	0	0	0

"x_i + Dx_i = 10 "< or = 10 "x_k + (1-A_{ik})*M pass

"x_k + Dx_k = 15 "< or = 6000 "x_i + (1-B_{ik})*M pass

"y_i + Dy_i = 2 "< or = 6011 "yk + (1-Cik)*M pass

"y_k + Dy_k = 15.5 "< or = 6000 "yi + (1-Dik)*M pass

"z_i + Dz_i = 7.5 "< or = 6012 "zk + (1-Eik)*M pass

"z_k + Dz_k = 13.5 "< or = 6000 "zi + (1-Fik)*M pass

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
3	Sprinkler	2	2	2	14	18	18	3	9	9	1.5	0.16	2
4C	Studs C	1	15	15	0	5	5	11	5	5	11	0.05	3

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
1	0	0	0	0	0

"x_i + Dx_i = 11 "< or = 15 "x_k + (1-A_{ik})*M pass

"x_k + Dx_k = 20 "< or = 6002 "x_i + (1-B_{ik})*M pass

"y_i + Dy_i = 11 "< or = 6015 "yk + (1-Cik)*M pass

"y_k + Dy_k = 20 "< or = 6002 "yi + (1-Dik)*M pass

"z_i + Dz_i = 15.5 "< or = 6000 "zk + (1-Eik)*M pass

"z_k + Dz_k = 11 "< or = 6014 "zi + (1-Fik)*M pass

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
3	Sprinkler	2	2	2	14	18	18	3	9	9	1.5	0.16	2
4A	Stud A	1	0	16	0	12	6	11	12	6	11	0.13	3

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
0	1	0	0	0	0

"$x_i + Dx_i$ =	11	"< or =	6000	"$x_k + (1-A_{ik})$*M	pass
"$x_k + Dx_k$ =	12	"< or =	2	"$x_i + (1-B_{ik})$*M	fail
"$y_i + Dy_i$ =	11	"< or =	6016	"yk + (1-Cik)*M	pass
"$y_k + Dy_k$ =	22	"< or =	6002	"yi + (1-Dik)*M	pass
"$z_i + Dz_i$ =	15.5	"< or =	6000	"zk + (1-Eik)*M	pass
"$z_k + Dz_k$ =	11	"< or =	6014	"zi + (1-Fik)*M	pass

COMPLETE CURTAIN WALL A, START/COMPLETE PLUMBING RI AND STUD C, START CURTAIN WALL B & HVAC

Day 3

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
19B	Cur Wall B		10	0	0	10	4	15	10	4	15	0.10	1
3	Sprinkler	2	2	2	14	18	18	3	9	9	1.5	0.16	2

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
0	1	0	0	0	0

"x_i + Dx_i = 20 "< or = 6002 "x_k + (1-A_{ik})*M pass

"x_k + Dx_k = 11 "< or = 10 "x_i + (1-B_{ik})*M fail

"y_i + Dy_i = 4 "< or = 6002 "yk + (1-Cik)*M pass

"y_k + Dy_k = 11 "< or = 6000 "yi + (1-Dik)*M pass

"z_i + Dz_i = 15 "< or = 6014 "zk + (1-Eik)*M pass

"z_k + Dz_k = 15.5 "< or = 6000 "zi + (1-Fik)*M pass

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
19B	Cur Wall B	1	10	0	0	10	4	15	10	4	15	0.10	1
20	Glazing	2	0	9	4	4	11	6	2	5.5	3	0.04	1

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
0	1	0	0	0	0

"x_i + Dx_i = 20 "< or = 6000 "x_k + (1-A_{ik})*M pass

"x_k + Dx_k = 2 "< or = 10 "x_i + (1-B_{ik})*M pass

"y_i + Dy_i = 4 "< or = 6009 "yk + (1-Cik)*M pass

"y_k + Dy_k = 14.5 "< or = 6000 "yi + (1-Dik)*M pass

"z_i + Dz_i = 15 "< or = 6004 "zk + (1-Eik)*M pass

"z_k + Dz_k = 7 "< or = 6000 "zi + (1-Fik)*M pass

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
19B	Cur Wall B	1	10	0	0	10	4	15	10	4	15	0.10	1
2	HVAC	1	10	11	12	5	4.5	3	5	4.5	3	0.01	3

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
0	0	1	0	0	0

"x_i + Dx_i = 20 "< or = 6010 "x_k + (1-A_{ik})*M pass

"x_k + Dx_k = 15 "< or = 6010 "x_i + (1-B_{ik})*M pass

"y_i + Dy_i = 4 "< or = 11 "yk + (1-Cik)*M pass

"y_k + Dy_k = 15.5 "< or = 6000 "yi + (1-Dik)*M pass

"z_i + Dz_i = 15 "< or = 6012 "zk + (1-Eik)*M pass

"z_k + Dz_k = 15 "< or = 6000 "zi + (1-Fik)*M pass

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
19B	Cur Wall B	1	10	0	0	10	4	15	10	4	15	0.10	1
4A	Stud A	1	0	16	0	12	6	11	12	6	11	0.13	3

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
0	0	1	0	0	0

"x_i + Dx_i = 20 "< or = 6000 "x_k + (1-A_{ik})*M pass

"x_k + Dx_k = 12 "< or = 6010 "x_i + (1-B_{ik})*M pass

"y_i + Dy_i = 4 "< or = 16 "yk + (1-Cik)*M pass

"y_k + Dy_k = 22 "< or = 6000 "yi + (1-Dik)*M pass

"z_i + Dz_i = 15 "< or = 6000 "zk + (1-Eik)*M pass

"z_k + Dz_k = 11 "< or = 6000 "zi + (1-Fik)*M pass

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
19B	Cur Wall B	1	10	0	0	10	4	15	10	4	15	0.10	1
25C	Insulation C	1	15	15	0	5	5	11	5	5	11	0.05	3

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
0	0	1	0	0	0

"x_i + Dx_i = 20 "< or = 6015 "x_k + (1-A_{ik})*M pass

"x_k + Dx_k = 20 "< or = 6010 "x_i + (1-B_{ik})*M pass

"y_i + Dy_i = 4 "< or = 15 "yk + (1-Cik)*M pass

"y_k + Dy_k = 20 "< or = 6000 "yi + (1-Dik)*M pass

"z_i + Dz_i = 15 "< or = 6000 "zk + (1-Eik)*M pass

"z_k + Dz_k = 11 "< or = 6000 "zi + (1-Fik)*M pass

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
19B	Cur Wall B	1	10	0	0	10	4	15	10	4	15	0.10	1
4B	Stud B	1	12	0	0	9	15	11	9	15	11	0.25	3

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
0	0	1	0	0	0

"x_i + Dx_i = 20 "< or = 6012 "x_k + (1-A_{ik})*M pass

"x_k + Dx_k = 21 "< or = 6010 "x_i + (1-B_{ik})*M pass

"y_i + Dy_i = 4 "< or = 0 "yk + (1-Cik)*M fail

"y_k + Dy_k = 15 "< or = 6000 "yi + (1-Dik)*M pass
"z_i + Dz_i = 15 "< or = 6000 "zk + (1-Eik)*M pass
"z_k + Dz_k = 11 "< or = 6000 "zi + (1-Fik)*M pass

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
19B	Cur Wall B	1	10	0	0	10	4	15	10	4	15	0.10	1
4D	Studs D	1	17	0	0	3	12	11	3	12	11	0.07	3

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
0	0	1	0	0	0

"x_i + Dx_i = 20 "< or = 6017 "x_k + (1-A_{ik})*M pass
"x_k + Dx_k = 20 "< or = 6010 "x_i + (1-B_{ik})*M pass
"y_i + Dy_i = 4 "< or = 0 "yk + (1-Cik)*M fail
"y_k + Dy_k = 12 "< or = 6000 "yi + (1-Dik)*M pass
"z_i + Dz_i = 15 "< or = 6000 "zk + (1-Eik)*M pass
"z_k + Dz_k = 11 "< or = 6000 "zi + (1-Fik)*M pass

COMPLETE CURTAIN WALL B & HVAC, START GLAZING & COMPLETE INSULATION C

DAY 4

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
3	Sprinkler	2	2	2	14	18	18	3	9	9	1.5	0.16	2
4B	Stud B	1	12	0	0	9	15	11	9	15	11	0.25	3

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
1	0	0	0	0	0

"$x_i + Dx_i$ =	11	"< or =	12	"$x_k + (1-A_{ik})$*M	pass
"$x_k + Dx_k$ =	21	"< or =	6002	"$x_i + (1-B_{ik})$*M	pass
"$y_i + Dy_i$ =	11	"< or =	6000	"yk + (1-Cik)*M	pass
"$y_k + Dy_k$ =	15	"< or =	6002	"yi + (1-Dik)*M	pass
"$z_i + Dz_i$ =	15.5	"< or =	6000	"zk + (1-Eik)*M	pass
"$z_k + Dz_k$ =	11	"< or =	6014	"zi + (1-Fik)*M	pass

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
3	Sprinkler	2	2	2	14	18	18	3	9	9	1.5	0.16	2
4D	Studs D	1	17	0	0	3	12	11	3	12	11	0.07	3

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
1	0	0	0	0	0

"$x_i + Dx_i$ =	11	"< or =	17	"$x_k + (1-A_{ik})$*M	pass
"$x_k + Dx_k$ =	20	"< or =	6002	"$x_i + (1-B_{ik})$*M	pass
"$y_i + Dy_i$ =	11	"< or =	6000	"yk + (1-Cik)*M	pass
"$y_k + Dy_k$ =	12	"< or =	6002	"yi + (1-Dik)*M	pass
"$z_i + Dz_i$ =	15.5	"< or =	6000	"zk + (1-Eik)*M	pass
"$z_k + Dz_k$ =	11	"< or =	6014	"zi + (1-Fik)*M	pass

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
3	Sprinkler	2	2	2	14	18	18	3	9	9	1.5	0.16	2
20	Glazing	2	0	9	4	4	11	6	2	5.5	3	0.04	1

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
0	1	0	0	0	0

"$x_i + Dx_i$ =	11	"< or =	6000	"$x_k + (1-A_{ik})$*M	pass
"$x_k + Dx_k$ =	2	"< or =	2	"$x_i + (1-B_{ik})$*M	pass
"$y_i + Dy_i$ =	11	"< or =	6009	"yk + (1-Cik)*M	pass

"$y_k + Dy_k$ = 14.5 "< or = 6002 "yi + (1-Dik)*M pass

"$z_i + Dz_i$ = 15.5 "< or = 6004 "zk + (1-Eik)*M pass

"$z_k + Dz_k$ = 7 "< or = 6014 "zi + (1-Fik)*M pass

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
3	Sprinkler	2	2	2	14	18	18	3	9	9	1.5	0.16	2
6C	Drywall C	1	15	15	0	5	5	11	5	5	11	0.05	4

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
1	0	0	0	0	0

"$x_i + Dx_i$ = 11 "< or = 15 "$x_k + (1-A_{ik})$*M pass

"$x_k + Dx_k$ = 20 "< or = 6002 "$x_i + (1-B_{ik})$*M pass

"$y_i + Dy_i$ = 11 "< or = 6015 "yk + (1-Cik)*M pass

"$y_k + Dy_k$ = 20 "< or = 6002 "yi + (1-Dik)*M pass

"$z_i + Dz_i$ = 15.5 "< or = 6000 "zk + (1-Eik)*M pass

"$z_k + Dz_k$ = 11 "< or = 6014 "zi + (1-Fik)*M pass

COMPLETE GLAZING, START/COMPLETE STUDS B & D, START SPRINKLER,START/COMPLETE DRYWALL C

DAY 5

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
3	Sprinkler	2	11	2	14	9	9	3	4.5	4.5	1.5	0.04	2
4A	Stud A	1	0	16	0	12	6	11	12	6	11	0.13	3

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
0	1	0	0	0	0

"x_i + Dx_i =	15.5	"< or =	6000	"x_k + (1-A_{ik})*M	pass
"x_k + Dx_k =	12	"< or =	11	"x_i + (1-B_{ik})*M	fail
"y_i + Dy_i =	6.5	"< or =	6016	"yk + (1-Cik)*M	pass
"y_k + Dy_k =	22	"< or =	6002	"yi + (1-Dik)*M	pass
"z_i + Dz_i =	15.5	"< or =	6000	"zk + (1-Eik)*M	pass
"z_k + Dz_k =	11	"< or =	6014	"zi + (1-Fik)*M	pass

Activity	Description	Dur	xi	yi	zi	Pi	Qi	Ri	Dx	Dy	Dz	Af	SI
3	Sprinkler	2	11	2	14	9	9	3	4.5	4.5	1.5	0.04	2
25B	Insulation B	1	12	0	0	11	15	11	11	15	11	0.30	3

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
1	0	0	0	0	0

"x_i + Dx_i =	15.5	"< or =	12	"x_k + (1-A_{ik})*M	fail
"x_k + Dx_k =	23	"< or =	6011	"x_i + (1-B_{ik})*M	pass
"y_i + Dy_i =	6.5	"< or =	6000	"yk + (1-Cik)*M	pass
"y_k + Dy_k =	15	"< or =	6002	"yi + (1-Dik)*M	pass
"z_i + Dz_i =	15.5	"< or =	6000	"zk + (1-Eik)*M	pass
"z_k + Dz_k =	11	"< or =	6014	"zi + (1-Fik)*M	pass

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
3	Sprinkler	2	11	2	14	9	9	3	4.5	4.5	1.5	0.04	2
25D	Insulation D	1	17	0	0	3	12	11	3	12	11	0.07	3

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
1	0	0	0	0	0

"x_i + Dx_i =	15.5	"< or =	17	"x_k + (1-A_{ik})*M	fail
"x_k + Dx_k =	20	"< or =	6011	"x_i + (1-B_{ik})*M	pass
"y_i + Dy_i =	6.5	"< or =	6000	"yk + (1-Cik)*M	pass
"y_k + Dy_k =	12	"< or =	6002	"yi + (1-Dik)*M	pass
"z_i + Dz_i =	15.5	"< or =	6000	"zk + (1-Eik)*M	pass

"z_k + Dz_k =   11 "< or = 6014 "zi + (1-Fik)*M   pass

COMPLETE SPRINKLERS

DAY 6

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
4A	Stud A	1	0	16	0	12	6	11	12	6	11	0.13	3
25B	Insulation B	1	12	0	0	4	15	11	4	15	11	0.11	3

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
1	0	0	0	0	0

"x_i + Dx_i = 12 "< or = 12 "x_k + (1-A_{ik})*M pass

"x_k + Dx_k = 16 "< or = 6000 "x_i + (1-B_{ik})*M pass

"y_i + Dy_i = 22 "< or = 6000 "yk + (1-Cik)*M pass

"y_k + Dy_k = 15 "< or = 6016 "yi + (1-Dik)*M pass

"z_i + Dz_i = 11 "< or = 6000 "zk + (1-Eik)*M pass

"z_k + Dz_k = 11 "< or = 6000 "zi + (1-Fik)*M pass

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
4A	Stud A	1	0	16	0	12	6	11	12	6	11	0.13	3
25D	Insulation D	1	17	0	0	3	12	11	3	12	11	0.07	3

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
1	0	0	0	0	0

"x_i + Dx_i = 12 "< or = 17 "x_k + (1-A_{ik})*M pass

"x_k + Dx_k = 20 "< or = 6000 "x_i + (1-B_{ik})*M pass

"y_i + Dy_i = 22 "< or = 6000 "yk + (1-Cik)*M pass

"y_k + Dy_k = 12 "< or = 6016 "yi + (1-Dik)*M pass

"z_i + Dz_i = 11 "< or = 6000 "zk + (1-Eik)*M pass

"z_k + Dz_k = 11 "< or = 6000 "zi + (1-Fik)*M pass

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
25B	Insulation B	1	12	0	0	11	15	11	11	15	11	0.30	3
25D	Insulation D	1	17	0	0	3	12	11	3	12	11	0.07	3

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
1	0	0	0	0	0

"x_i + Dx_i = 23 "< or = 17 "x_k + (1-A_{ik})*M pass

"x_k + Dx_k = 20 "< or = 6012 "x_i + (1-B_{ik})*M pass

"y_i + Dy_i = 15 "< or = 6000 "yk + (1-Cik)*M pass

"y_k + Dy_k = 12 "< or = 6000 "yi + (1-Dik)*M pass

"z_i + Dz_i = 11 "< or = 6000 "zk + (1-Eik)*M pass

"z_k + Dz_k = 11 "< or = 6000 "zi + (1-Fik)*M pass

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
4A	Stud A	1	0	16	0	12	6	11	12	6	11	0.13	3
17	V Fans	1	14	4	11	4	4	3	4	4	3	0.01	4

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
1	0	0	0	0	0

"x_i + Dx_i = 12 "< or = 14 "x_k + (1-A_{ik})*M pass

"x_k + Dx_k = 18 "< or = 6000 "x_i + (1-B_{ik})*M pass

"y_i + Dy_i = 22 "< or = 6004 "yk + (1-Cik)*M pass

"y_k + Dy_k = 8 "< or = 6016 "yi + (1-Dik)*M pass

"z_i + Dz_i = 11 "< or = 6011 "zk + (1-Eik)*M pass

"z_k + Dz_k = 14 "< or = 6000 "zi + (1-Fik)*M pass

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
4A	Stud A	1	0	16	0	12	6	11	12	6	11	0.13	3
22	Proj Scrn	1	0	0	11	12	4	3	12	4	3	0.02	4

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
0	0	0	1	0	0

"x_i + Dx_i = 12 "< or = 6000 "x_k + (1-A_{ik})*M pass

"x_k + Dx_k = 12 "< or = 6000 "x_i + (1-B_{ik})*M pass

"y_i + Dy_i = 22 "< or = 6000 "yk + (1-Cik)*M pass

"y_k + Dy_k = 4 "< or = 16 "yi + (1-Dik)*M pass

"z_i + Dz_i = 11 "< or = 6011 "zk + (1-Eik)*M pass

"z_k + Dz_k = 14 "< or = 6000 "zi + (1-Fik)*M pass

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
4A	Stud A	1	0	16	0	12	6	11	12	6	11	0.13	3
27	Projector	1	4	9	11	4	4	3	4	4	3	0.01	4

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
0	0	0	1	0	0

"x_i + Dx_i = 12 "< or = 6004 "x_k + (1-A_{ik})*M pass

"x_k + Dx_k = 8 "< or = 6000 "x_i + (1-B_{ik})*M pass

"y_i + Dy_i = 22 "< or = 6009 "yk + (1-Cik)*M pass

"$y_k + Dy_k$ = 13 "< or = 16 "yi + (1-Dik)*M pass

"$z_i + Dz_i$ = 11 "< or = 6011 "zk + (1-Eik)*M pass

"$z_k + Dz_k$ = 14 "< or = 6000 "zi + (1-Fik)*M pass

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
4A	Stud A	1	0	16	0	12	6	11	12	6	11	0.13	3
25C	Insulation C	1	15	15	0	5	5	11	5	5	11	0.05	3

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
1	0	0	0	0	0

"$x_i + Dx_i$ = 12 "< or = 15 "$x_k + (1-A_{ik})$*M pass

"$x_k + Dx_k$ = 20 "< or = 6000 "$x_i + (1-B_{ik})$*M pass

"$y_i + Dy_i$ = 22 "< or = 6015 "yk + (1-Cik)*M pass

"$y_k + Dy_k$ = 20 "< or = 6016 "yi + (1-Dik)*M pass

"$z_i + Dz_i$ = 11 "< or = 6000 "zk + (1-Eik)*M pass

"$z_k + Dz_k$ = 11 "< or = 6000 "zi + (1-Fik)*M pass

START/COMPLETE STUD WALL A, INSULATION B, INSULATION D, VENTILATION FANS, PROJECTOR SCREEN AND PROJECTOR

DAY 7

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
25A	Insulation A	1	0	16	0	12	4	11	12	4	11	0.09	3
6B	Drywall B	1	12	0	0	3	15	11	3	15	11	0.08	4

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
1	0	0	0	0	0

"x_i + Dx_i =	12	"< or =	12	"x_k + (1-A_{ik})*M	pass
"x_k + Dx_k =	15	"< or =	6000	"x_i + (1-B_{ik})*M	pass
"y_i + Dy_i =	20	"< or =	6000	"yk + (1-Cik)*M	pass
"y_k + Dy_k =	15	"< or =	6016	"yi + (1-Dik)*M	pass
"z_i + Dz_i =	11	"< or =	6000	"zk + (1-Eik)*M	pass
"z_k + Dz_k =	11	"< or =	6000	"zi + (1-Fik)*M	pass

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
25A	Insulation A	1	0	16	0	12	4	11	12	4	11	0.09	3
6D	Drywall D	1	17	0	0	3	12	11	3	12	11	0.07	4

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
1	0	0	0	0	0

"x_i + Dx_i =	12	"< or =	17	"x_k + (1-A_{ik})*M	pass
"x_k + Dx_k =	20	"< or =	6000	"x_i + (1-B_{ik})*M	pass
"y_i + Dy_i =	20	"< or =	6000	"yk + (1-Cik)*M	pass
"y_k + Dy_k =	12	"< or =	6016	"yi + (1-Dik)*M	pass
"z_i + Dz_i =	11	"< or =	6000	"zk + (1-Eik)*M	pass
"z_k + Dz_k =	11	"< or =	6000	"zi + (1-Fik)*M	pass

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
6B	Drywall B	1	12	0	0	3	15	11	3	15	11	0.08	4
6D	Drywall D	1	17	0	0	3	12	11	3	12	11	0.07	4

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
1	0	0	0	0	0

"x_i + Dx_i =	15	"< or =	17	"x_k + (1-A_{ik})*M	pass
"x_k + Dx_k =	20	"< or =	6012	"x_i + (1-B_{ik})*M	pass
"y_i + Dy_i =	15	"< or =	6000	"yk + (1-Cik)*M	pass
"y_k + Dy_k =	12	"< or =	6000	"yi + (1-Dik)*M	pass
"z_i + Dz_i =	11	"< or =	6000	"zk + (1-Eik)*M	pass

"$z_k + Dz_k$ = 11 "< or = 6000 "zi + (1-Fik)*M pass

DAY 7 - START/COMPLETE INSULATION A AND DRYWALL B
(DRYWALL D WOULD REQUIRE A SECOND CREW)

Day 8

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
6D	Drywall D	1	17	0	0	3	12	11	3	12	11	0.07	4
12	Towel Warmer	1	12	6	4	2	1	1	2	1	1	0.00	4

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
0	1	0	0	0	0

"x_i + Dx_i =	20	"< or =	6012	"x_k + (1-A_{ik})*M	pass
"x_k + Dx_k =	14	"< or =	17	"x_i + (1-B_{ik})*M	pass
"y_i + Dy_i =	12	"< or =	6006	"yk + (1-Cik)*M	pass
"y_k + Dy_k =	7	"< or =	6000	"yi + (1-Dik)*M	pass
"z_i + Dz_i =	11	"< or =	6004	"zk + (1-Eik)*M	pass
"z_k + Dz_k =	5	"< or =	6000	"zi + (1-Fik)*M	pass

START/COMPLETE DRYWALL D AND TOWEL WARMER (ALL OTHERS RESTRICTED)

Day 9

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
6A	Drywall A	1	0	16	0	12	6	11	12	6	11	0.13	4
26	Lockers	1	14	6	0	6	6	8	6	6	8	0.05	4

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
1	0	0	0	0	0

"$x_i + Dx_i$ =	12	"< or =	14	"$x_k + (1-A_{ik})$*M	pass
"$x_k + Dx_k$ =	20	"< or =	6000	"$x_i + (1-B_{ik})$*M	pass
"$y_i + Dy_i$ =	22	"< or =	6006	"yk + (1-Cik)*M	pass
"$y_k + Dy_k$ =	12	"< or =	6016	"yi + (1-Dik)*M	pass
"$z_i + Dz_i$ =	11	"< or =	6000	"zk + (1-Eik)*M	pass
"$z_k + Dz_k$ =	8	"< or =	6000	"zi + (1-Fik)*M	pass

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
6A	Drywall A	1	0	16	0	12	6	11	12	6	11	0.13	4
5	Doors	1	9	9	0	11	11	8	11	11	8	0.16	4

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
1	0	0	0	0	0

"$x_i + Dx_i$ =	12	"< or =	9	"$x_k + (1-A_{ik})$*M	fail
"$x_k + Dx_k$ =	20	"< or =	6000	"$x_i + (1-B_{ik})$*M	pass
"$y_i + Dy_i$ =	22	"< or =	6009	"yk + (1-Cik)*M	pass
"$y_k + Dy_k$ =	20	"< or =	6016	"yi + (1-Dik)*M	pass
"$z_i + Dz_i$ =	11	"< or =	6000	"zk + (1-Eik)*M	pass
"$z_k + Dz_k$ =	8	"< or =	6000	"zi + (1-Fik)*M	pass

START/COMPLETE DRYWALL A AND LOCKERS(ALL OTHERS RESTRICTED)

Day 10

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
7	Paint	1	0	0	0	20	20	11	20	20	11	0.73	4
5	Doors	1	9	9	0	11	11	8	11	11	8	0.16	4

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
1	1	1	1	0	0

"x_i + Dx_i =	20	"< or =	9	"x_k + (1-A_{ik})*M	fail
"x_k + Dx_k =	20	"< or =	0	"x_i + (1-B_{ik})*M	fail
"y_i + Dy_i =	20	"< or =	9	"yk + (1-Cik)*M	fail
"y_k + Dy_k =	20	"< or =	0	"yi + (1-Dik)*M	fail
"z_i + Dz_i =	11	"< or =	6000	"zk + (1-Eik)*M	pass
"z_k + Dz_k =	8	"< or =	6000	"zi + (1-Fik)*M	pass

PAINTING

Day 11

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
8	Ceiling grid	1	0	0	10	20	20	3	20	20	3	0.20	4
5	Doors	1	9	9	0	11	11	8	11	11	8	0.16	4

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
1	0	0	0	0	1

"x_i + Dx_i =	20	"< or =	9	"x_k + (1-A_{ik})*M	fail
"x_k + Dx_k =	20	"< or =	6000	"x_i + (1-B_{ik})*M	pass
"y_i + Dy_i =	20	"< or =	6009	"yk + (1-Cik)*M	pass
"y_k + Dy_k =	20	"< or =	6000	"yi + (1-Dik)*M	pass
"z_i + Dz_i =	13	"< or =	6000	"zk + (1-Eik)*M	pass
"z_k + Dz_k =	8	"< or =	10	"zi + (1-Fik)*M	pass

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
8	Ceiling grid	1	0	0	10	20	20	3	20	20	3	0.20	4
21	Shades	1	1	9	10	4	11	3	4	11	3	0.02	4

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
1	0	0	0	0	0

"x_i + Dx_i =	20	"< or =	1	"x_k + (1-A_{ik})*M	fail
"x_k + Dx_k =	5	"< or =	6000	"x_i + (1-B_{ik})*M	pass
"y_i + Dy_i =	20	"< or =	6009	"yk + (1-Cik)*M	pass
"y_k + Dy_k =	20	"< or =	6000	"yi + (1-Dik)*M	pass
"z_i + Dz_i =	13	"< or =	6010	"zk + (1-Eik)*M	pass
"z_k + Dz_k =	13	"< or =	6010	"zi + (1-Fik)*M	pass

CEILING GRID ONLY

Day 12

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
14	Spot Lights	1	2	2	11	9	15	3	9	15	3	0.07	4
15	Perimeter Lights	1	12	3	11	8	6	3	8	6	3	0.02	4

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
1	0	0	0	0	0

"x_i + Dx_i =	11	"< or =	12	"x_k + (1-A_{ik})*M	pass
"x_k + Dx_k =	20	"< or =	6002	"x_i + (1-B_{ik})*M	pass
"y_i + Dy_i =	17	"< or =	6003	"yk + (1-Cik)*M	pass
"y_k + Dy_k =	9	"< or =	6002	"yi + (1-Dik)*M	pass
"z_i + Dz_i =	14	"< or =	6011	"zk + (1-Eik)*M	pass
"z_k + Dz_k =	14	"< or =	6011	"zi + (1-Fik)*M	pass

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
14	Spot Lights	1	2	2	11	9	15	3	9	15	3	0.07	4
9	Diffusers	2	0	0	10	20	20	3	10	10	1.5	0.20	4

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
0	1	0	1	0	1

"x_i + Dx_i =	11	"< or =	6000	"x_k + (1-A_{ik})*M	pass
"x_k + Dx_k =	10	"< or =	2	"x_i + (1-B_{ik})*M	fail
"y_i + Dy_i =	17	"< or =	6000	"yk + (1-Cik)*M	pass
"y_k + Dy_k =	10	"< or =	2	"yi + (1-Dik)*M	fail
"z_i + Dz_i =	14	"< or =	6010	"zk + (1-Eik)*M	pass
"z_k + Dz_k =	11.5	"< or =	11	"zi + (1-Fik)*M	fail

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
14	Spot Lights	1	2	2	11	9	15	3	9	15	3	0.07	4
10	Ceiling Tiles	1	0	0	10	20	20	3	20	20	3	0.20	4

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
0	1	0	1	0	1

"x_i + Dx_i =	11	"< or =	6000	"x_k + (1-A_{ik})*M	pass
"x_k + Dx_k =	20	"< or =	2	"x_i + (1-B_{ik})*M	fail
"y_i + Dy_i =	17	"< or =	6000	"yk + (1-Cik)*M	pass
"y_k + Dy_k =	20	"< or =	2	"yi + (1-Dik)*M	fail

"z_i + Dz_i = 14 "< or = 6010 "zk + (1-Eik)*M pass

"z_k + Dz_k = 13 "< or = 11 "zi + (1-Fik)*M fail

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
14	Spot Lights	1	2	2	11	9	15	3	9	15	3	0.07	4
21	Shades	1	1	9	10	4	11	3	4	11	3	0.02	4

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
0	1	0	0	0	1

"x_i + Dx_i = 11 "< or = 6001 "x_k + (1-A_{ik})*M pass

"x_k + Dx_k = 5 "< or = 2 "x_i + (1-B_{ik})*M fail

"y_i + Dy_i = 17 "< or = 6009 "yk + (1-Cik)*M pass

"y_k + Dy_k = 20 "< or = 6002 "yi + (1-Dik)*M pass

"z_i + Dz_i = 14 "< or = 6010 "zk + (1-Eik)*M pass

"z_k + Dz_k = 13 "< or = 11 "zi + (1-Fik)*M fail

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
14	Spot Lights	1	2	2	11	9	15	3	9	15	3	0.07	4
24	Sound	1	0	0	8	12	16	3	12	16	3	0.10	4

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
0	1	1	0	0	1

"x_i + Dx_i = 11 "< or = 6000 "x_k + (1-A_{ik})*M pass

"x_k + Dx_k = 12 "< or = 2 "x_i + (1-B_{ik})*M fail

"y_i + Dy_i = 17 "< or = 0 "yk + (1-Cik)*M fail

"y_k + Dy_k = 16 "< or = 6002 "yi + (1-Dik)*M pass

"z_i + Dz_i = 14 "< or = 6008 "zk + (1-Eik)*M pass

"z_k + Dz_k = 11 "< or = 11 "zi + (1-Fik)*M pass

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
14	Spot Lights	1	2	2	11	9	15	3	9	15	3	0.07	4
18	Chair Rail	1	0	2	4	12	14	6	12	14	6	0.17	4

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
0	1	1	0	0	1

"x_i + Dx_i = 11 "< or = 6000 "x_k + (1-A_{ik})*M pass

"x_k + Dx_k = 12 "< or = 2 "x_i + (1-B_{ik})*M fail

"y_i + Dy_i = 17 "< or = 2 "yk + (1-Cik)*M fail

"$y_k + Dy_k$ = 16 "< or = 6002 "yi + (1-Dik)*M pass

"$z_i + Dz_i$ = 14 "< or = 6004 "zk + (1-Eik)*M pass

"$z_k + Dz_k$ = 10 "< or = 11 "zi + (1-Fik)*M pass

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
14	Spot Lights	1	2	2	11	9	15	3	9	15	3	0.07	4
11	Floor Tiles	1	0	0	0	12	16	6	12	16	6	0.19	4

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
0	1	1	0	0	1

"$x_i + Dx_i$ = 11 "< or = 6000 "$x_k + (1-A_{ik})$*M pass

"$x_k + Dx_k$ = 12 "< or = 2 "$x_i + (1-B_{ik})$*M fail

"$y_i + Dy_i$ = 17 "< or = 0 "yk + (1-Cik)*M fail

"$y_k + Dy_k$ = 16 "< or = 6002 "yi + (1-Dik)*M pass

"$z_i + Dz_i$ = 14 "< or = 6000 "zk + (1-Eik)*M pass

"$z_k + Dz_k$ = 6 "< or = 11 "zi + (1-Fik)*M fail

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
14	Spot Lights	1	2	2	11	9	15	3	9	15	3	0.07	4
13	Marble Tub	1	12	0	0	9	4	8	9	4	8	0.05	4

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
1	0	0	0	0	1

"$x_i + Dx_i$ = 11 "< or = 12 "$x_k + (1-A_{ik})$*M pass

"$x_k + Dx_k$ = 21 "< or = 6002 "$x_i + (1-B_{ik})$*M pass

"$y_i + Dy_i$ = 17 "< or = 6000 "yk + (1-Cik)*M pass

"$y_k + Dy_k$ = 4 "< or = 6002 "yi + (1-Dik)*M pass

"$z_i + Dz_i$ = 14 "< or = 6000 "zk + (1-Eik)*M pass

"$z_k + Dz_k$ = 8 "< or = 11 "zi + (1-Fik)*M pass

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
14	Spot Lights	1	2	2	11	9	15	3	9	15	3	0.07	4
16	Floor Mural	3	12	0	0	9	12	6	3	4	2	0.11	4

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
1	0	0	0	0	0

"$x_i + Dx_i$ =	11	"< or =	12	"$x_k + (1-A_{ik})$*M	pass
"$x_k + Dx_k$ =	15	"< or =	6002	"$x_i + (1-B_{ik})$*M	pass
"$y_i + Dy_i$ =	17	"< or =	6000	"yk + (1-Cik)*M	pass
"$y_k + Dy_k$ =	4	"< or =	6002	"yi + (1-Dik)*M	pass
"$z_i + Dz_i$ =	14	"< or =	6000	"zk + (1-Eik)*M	pass
"$z_k + Dz_k$ =	2	"< or =	6011	"zi + (1-Fik)*M	pass

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
14	Spot Lights	1	2	2	11	9	15	3	9	15	3	0.07	4
5	Doors	1	9	9	0	11	11	8	11	11	8	0.16	4

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
1	0	0	0	0	1

"$x_i + Dx_i$ =	11	"< or =	9	"$x_k + (1-A_{ik})$*M	fail
"$x_k + Dx_k$ =	20	"< or =	6002	"$x_i + (1-B_{ik})$*M	pass
"$y_i + Dy_i$ =	17	"< or =	6009	"yk + (1-Cik)*M	pass
"$y_k + Dy_k$ =	20	"< or =	6002	"yi + (1-Dik)*M	pass
"$z_i + Dz_i$ =	14	"< or =	6000	"zk + (1-Eik)*M	pass
"$z_k + Dz_k$ =	8	"< or =	11	"zi + (1-Fik)*M	pass

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
14	Spot Lights	1	2	2	11	9	15	3	9	15	3	0.07	4
23	Theater S	1	1	6	0	10	10	6	10	10	6	0.10	4

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
0	1	0	1	0	1

"$x_i + Dx_i$ =	11	"< or =	6001	"$x_k + (1-A_{ik})$*M	pass
"$x_k + Dx_k$ =	11	"< or =	2	"$x_i + (1-B_{ik})$*M	fail
"$y_i + Dy_i$ =	17	"< or =	6006	"yk + (1-Cik)*M	pass
"$y_k + Dy_k$ =	16	"< or =	2	"yi + (1-Dik)*M	fail
"$z_i + Dz_i$ =	14	"< or =	6000	"zk + (1-Eik)*M	pass
"$z_k + Dz_k$ =	6	"< or =	11	"zi + (1-Fik)*M	pass

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
15	Perimeter Lights	1	12	3	11	8	6	3	8	6	3	0.02	4
13	Marble Tub	1	12	0	0	9	4	8	9	4	8	0.05	4

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
0	0	1	0	0	1

"x_i + Dx_i =	20	"< or =	6012	"x_k + (1-A_{ik})*M	pass
"x_k + Dx_k =	21	"< or =	6012	"x_i + (1-B_{ik})*M	pass
"y_i + Dy_i =	9	"< or =	0	"yk + (1-Cik)*M	fail
"y_k + Dy_k =	4	"< or =	6003	"yi + (1-Dik)*M	pass
"z_i + Dz_i =	14	"< or =	6000	"zk + (1-Eik)*M	pass
"z_k + Dz_k =	8	"< or =	11	"zi + (1-Fik)*M	pass

Complete Spot Lights and Perimeter Lights

Day 13

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
9	Diffusers	2	0	0	10	20	20	3	10	10	1.5	0.20	4
10	Ceiling Tiles	1	0	0	10	20	20	3	20	20	3	0.20	4

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
0	1	0	0	0	0

"x_i + Dx_i =	10	"< or =	6000	"x_k + (1-A_{ik})*M	pass
"x_k + Dx_k =	20	"< or =	0	"x_i + (1-B_{ik})*M	fail
"y_i + Dy_i =	10	"< or =	6000	"yk + (1-Cik)*M	pass
"y_k + Dy_k =	20	"< or =	6000	"yi + (1-Dik)*M	pass
"z_i + Dz_i =	11.5	"< or =	6010	"zk + (1-Eik)*M	pass
"z_k + Dz_k =	13	"< or =	6010	"zi + (1-Fik)*M	pass

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
9	Diffusers	2	0	0	10	20	20	3	10	10	1.5	0.20	4
21	Shades	1	1	9	10	4	11	3	4	11	3	0.02	4

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
0	1	0	0	0	0

"x_i + Dx_i =	10	"< or =	6001	"x_k + (1-A_{ik})*M	pass
"x_k + Dx_k =	5	"< or =	0	"x_i + (1-B_{ik})*M	fail
"y_i + Dy_i =	10	"< or =	6009	"yk + (1-Cik)*M	pass
"y_k + Dy_k =	20	"< or =	6000	"yi + (1-Dik)*M	pass
"z_i + Dz_i =	11.5	"< or =	6010	"zk + (1-Eik)*M	pass
"z_k + Dz_k =	13	"< or =	6010	"zi + (1-Fik)*M	pass

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
9	Diffusers	2	0	0	10	20	20	3	10	10	1.5	0.20	4
24	Sound	1	0	0	8	12	16	3	12	16	3	0.10	4

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
0	1	0	0	0	1

"x_i + Dx_i =	10	"< or =	6000	"x_k + (1-A_{ik})*M	pass
"x_k + Dx_k =	12	"< or =	0	"x_i + (1-B_{ik})*M	fail
"y_i + Dy_i =	10	"< or =	6000	"yk + (1-Cik)*M	pass
"y_k + Dy_k =	16	"< or =	6000	"yi + (1-Dik)*M	pass

"$z_i + Dz_i$ = 11.5 "< or = 6008 "zk + (1-Eik)*M pass

"$z_k + Dz_k$ = 11 "< or = 10 "zi + (1-Fik)*M fail

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
9	Diffusers	2	0	0	10	20	20	3	10	10	1.5	0.20	4
18	Chair Rail	1	0	2	4	12	14	6	12	14	6	0.17	4

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
0	1	0	0	0	1

"$x_i + Dx_i$ = 10 "< or = 6000 "$x_k + (1-A_{ik})$*M pass

"$x_k + Dx_k$ = 12 "< or = 0 "$x_i + (1-B_{ik})$*M fail

"$y_i + Dy_i$ = 10 "< or = 6002 "yk + (1-Cik)*M pass

"$y_k + Dy_k$ = 16 "< or = 6000 "yi + (1-Dik)*M pass

"$z_i + Dz_i$ = 11.5 "< or = 6004 "zk + (1-Eik)*M pass

"$z_k + Dz_k$ = 10 "< or = 10 "zi + (1-Fik)*M pass

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
9	Diffusers	2	0	0	10	20	20	3	10	10	1.5	0.20	4
11	Floor Tiles	1	0	0	0	12	16	6	12	16	6	0.19	4

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
1	1	1	0	0	1

"$x_i + Dx_i$ = 10 "< or = 0 "$x_k + (1-A_{ik})$*M fail

"$x_k + Dx_k$ = 12 "< or = 0 "$x_i + (1-B_{ik})$*M fail

"$y_i + Dy_i$ = 10 "< or = 0 "yk + (1-Cik)*M fail

"$y_k + Dy_k$ = 16 "< or = 6000 "yi + (1-Dik)*M pass

"$z_i + Dz_i$ = 11.5 "< or = 6000 "zk + (1-Eik)*M pass

"$z_k + Dz_k$ = 6 "< or = 10 "zi + (1-Fik)*M pass

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
9	Diffusers	2	0	0	10	20	20	3	10	10	1.5	0.20	4
13	Marble Tub	1	12	0	0	9	4	8	9	4	8	0.05	4

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
1	0	0	0	0	1

"$x_i + Dx_i$ = 10 "< or = 12 "$x_k + (1-A_{ik})$*M pass

"$x_k + Dx_k$ = 21 "< or = 6000 "$x_i + (1-B_{ik})$*M pass

"y_i + Dy_i = 10 "< or = 6000 "yk + (1-Cik)*M pass

"y_k + Dy_k = 4 "< or = 6000 "yi + (1-Dik)*M pass

"z_i + Dz_i = 11.5 "< or = 6000 "zk + (1-Eik)*M pass

"z_k + Dz_k = 8 "< or = 10 "zi + (1-Fik)*M pass

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
9	Diffusers	2	0	0	10	20	20	3	10	10	1.5	0.20	4
5	Doors	1	9	9	0	11	11	8	11	11	8	0.16	4

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
1	0	0	0	0	0

"x_i + Dx_i = 10 "< or = 9 "x_k + (1-A_{ik})*M fail

"x_k + Dx_k = 20 "< or = 6000 "x_i + (1-B_{ik})*M pass

"y_i + Dy_i = 10 "< or = 6009 "yk + (1-Cik)*M pass

"y_k + Dy_k = 20 "< or = 6000 "yi + (1-Dik)*M pass

"z_i + Dz_i = 11.5 "< or = 6000 "zk + (1-Eik)*M pass

"z_k + Dz_k = 8 "< or = 6010 "zi + (1-Fik)*M pass

START DIFFUSERS WITH MARBLE TUB

Day 14

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
9	Diffusers	1	10	10	10	10	10	3	10	10	3	0.05	4
21	Shades	1	1	9	10	4	11	3	4	11	3	0.02	4

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
0	1	0	0	0	0

"x_i + Dx_i =	20	"< or =	6001	"x_k + (1-A_{ik})*M	pass
"x_k + Dx_k =	5	"< or =	10	"x_i + (1-B_{ik})*M	pass
"y_i + Dy_i =	20	"< or =	6009	"yk + (1-Cik)*M	pass
"y_k + Dy_k =	20	"< or =	6010	"yi + (1-Dik)*M	pass
"z_i + Dz_i =	13	"< or =	6010	"zk + (1-Eik)*M	pass
"z_k + Dz_k =	13	"< or =	6010	"zi + (1-Fik)*M	pass

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
9	Diffusers	1	10	10	10	10	10	3	10	10	3	0.05	4
24	Sound	1	0	0	8	12	16	3	12	16	3	0.10	4

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
0	1	0	0	0	1

"x_i + Dx_i =	20	"< or =	6000	"x_k + (1-A_{ik})*M	pass
"x_k + Dx_k =	12	"< or =	10	"x_i + (1-B_{ik})*M	fail
"y_i + Dy_i =	20	"< or =	6000	"yk + (1-Cik)*M	pass
"y_k + Dy_k =	16	"< or =	6010	"yi + (1-Dik)*M	pass
"z_i + Dz_i =	13	"< or =	6008	"zk + (1-Eik)*M	pass
"z_k + Dz_k =	11	"< or =	10	"zi + (1-Fik)*M	fail

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
9	Diffusers	1	10	10	10	10	10	3	10	10	3	0.05	4
18	Chair Rail	1	0	2	4	12	14	6	12	14	6	0.17	4

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
0	1	0	0	0	1

"x_i + Dx_i =	20	"< or =	6000	"x_k + (1-A_{ik})*M	pass
"x_k + Dx_k =	12	"< or =	10	"x_i + (1-B_{ik})*M	fail
"y_i + Dy_i =	20	"< or =	6002	"yk + (1-Cik)*M	pass
"y_k + Dy_k =	16	"< or =	6010	"yi + (1-Dik)*M	pass

"z_i + Dz_i = 13 "< or = 6004 "zk + (1-Eik)*M pass

"z_k + Dz_k = 10 "< or = 10 "zi + (1-Fik)*M pass

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
9	Diffusers	1	10	10	10	10	10	3	10	10	3	0.05	4
11	Floor Tiles	1	0	0	0	12	16	6	12	16	6	0.19	4

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
0	1	0	0	0	1

"x_i + Dx_i = 20 "< or = 6000 "x_k + (1-A_{ik})*M pass

"x_k + Dx_k = 12 "< or = 10 "x_i + (1-B_{ik})*M fail

"y_i + Dy_i = 20 "< or = 6000 "yk + (1-Cik)*M pass

"y_k + Dy_k = 16 "< or = 6010 "yi + (1-Dik)*M pass

"z_i + Dz_i = 13 "< or = 6000 "zk + (1-Eik)*M pass

"z_k + Dz_k = 6 "< or = 10 "zi + (1-Fik)*M pass

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
9	Diffusers	1	10	10	10	10	10	3	10	10	3	0.05	4
16	Floor Mural	3	12	0	0	9	12	6	3	4	2	0.11	4

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
1	0	0	0	0	1

"x_i + Dx_i = 20 "< or = 12 "x_k + (1-A_{ik})*M fail

"x_k + Dx_k = 15 "< or = 6010 "x_i + (1-B_{ik})*M fail

"y_i + Dy_i = 20 "< or = 6000 "yk + (1-Cik)*M fail

"y_k + Dy_k = 4 "< or = 6010 "yi + (1-Dik)*M pass

"z_i + Dz_i = 13 "< or = 6000 "zk + (1-Eik)*M pass

"z_k + Dz_k = 2 "< or = 10 "zi + (1-Fik)*M pass

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
9	Diffusers	1	10	10	10	10	10	3	10	10	3	0.05	4
5	Doors	1	9	9	0	11	11	8	11	11	8	0.16	4

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
1	0	0	0	0	1

"x_i + Dx_i = 20 "< or = 9 "x_k + (1-A_{ik})*M fail

"x_k + Dx_k = 20 "< or = 6010 "x_i + (1-B_{ik})*M pass

"y_i + Dy_i = 20 "< or = 6009 "yk + (1-Cik)*M pass

"y_k + Dy_k = 20 "< or = 6010 "yi + (1-Dik)*M pass
"z_i + Dz_i = 13 "< or = 6000 "zk + (1-Eik)*M pass
"z_k + Dz_k = 8 "< or = 10 "zi + (1-Fik)*M pass

COMPLETE DIFFUSERS AND SHADES

Day 15

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
10	Ceiling Tiles	1	0	0	10	20	20	3	20	20	3	0.20	4
24	Sound	1	0	0	8	12	16	3	12	16	3	0.10	4

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
1	1	0	0	0	0

"x_i + Dx_i =	20	"< or =	0	"x_k + (1-A_{ik})*M	fail
"x_k + Dx_k =	12	"< or =	0	"x_i + (1-B_{ik})*M	fail
"y_i + Dy_i =	20	"< or =	6000	"yk + (1-Cik)*M	pass
"y_k + Dy_k =	16	"< or =	6000	"yi + (1-Dik)*M	pass
"z_i + Dz_i =	13	"< or =	6008	"zk + (1-Eik)*M	pass
"z_k + Dz_k =	11	"< or =	6010	"zi + (1-Fik)*M	pass

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
10	Ceiling Tiles	1	0	0	10	20	20	3	20	20	3	0.20	4
18	Chair Rail	1	0	2	4	12	14	6	12	14	6	0.17	4

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
0	1	0	0	0	1

"x_i + Dx_i =	20	"< or =	6000	"x_k + (1-A_{ik})*M	pass
"x_k + Dx_k =	12	"< or =	0	"x_i + (1-B_{ik})*M	fail
"y_i + Dy_i =	20	"< or =	6002	"yk + (1-Cik)*M	pass
"y_k + Dy_k =	16	"< or =	6000	"yi + (1-Dik)*M	pass
"z_i + Dz_i =	13	"< or =	6004	"zk + (1-Eik)*M	pass
"z_k + Dz_k =	10	"< or =	10	"zi + (1-Fik)*M	pass

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
10	Ceiling Tiles	1	0	0	10	20	20	3	20	20	3	0.20	4
11	Floor Tiles	1	0	0	0	12	16	12	12	16	12	0.38	4

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
1	1	0	0	0	1

"x_i + Dx_i =	20	"< or =	0	"x_k + (1-A_{ik})*M	fail
"x_k + Dx_k =	12	"< or =	0	"x_i + (1-B_{ik})*M	fail
"y_i + Dy_i =	20	"< or =	6000	"yk + (1-Cik)*M	pass
"y_k + Dy_k =	16	"< or =	6000	"yi + (1-Dik)*M	pass

"z_i + Dz_i = 13 "< or = 6000 "zk + (1-Eik)*M pass

"z_k + Dz_k = 12 "< or = 10 "zi + (1-Fik)*M fail

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
10	Ceiling Tiles	1	0	0	10	20	20	3	20	20	3	0.20	4
16	Floor Mural	3	12	4	0	9	6	6	3	2	2	0.05	4

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
1	0	1	0	0	1

"x_i + Dx_i = 20 "< or = 12 "x_k + (1-A_{ik})*M fail

"x_k + Dx_k = 15 "< or = 6000 "x_i + (1-B_{ik})*M pass

"y_i + Dy_i = 20 "< or = 4 "yk + (1-Cik)*M fail

"y_k + Dy_k = 6 "< or = 6000 "yi + (1-Dik)*M pass

"z_i + Dz_i = 13 "< or = 6000 "zk + (1-Eik)*M pass

"z_k + Dz_k = 2 "< or = 10 "zi + (1-Fik)*M pass

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
10	Ceiling Tiles	1	0	0	10	20	20	3	20	20	3	0.20	4
5	Doors	1	9	9	0	11	11	8	11	11	8	0.16	4

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
1	1	1	0	0	1

"x_i + Dx_i = 20 "< or = 9 "x_k + (1-A_{ik})*M fail

"x_k + Dx_k = 20 "< or = 0 "x_i + (1-B_{ik})*M fail

"y_i + Dy_i = 20 "< or = 9 "yk + (1-Cik)*M fail

"y_k + Dy_k = 20 "< or = 6000 "yi + (1-Dik)*M pass

"z_i + Dz_i = 13 "< or = 6000 "zk + (1-Eik)*M pass

"z_k + Dz_k = 8 "< or = 10 "zi + (1-Fik)*M pass

START/COMPLETE CEILING TILES

Day 16

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
24	Sound	1	0	0	8	12	16	3	12	16	3	0.10	4
18	Chair Rail	1	0	2	4	12	14	6	12	14	6	0.17	4

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
0	1	0	0	0	1

"x_i + Dx_i =	12	"< or =	6000	"x_k + (1-A_{ik})*M	pass
"x_k + Dx_k =	12	"< or =	0	"x_i + (1-B_{ik})*M	fail
"y_i + Dy_i =	16	"< or =	6002	"yk + (1-Cik)*M	pass
"y_k + Dy_k =	16	"< or =	6000	"yi + (1-Dik)*M	pass
"z_i + Dz_i =	11	"< or =	6004	"zk + (1-Eik)*M	pass
"z_k + Dz_k =	10	"< or =	8	"zi + (1-Fik)*M	fail

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
24	Sound	1	0	0	8	12	16	3	12	16	3	0.10	4
11	Floor Tiles	1	0	0	0	12	16	6	12	16	6	0.19	4

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
1	1	0	0	0	1

"x_i + Dx_i =	12	"< or =	0	"x_k + (1-A_{ik})*M	fail
"x_k + Dx_k =	12	"< or =	0	"x_i + (1-B_{ik})*M	fail
"y_i + Dy_i =	16	"< or =	6000	"yk + (1-Cik)*M	pass
"y_k + Dy_k =	16	"< or =	6000	"yi + (1-Dik)*M	pass
"z_i + Dz_i =	11	"< or =	6000	"zk + (1-Eik)*M	pass
"z_k + Dz_k =	6	"< or =	8	"zi + (1-Fik)*M	pass

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
24	Sound	1	0	0	8	12	16	3	12	16	3	0.10	4
16	Floor Mural	3	12	4	0	9	6	6	3	2	2	0.05	4

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
1	0	0	0	0	1

"x_i + Dx_i =	12	"< or =	12	"x_k + (1-A_{ik})*M	pass
"x_k + Dx_k =	15	"< or =	6000	"x_i + (1-B_{ik})*M	pass
"y_i + Dy_i =	16	"< or =	6004	"yk + (1-Cik)*M	pass
"y_k + Dy_k =	6	"< or =	6000	"yi + (1-Dik)*M	pass

"z_i + Dz_i = 11 "< or = 6000 "zk + (1-Eik)*M pass

"z_k + Dz_k = 2 "< or = 8 "zi + (1-Fik)*M pass

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
24	Sound	1	0	0	8	12	16	3	12	16	3	0.10	4
5	Doors	1	9	9	0	11	11	8	11	11	8	0.16	4

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
1	0	0	0	0	1

"x_i + Dx_i = 12 "< or = 9 "x_k + (1-A_{ik})*M fail

"x_k + Dx_k = 20 "< or = 6000 "x_i + (1-B_{ik})*M pass

"y_i + Dy_i = 16 "< or = 6009 "yk + (1-Cik)*M pass

"y_k + Dy_k = 20 "< or = 6000 "yi + (1-Dik)*M pass

"z_i + Dz_i = 11 "< or = 6000 "zk + (1-Eik)*M pass

"z_k + Dz_k = 8 "< or = 8 "zi + (1-Fik)*M pass

START/COMPETE SOUND SYSTEM and START FLOOR MURAL

Day 17

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
16	Floor Mural	2	12	4	0	6	4	6	3	2	3	0.02	4
18	Chair Rail	1	0	2	4	12	14	6	12	14	6	0.17	4

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
0	1	0	0	0	0

"x_i + Dx_i =	15	"< or =	6000	"x_k + (1-A_{ik})*M	pass
"x_k + Dx_k =	12	"< or =	12	"x_i + (1-B_{ik})*M	pass
"y_i + Dy_i =	6	"< or =	6002	"yk + (1-Cik)*M	pass
"y_k + Dy_k =	16	"< or =	6004	"yi + (1-Dik)*M	pass
"z_i + Dz_i =	3	"< or =	6004	"zk + (1-Eik)*M	pass
"z_k + Dz_k =	10	"< or =	6000	"zi + (1-Fik)*M	pass

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
16	Floor Mural	2	12	4	0	6	4	6	3	2	3	0.02	4
11	Floor Tiles	1	0	0	0	12	16	6	12	16	6	0.19	4

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
0	1	0	0	0	0

"x_i + Dx_i =	15	"< or =	6000	"x_k + (1-A_{ik})*M	pass
"x_k + Dx_k =	12	"< or =	12	"x_i + (1-B_{ik})*M	pass
"y_i + Dy_i =	6	"< or =	6000	"yk + (1-Cik)*M	pass
"y_k + Dy_k =	16	"< or =	6004	"yi + (1-Dik)*M	pass
"z_i + Dz_i =	3	"< or =	6000	"zk + (1-Eik)*M	pass
"z_k + Dz_k =	6	"< or =	6000	"zi + (1-Fik)*M	pass

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
16	Floor Mural	2	12	4	0	6	4	6	3	2	3	0.02	4
5	Doors	1	9	9	0	11	11	8	11	11	8	0.16	4

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
0	0	0	1	0	0

"x_i + Dx_i =	15	"< or =	6009	"x_k + (1-A_{ik})*M	pass
"x_k + Dx_k =	20	"< or =	6012	"x_i + (1-B_{ik})*M	pass
"y_i + Dy_i =	6	"< or =	6009	"yk + (1-Cik)*M	pass
"y_k + Dy_k =	20	"< or =	4	"yi + (1-Dik)*M	fail

"z_i + Dz_i = 3 "< or = 6000 "zk + (1-Eik)*M pass

"z_k + Dz_k = 8 "< or = 6000 "zi + (1-Fik)*M pass

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
18	Chair Rail	1	0	2	4	12	14	6	12	14	6	0.17	4
11	Floor Tiles	1	0	0	0	12	16	6	12	16	6	0.19	4

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
1	0	0	0	0	1

"x_i + Dx_i = 12 "< or = 0 "x_k + (1-A_{ik})*M fail

"x_k + Dx_k = 12 "< or = 6000 "x_i + (1-B_{ik})*M pass

"y_i + Dy_i = 16 "< or = 6000 "yk + (1-Cik)*M pass

"y_k + Dy_k = 16 "< or = 6002 "yi + (1-Dik)*M pass

"z_i + Dz_i = 10 "< or = 6000 "zk + (1-Eik)*M pass

"z_k + Dz_k = 6 "< or = 4 "zi + (1-Fik)*M fail

Choose Floor Tile over Chair Rail because larger Af factor and further activity dependency

START/COMPLETE FLOOR TILE and CONTINUE FLOOR MURAL

Day 18

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
16	Floor Mural	1	12	4	0	3	2	6	3	2	6	0.01	4
18	Chair Rail	1	0	2	4	12	14	6	12	14	6	0.17	4

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
0	1	0	0	0	0

"x_i + Dx_i = 15 "< or = 6000 "x_k + (1-A_{ik})*M pass

"x_k + Dx_k = 12 "< or = 12 "x_i + (1-B_{ik})*M pass

"y_i + Dy_i = 6 "< or = 6002 "yk + (1-Cik)*M pass

"y_k + Dy_k = 16 "< or = 6004 "yi + (1-Dik)*M pass

"z_i + Dz_i = 6 "< or = 6004 "zk + (1-Eik)*M pass

"z_k + Dz_k = 10 "< or = 6000 "zi + (1-Fik)*M pass

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
16	Floor Mural	1	12	4	0	3	2	6	3	2	6	0.01	4
5	Doors	1	9	9	0	11	11	8	11	11	8	0.16	4

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
0	0	0	1	0	0

"x_i + Dx_i = 15 "< or = 6009 "x_k + (1-A_{ik})*M pass

"x_k + Dx_k = 20 "< or = 6012 "x_i + (1-B_{ik})*M pass

"y_i + Dy_i = 6 "< or = 6009 "yk + (1-Cik)*M pass

"y_k + Dy_k = 20 "< or = 4 "yi + (1-Dik)*M fail

"z_i + Dz_i = 6 "< or = 6000 "zk + (1-Eik)*M pass

"z_k + Dz_k = 8 "< or = 6000 "zi + (1-Fik)*M pass

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
16	Floor Mural	1	12	4	0	3	2	6	3	2	6	0.01	4
23	Theater S	1	1	6	0	10	10	6	10	10	6	0.10	4

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
0	1	0	0	0	0

"x_i + Dx_i = 15 "< or = 6001 "x_k + (1-A_{ik})*M pass

"x_k + Dx_k = 11 "< or = 12 "x_i + (1-B_{ik})*M pass

"y_i + Dy_i = 6 "< or = 6006 "yk + (1-Cik)*M pass

"y_k + Dy_k = 16 "< or = 6004 "yi + (1-Dik)*M pass

"z_i + Dz_i = 6 "< or = 6000 "zk + (1-Eik)*M pass

"z_k + Dz_k = 6 "< or = 6000 "zi + (1-Fik)*M pass

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
18	Chair Rail	1	0	2	4	12	14	6	12	14	6	0.17	4
23	Theater S	1	1	6	0	10	10	6	10	10	6	0.10	4

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
1	0	0	0	0	0

"x_i + Dx_i = 12 "< or = 1 "x_k + (1-A_{ik})*M fail

"x_k + Dx_k = 11 "< or = 6000 "x_i + (1-B_{ik})*M pass

"y_i + Dy_i = 16 "< or = 6006 "yk + (1-Cik)*M pass

"y_k + Dy_k = 16 "< or = 6002 "yi + (1-Dik)*M pass

"z_i + Dz_i = 10 "< or = 6000 "zk + (1-Eik)*M pass

"z_k + Dz_k = 6 "< or = 6004 "zi + (1-Fik)*M pass

COMPLETE FLOOR MURAL and START/COMPLETE CHAIR RAIL
(larger Af in tie with Theater Seats)

Day 19

Activity	Description	Dur	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	A_f	SI
5	Doors	1	9	9	0	11	11	8	11	11	8	0.16	4
23	Theater S	1	1	6	0	10	10	6	10	10	6	0.10	4

A_{ik}	B_{ik}	C_{ik}	D_{ik}	E_{ik}	F_{ik}
0	1	0	0	0	0

"x_i + Dx_i =	20	"< or =	6001	"x_k + (1-A_{ik})*M	pass
"x_k + Dx_k =	11	"< or =	9	"x_i + (1-B_{ik})*M	pass
"y_i + Dy_i =	20	"< or =	6006	"yk + (1-Cik)*M	pass
"y_k + Dy_k =	16	"< or =	6009	"yi + (1-Dik)*M	pass
"z_i + Dz_i =	8	"< or =	6000	"zk + (1-Eik)*M	pass
"z_k + Dz_k =	6	"< or =	6000	"zi + (1-Fik)*M	pass

COMPLETE DOORS and THEATER SEATS

PROJECT COMPLETE

Appendix B: Case Study II: Spreadsheet Analysis

Activity	Description	Duration	x_i	y_i	z_i	P_i	Q_i	R_i	Dx	Dy	Dz	V_f	SI	Predecessor
7	Smoke Dampers D	2	26	12	6	36	24	2	18	12	1	0.05	2	
13	Smoke Conduit D	2	26	12	6	36	24	2	18	12	1	0.05	2	
19	Smoke Wiring D	1	26	12	6	36	24	2	36	24	2	0.05	2	13
4	Smoke Dampers A	2	0	31	6	19	21	2	9.5	10.5	1	0.02	2	
10	Smoke Conduit A	2	0	31	6	19	21	2	9.5	10.5	1	0.02	2	
16	Smoke Wiring A	1	0	31	6	19	21	2	19	21	2	0.02	2	10
5	Smoke Dampers B	1	0	18	6	25	14	2	25	14	2	0.02	2	22
11	Smoke Conduit B	2	0	18	6	25	14	2	12.5	7	1	0.02	2	5
17	Smoke Wiring B	1	0	18	6	25	14	2	25	14	2	0.02	2	11
9	Smoke Dampers F	2	17	0	6	70	3	2	35	1.5	1	0.01	2	
15	Smoke Conduit F	2	17	0	6	70	3	2	35	1.5	1	0.01	2	
21	Smoke Wiring F	1	17	0	6	70	3	2	70	3	2	0.01	2	15
8	Smoke Dampers E	2	76	8	6	12	19	2	6	9.5	1	0.01	2	
14	Smoke Conduit E	2	76	8	6	12	19	2	6	9.5	1	0.01	2	
20	Smoke Wiring E	1	76	8	6	12	19	2	12	19	2	0.01	2	14
6	Smoke Dampers C	2	0	0	6	11	18	2	5.5	9	1	0.01	2	
12	Smoke Conduit C	2	0	0	6	11	18	2	5.5	9	1	0.01	2	
18	Smoke Wiring C	1	0	0	6	11	18	2	11	18	2	0.01	2	12
2	Stud Wall A	3	0	23	0	21	7	8	7	2.33	2.67	0.03	3	1
3	Stud Wall B	2	66	24	0	8	11	8	4	5.5	4	0.02	3	
22	Duct Installation	3	0	18	6	25	14	2	8.33	4.67	0.67	0.02	3	
1	Sump Installation	2	0	27	0	8	6	8	4	3	4	0.01	3	
23	Signage	1	0	20	4	87	17	4	87	17	4	0.17	4	

Day 1

Activity	Description	Duration	xi	yi	zi	Pi	Qi	Ri	Dx	Dy	Dz	Af	SI
7	Smoke Dampers D	2	26	12	6	36	24	2	18	12	1		2
4	Smoke Dampers A	2	0	31	6	19	21	2	9.5	10.5	1		2

Aik	Bik	Cik	Dik	Eik	Fik
0	1	0	0	0	0

44	< or =	6000	xk + (1-Aik)*M	pass	PASS
9.5	< or =	26	xi + (1-Bik)*M	pass	
24	< or =	6000	xi + (1-Cik)*M	pass	
41.5	< or =	6012	xi + (1-Dik)*M	pass	
7	< or =	6006	xi + (1-Eik)*M	pass	
7	< or =	6006	xi + (1-Fik)*M	pass	

Activity	Description	Duration	xi	yi	zi	Pi	Qi	Ri	Dx	Dy	Dz	Af	SI
7	Smoke Dampers D	2	26	12	6	36	24	2	18	12	1		2
5	Smoke Dampers B	1	0	18	6	25	14	2	25	14	2		2

Aik	Bik	Cik	Dik	Eik	Fik
0	1	0	0	0	0

44	< or =	6000	xk + (1-Aik)*M	pass	PASS
25	< or =	26	xi + (1-Bik)*M	pass	
24	< or =	6000	xi + (1-Cik)*M	pass	
32	< or =	6012	xi + (1-Dik)*M	pass	
7	< or =	6006	xi + (1-Eik)*M	pass	
8	< or =	6006	xi + (1-Fik)*M	pass	

Activity	Description	Duration	xi	yi	zi	Pi	Qi	Ri	Dx	Dy	Dz	Af	SI
7	Smoke Dampers D	2	26	12	6	36	24	2	18	12	1		2
9	Smoke Dampers F	2	17	0	6	78	3	2	39	1.5	1		2

Aik	Bik	Cik	Dik	Eik	Fik
0	0	0	0	0	0

44	< or =	6017	xk + (1-Aik)*M	pass	PASS
56	< or =	6026	xi + (1-Bik)*M	pass	
24	< or =	6000	xi + (1-Cik)*M	pass	
1.5	< or =	6012	xi + (1-Dik)*M	pass	
7	< or =	6006	xi + (1-Eik)*M	pass	
7	< or =	6006	xi + (1-Fik)*M	pass	

Activity	Description	Duration	xi	yi	zi	Pi	Qi	Ri	Dx	Dy	Dz	Af	SI

7	Smoke Dampers D	2	26	12	6	36	24	2	18	12	1		2
8	Smoke Dampers E	2	76	8	6	12	19	2	6	9.5	1		2

Aik	Bik	Cik	Dik	Eik	Fik
1	0	0	0	0	0

44 < or = 76 xk + (1-Aik)*M pass PASS
82 < or = 6026 xi + (1-Bik)*M pass
24 < or = 6000 xi + (1-Cik)*M pass
17.5 < or = 6012 xi + (1-Dik)*M pass
7 < or = 6006 xi + (1-Eik)*M pass
7 < or = 6006 xi + (1-Fik)*M pass

Activity	Description	Duration	xi	yi	zi	Pi	Qi	Ri	Dx	Dy	Dz	Af	SI
7	Smoke Dampers D	2	26	12	6	36	24	2	18	12	1		2
6	Smoke Dampers C	2	0	0	6	11	18	2	5.5	9	1		2

Aik	Bik	Cik	Dik	Eik	Fik
0	1	0	0	0	0

44 < or = 6000 xk + (1-Aik)*M pass PASS
5.5 < or = 26 xi + (1-Bik)*M pass
24 < or = 6000 xi + (1-Cik)*M pass
9 < or = 6012 xi + (1-Dik)*M pass
7 < or = 6006 xi + (1-Eik)*M pass
7 < or = 6006 xi + (1-Fik)*M pass

Activity	Description	Duration	xi	yi	zi	Pi	Qi	Ri	Dx	Dy	Dz	Af	SI
7	Smoke Dampers D	2	26	12	6	36	24	2	18	12	1		2
3	Stud Wall B	2	66	24	0	8	11	8	4	5.5	4		3

Aik	Bik	Cik	Dik	Eik	Fik
1	0	0	0	0	0

44 < or = 66 xk + (1-Aik)*M pass PASS
4 < or = 6026 xi + (1-Bik)*M pass
24 < or = 6000 xi + (1-Cik)*M pass
29.5 < or = 6012 xi + (1-Dik)*M pass
7 < or = 6000 xi + (1-Eik)*M pass
4 < or = 6006 xi + (1-Fik)*M pass

Activity	Description	Duration	xi	yi	zi	Pi	Qi	Ri	Dx	Dy	Dz	Af	SI
7	Smoke Dampers D	2	26	12	6	36	24	2	18	12	1		2
22	Duct Installation	3	0	18	6	25	14	2	8.33	4.67	0.7		3

Aik	Bik	Cik	Dik	Eik	Fik
0	1	0	1	0	0

44 < or =	6000	xk + (1-Aik)*M	pass	FAIL
8.33 < or =	26	xi + (1-Bik)*M	pass	
24 < or =	6000	xi + (1-Cik)*M	pass	
22.7 < or =	12	xi + (1-Dik)*M	fail	
7 < or =	6006	xi + (1-Eik)*M	pass	
6.67 < or =	6006	xi + (1-Fik)*M	pass	

Activity	Description	Duration	xi	yi	zi	Pi	Qi	Ri	Dx	Dy	Dz	Af	SI
7	Smoke Dampers D	2	26	12	6	36	24	2	18	12	1		2
1	Sump Installation	2	0	27	0	8	6	8	4	3	4		3

Aik	Bik	Cik	Dik	Eik	Fik
0	1	0	0	0	1

44 < or =	6000	xk + (1-Aik)*M	pass	PASS
4 < or =	26	xi + (1-Bik)*M	pass	
24 < or =	6000	xi + (1-Cik)*M	pass	
30 < or =	6012	xi + (1-Dik)*M	pass	
7 < or =	6000	xi + (1-Eik)*M	pass	
4 < or =	6	xi + (1-Fik)*M	pass	

Activity	Description	Duration	xi	yi	zi	Pi	Qi	Ri	Dx	Dy	Dz	Af	SI
7	Smoke Dampers D	2	26	12	6	36	24	2	18	12	1		2
23	Signage	1	0	20	4	87	17	4	87	17	4		4

Aik	Bik	Cik	Dik	Eik	Fik
0	1	0	1	0	1

44 < or =	6000	xk + (1-Aik)*M	pass	FAIL
87 < or =	26	xi + (1-Bik)*M	fail	
24 < or =	6000	xi + (1-Cik)*M	pass	
37 < or =	12	xi + (1-Dik)*M	fail	
7 < or =	6004	xi + (1-Eik)*M	pass	
8 < or =	6	xi + (1-Fik)*M	fail	

Assume only one(1) crew available for dampers and one(1) for conduit.

Smoke Dampers D
Smoke Conduit A
Stud Wall B
Sump Installation

Day 2

Activity	Description	Duration	xi	yi	zi	Pi	Qi	Ri	Dx	Dy	Dz	Af	SI
7	Smoke Dampers D	1	44	12	6	18	24	2	18	24	2		2
1	Sump Installation	1	4	27	0	4	6	8	4	6	8		3

Aik	Bik	Cik	Dik	Eik	Fik
0	1	0	0	0	0

62 < or = 6004 xk + (1-Aik)*M pass PASS
8 < or = 44 xi + (1-Bik)*M pass
36 < or = 6000 xi + (1-Cik)*M pass
33 < or = 6012 xi + (1-Dik)*M pass
8 < or = 6000 xi + (1-Eik)*M pass
8 < or = 6006 xi + (1-Fik)*M pass

Activity	Description	Duration	xi	yi	zi	Pi	Qi	Ri	Dx	Dy	Dz	Af	SI
7	Smoke Dampers D	1	44	12	6	18	24	2	18	24	2		2
10	Smoke Conduit A	1	9.5	31	6	9.5	21	2	9.5	21	2		2

Aik	Bik	Cik	Dik	Eik	Fik
0	1	0	0	0	0

62 < or = 6010 xk + (1-Aik)*M pass PASS
19 < or = 44 xi + (1-Bik)*M pass
36 < or = 6000 xi + (1-Cik)*M pass
52 < or = 6012 xi + (1-Dik)*M pass
8 < or = 6006 xi + (1-Eik)*M pass
8 < or = 6006 xi + (1-Fik)*M pass

Activity	Description	Duration	xi	yi	zi	Pi	Qi	Ri	Dx	Dy	Dz	Af	SI
7	Smoke Dampers D	1	44	12	6	18	24	2	18	24	2		2
3	Stud Wall B	2	66	24	0	8	11	8	4	5.5	4		3

Aik	Bik	Cik	Dik	Eik	Fik
1	0	0	0	0	0

62 < or = 66 xk + (1-Aik)*M pass PASS
70 < or = 6044 xi + (1-Bik)*M pass
36 < or = 6000 xi + (1-Cik)*M pass
29.5 < or = 6012 xi + (1-Dik)*M pass
8 < or = 6000 xi + (1-Eik)*M pass
4 < or = 6006 xi + (1-Fik)*M pass

Activity	Description	Duration	xi	yi	zi	Pi	Qi	Ri	Dx	Dy	Dz	Af	SI
7	Smoke Dampers D	1	44	12	6	18	24	2	18	24	2		2
22	Duct Installation	3	0	18	6	25	14	2	8.33	4.67	0.7		3

Aik	Bik	Cik	Dik	Eik	Fik
0	1	0	0	0	0

62 < or = 6000 xk + (1-Aik)*M pass PASS
8.33 < or = 44 xi + (1-Bik)*M pass
36 < or = 6000 xi + (1-Cik)*M pass
22.7 < or = 6012 xi + (1-Dik)*M pass
8 < or = 6006 xi + (1-Eik)*M pass
6.67 < or = 6006 xi + (1-Fik)*M pass

Activity	Description	Duration	xi	yi	zi	Pi	Qi	Ri	Dx	Dy	Dz	Af	SI
1	Sump Installation	1	4	27	0	4	6	8	4	6	8		3
22	Duct Installation	3	0	18	6	25	14	2	8.33	4.67	0.7		3

Aik	Bik	Cik	Dik	Eik	Fik
0	1	1	0	0	0

8 < or = 6000 xk + (1-Aik)*M pass FAIL
8.33 < or = 4 xi + (1-Bik)*M fail
33 < or = 0 xi + (1-Cik)*M fail
22.7 < or = 6027 xi + (1-Dik)*M pass
8 < or = 6006 xi + (1-Eik)*M pass
6.67 < or = 6000 xi + (1-Fik)*M pass

Activity	Description	Duration	xi	yi	zi	Pi	Qi	Ri	Dx	Dy	Dz	Af	SI
7	Smoke Dampers D	1	44	12	6	18	24	2	18	24	2		2
23	Signage	1	0	20	4	87	17	4	87	17	4		4

Aik	Bik	Cik	Dik	Eik	Fik
0	1	0	1	0	1

62 < or = 6000 xk + (1-Aik)*M pass FAIL
87 < or = 44 xi + (1-Bik)*M fail
36 < or = 6000 xi + (1-Cik)*M pass
37 < or = 12 xi + (1-Dik)*M fail
8 < or = 6004 xi + (1-Eik)*M pass
8 < or = 6 xi + (1-Fik)*M fail

Smoke Dampers D
Smoke Conduit A
Stud Wall B
Sump Installation

Day 3

Activity	Description	Duration	xi	yi	zi	Pi	Qi	Ri	Dx	Dy	Dz	Af	SI
13	Smoke Conduit D	2	26	12	6	36	24	2	18	12	1		2
4	Smoke Dampers A	2	0	31	6	19	21	2	9.5	10.5	1		2

Aik	Bik	Cik	Dik	Eik	Fik
0	1	0	0	0	0

44	< or =	6000	xk + (1-Aik)*M	pass	PASS
9.5	< or =	26	xi + (1-Bik)*M	pass	
24	< or =	6000	xi + (1-Cik)*M	pass	
41.5	< or =	6012	xi + (1-Dik)*M	pass	
7	< or =	6006	xi + (1-Eik)*M	pass	
7	< or =	6006	xi + (1-Fik)*M	pass	

Activity	Description	Duration	xi	yi	zi	Pi	Qi	Ri	Dx	Dy	Dz	Af	SI
4	Smoke Dampers A	2	0	31	6	19	21	2	9.5	10.5	1		2
2	Stud Wall A	3	0	23	0	21	7	8	7	2.33	2.7		3

Aik	Bik	Cik	Dik	Eik	Fik
0	0	0	1	0	0

9.5	< or =	6000	xk + (1-Aik)*M	pass	PASS
7	< or =	6000	xi + (1-Bik)*M	pass	
41.5	< or =	6023	xi + (1-Cik)*M	pass	
25.3	< or =	31	xi + (1-Dik)*M	pass	
7	< or =	6000	xi + (1-Eik)*M	pass	
2.67	< or =	6006	xi + (1-Fik)*M	pass	

Activity	Description	Duration	xi	yi	zi	Pi	Qi	Ri	Dx	Dy	Dz	Af	SI
2	Stud Wall A	3	0	23	0	21	7	8	7	2.33	2.7		3
22	Duct Installation	3	0	18	6	25	14	2	8.33	4.67	0.7		3

Aik	Bik	Cik	Dik	Eik	Fik
0	0	1	0	0	0

7	< or =	6000	xk + (1-Aik)*M	pass	FAIL
8.33	< or =	6000	xi + (1-Bik)*M	pass	
25.3	< or =	0	xi + (1-Cik)*M	fail	
22.7	< or =	6023	xi + (1-Dik)*M	pass	
2.67	< or =	6006	xi + (1-Eik)*M	pass	
6.67	< or =	6000	xi + (1-Fik)*M	pass	

Activity	Description	Duration	xi	yi	zi	Pi	Qi	Ri	Dx	Dy	Dz	Af	SI

22	Duct Installation	3	0	18	6	25	14	2	8.33	4.67	0.7		3
4	Smoke Dampers A	2	0	31	6	19	21	2	9.5	10.5	1		2

Aik	Bik	Cik	Dik	Eik	Fik
0	0	1	0	0	0

8.33 < or = 6000 xk + (1-Aik)*M pass PASS
9.5 < or = 6000 xi + (1-Bik)*M pass
22.7 < or = 31 xi + (1-Cik)*M pass
41.5 < or = 6018 xi + (1-Dik)*M pass
6.67 < or = 6006 xi + (1-Eik)*M pass
7 < or = 6006 xi + (1-Fik)*M pass

Activity	Description	Duration	xi	yi	zi	Pi	Qi	Ri	Dx	Dy	Dz	Af	SI
22	Duct Installation	3	0	18	6	25	14	2	8.33	4.67	0.7		3
13	Smoke Conduit D	2	26	12	6	36	24	2	18	12	1		2

Aik	Bik	Cik	Dik	Eik	Fik
1	0	0	0	0	0

8.33 < or = 26 xk + (1-Aik)*M pass PASS
44 < or = 6000 xi + (1-Bik)*M pass
22.7 < or = 6000 xi + (1-Cik)*M pass
24 < or = 6018 xi + (1-Dik)*M pass
6.67 < or = 6006 xi + (1-Eik)*M pass
7 < or = 6006 xi + (1-Fik)*M pass

Smoke Conduit D
Smoke Dampers A
Duct Installation

Day 4

Activity	Description	Duration	xi	yi	zi	Pi	Qi	Ri	Dx	Dy	Dz	Af	SI
13	Smoke Conduit D	1	44	12	6	18	24	2	18	24	2		2
4	Smoke Dampers A	1	9.5	31	6	9.5	21	2	9.5	21	2		2

Aik	Bik	Cik	Dik	Eik	Fik
0	1	0	0	0	0

62 < or = 6010 xk + (1-Aik)*M pass PASS
19 < or = 44 xi + (1-Bik)*M pass
36 < or = 6000 xi + (1-Cik)*M pass
52 < or = 6012 xi + (1-Dik)*M pass
8 < or = 6006 xi + (1-Eik)*M pass
8 < or = 6006 xi + (1-Fik)*M pass

Activity	Description	Duration	xi	yi	zi	Pi	Qi	Ri	Dx	Dy	Dz	Af	SI
13	Smoke Conduit D	1	44	12	6	18	24	2	18	24	2		2
22	Duct Installation	2	8.3	18	6	16.7	14	2	8.35	7	1		3

Aik	Bik	Cik	Dik	Eik	Fik
0	1	0	0	0	0

62 < or = 6008 xk + (1-Aik)*M pass PASS
16.7 < or = 44 xi + (1-Bik)*M pass
36 < or = 6000 xi + (1-Cik)*M pass
25 < or = 6012 xi + (1-Dik)*M pass
8 < or = 6006 xi + (1-Eik)*M pass
7 < or = 6006 xi + (1-Fik)*M pass

Activity	Description	Duration	xi	yi	zi	Pi	Qi	Ri	Dx	Dy	Dz	Af	SI
4	Smoke Dampers A	1	9.5	31	6	9.5	21	2	9.5	21	2		2
22	Duct Installation	2	8.3	18	6	16.7	14	2	8.35	7	1		3

Aik	Bik	Cik	Dik	Eik	Fik
0	0	0	1	0	0

19 < or = 6008 xk + (1-Aik)*M pass PASS
16.7 < or = 6010 xi + (1-Bik)*M pass
52 < or = 6018 xi + (1-Cik)*M pass
25 < or = 31 xi + (1-Dik)*M pass
8 < or = 6006 xi + (1-Eik)*M pass
7 < or = 6006 xi + (1-Fik)*M pass

Activity	Description	Duration	xi	yi	zi	Pi	Qi	Ri	Dx	Dy	Dz	Af	SI
13	Smoke Conduit D	1	44	12	6	18	24	2	18	24	2		2
23	Signage	1	0	20	4	87	17	4	87	17	4		4

Aik	Bik	Cik	Dik	Eik	Fik
0	1	0	0	0	0

62 < or = 6000 xk + (1-Aik)*M pass FAIL
87 < or = 44 xi + (1-Bik)*M fail
36 < or = 6000 xi + (1-Cik)*M pass
37 < or = 6012 xi + (1-Dik)*M pass
8 < or = 6004 xi + (1-Eik)*M pass
8 < or = 6006 xi + (1-Fik)*M pass

Smoke Conduit D
Smoke Dampers A
Duct Installation

Day 5

Activity	Description	Duration	xi	yi	zi	Pi	Qi	Ri	Dx	Dy	Dz	Af	SI
22	Duct Installation	1	17	18	6	8.3	14	2	8.3	14	2		3
19	Smoke Wiring D	1	26	12	6	36	24	2	36	24	2		2

Aik	Bik	Cik	Dik	Eik	Fik
1	0	0	0	0	0

25 < or = 26 xk + (1-Aik)*M pass PASS
62 < or = 6017 xi + (1-Bik)*M pass
32 < or = 6000 xi + (1-Cik)*M pass
36 < or = 6018 xi + (1-Dik)*M pass
8 < or = 6006 xi + (1-Eik)*M pass
8 < or = 6006 xi + (1-Fik)*M pass

Activity	Description	Duration	xi	yi	zi	Pi	Qi	Ri	Dx	Dy	Dz	Af	SI
22	Duct Installation	1	17	18	6	8.3	14	2	8.3	14	2		3
9	Smoke Dampers F	2	17	0	6	70	3	2	35	1.5	1		2

Aik	Bik	Cik	Dik	Eik	Fik
0	0	0	1	0	0

25 < or = 6017 xk + (1-Aik)*M pass PASS
52 < or = 6017 xi + (1-Bik)*M pass
32 < or = 6000 xi + (1-Cik)*M pass
1.5 < or = 18 xi + (1-Dik)*M pass
8 < or = 6006 xi + (1-Eik)*M pass
7 < or = 6006 xi + (1-Fik)*M pass

Activity	Description	Duration	xi	yi	zi	Pi	Qi	Ri	Dx	Dy	Dz	Af	SI
9	Smoke Dampers F	2	17	0	6	70	3	2	35	1.5	1		2
14	Smoke Conduit E	2	76	8	6	12	19	2	6	9.5	1		2

Aik	Bik	Cik	Dik	Eik	Fik
1	0	0	0	0	0

52 < or = 76 xk + (1-Aik)*M pass PASS
82 < or = 6017 xi + (1-Bik)*M pass
1.5 < or = 6000 xi + (1-Cik)*M pass
17.5 < or = 6000 xi + (1-Dik)*M pass
7 < or = 6006 xi + (1-Eik)*M pass
7 < or = 6006 xi + (1-Fik)*M pass

Activity	Description	Duration	xi	yi	zi	Pi	Qi	Ri	Dx	Dy	Dz	Af	SI
22	Duct Installation	1	17	18	6	8.3	14	2	8.3	14	2		3
14	Smoke Conduit E	2	76	8	6	12	19	2	6	9.5	1		2

Aik	Bik	Cik	Dik	Eik	Fik
1	0	0	0	0	0

25 < or =	76 xk + (1-Aik)*M	pass	PASS
82 < or =	6017 xi + (1-Bik)*M	pass	
32 < or =	6000 xi + (1-Cik)*M	pass	
17.5 < or =	6018 xi + (1-Dik)*M	pass	
8 < or =	6006 xi + (1-Eik)*M	pass	
7 < or =	6006 xi + (1-Fik)*M	pass	

Activity	Description	Duration	xi	yi	zi	Pi	Qi	Ri	Dx	Dy	Dz	Af	SI
19	Smoke Wiring D	1	26	12	6	36	24	2	36	24	2		2
14	Smoke Conduit E	2	76	8	6	12	19	2	6	9.5	1		2

Aik	Bik	Cik	Dik	Eik	Fik
1	0	0	0	0	0

62 < or =	76 xk + (1-Aik)*M	pass	PASS
82 < or =	6026 xi + (1-Bik)*M	pass	
36 < or =	6000 xi + (1-Cik)*M	pass	
17.5 < or =	6012 xi + (1-Dik)*M	pass	
8 < or =	6006 xi + (1-Eik)*M	pass	
7 < or =	6006 xi + (1-Fik)*M	pass	

Activity	Description	Duration	xi	yi	zi	Pi	Qi	Ri	Dx	Dy	Dz	Af	SI
19	Smoke Wiring D	1	26	12	6	36	24	2	36	24	2		2
9	Smoke Dampers F	2	17	0	6	70	3	2	35	1.5	1		2

Aik	Bik	Cik	Dik	Eik	Fik
0	0	0	1	0	0

62 < or =	6017 xk + (1-Aik)*M	pass	PASS
52 < or =	6026 xi + (1-Bik)*M	pass	
36 < or =	6000 xi + (1-Cik)*M	pass	
1.5 < or =	12 xi + (1-Dik)*M	pass	
8 < or =	6006 xi + (1-Eik)*M	pass	
7 < or =	6006 xi + (1-Fik)*M	pass	

Activity	Description	Duration	xi	yi	zi	Pi	Qi	Ri	Dx	Dy	Dz	Af	SI
19	Smoke Wiring D	1	26	12	6	36	24	2	36	24	2		2
2	Stud Wall A	3	0	23	0	21	7	8	7	2.33	2.7		3

Aik	Bik	Cik	Dik	Eik	Fik
0	1	0	0	0	0

62	< or =	6000	xk + (1-Aik)*M	pass	PASS
7	< or =	26	xi + (1-Bik)*M	pass	
36	< or =	6023	xi + (1-Cik)*M	pass	
25.3	< or =	6012	xi + (1-Dik)*M	pass	
8	< or =	6000	xi + (1-Eik)*M	pass	
2.67	< or =	6006	xi + (1-Fik)*M	pass	

Duct Installation
Smoke Wiring D
Smoke Dampers F
Smoke Conduit E
Stud Wall A

Day 6

Activity	Description	Duration	xi	yi	zi	Pi	Qi	Ri	Dx	Dy	Dz	Af	SI
16	Smoke Wiring A	1	0	31	6	19	21	2	19	21	2		2
9	Smoke Dampers F	1	52	0	6	35	3	2	35	3	2		2

Aik	Bik	Cik	Dik	Eik	Fik
1	0	0	1	0	0

19	< or =	52	xk + (1-Aik)*M	pass PASS
87	< or =	6000	xi + (1-Bik)*M	pass
52	< or =	6000	xi + (1-Cik)*M	pass
3	< or =	31	xi + (1-Dik)*M	pass
8	< or =	6006	xi + (1-Eik)*M	pass
8	< or =	6006	xi + (1-Fik)*M	pass

Activity	Description	Duration	xi	yi	zi	Pi	Qi	Ri	Dx	Dy	Dz	Af	SI
16	Smoke Wiring A	1	0	31	6	19	21	2	19	21	2		2
14	Smoke Conduit E	1	82	8	6	6	19	2	6	19	2		2

Aik	Bik	Cik	Dik	Eik	Fik
1	0	0	1	0	0

19	< or =	82	xk + (1-Aik)*M	pass PASS
88	< or =	6000	xi + (1-Bik)*M	pass
52	< or =	6000	xi + (1-Cik)*M	pass
27	< or =	31	xi + (1-Dik)*M	pass
8	< or =	6006	xi + (1-Eik)*M	pass
8	< or =	6006	xi + (1-Fik)*M	pass

Activity	Description	Duration	xi	yi	zi	Pi	Qi	Ri	Dx	Dy	Dz	Af	SI
16	Smoke Wiring A	1	0	31	6	19	21	2	19	21	2		2
2	Stud Wall A	2	7	23	0	14	7	8	7	3.5	4		3

Aik	Bik	Cik	Dik	Eik	Fik
0	0	0	1	0	0

19	< or =	6007	xk + (1-Aik)*M	pass PASS
14	< or =	6000	xi + (1-Bik)*M	pass
52	< or =	6000	xi + (1-Cik)*M	pass
26.5	< or =	31	xi + (1-Dik)*M	pass
8	< or =	6000	xi + (1-Eik)*M	pass
4	< or =	6006	xi + (1-Fik)*M	pass

Activity	Description	Duration	xi	yi	zi	Pi	Qi	Ri	Dx	Dy	Dz	Af	SI
16	Smoke Wiring A	1	0	31	6	19	21	2	19	21	2		2

23	Signage	1	0	20	4	87	17	4	87	17	4	4

Aik	Bik	Cik	Dik	Eik	Fik
0	0	0	1	0	0

19 < or = 6000 xk + (1-Aik)*M pass FAIL
87 < or = 6000 xi + (1-Bik)*M pass
52 < or = 6000 xi + (1-Cik)*M pass
37 < or = 31 xi + (1-Dik)*M fail
8 < or = 6004 xi + (1-Eik)*M pass
8 < or = 6006 xi + (1-Fik)*M pass

Smoke Wiring A
Smoke Dampers F
Smoke Conduit E
Stud Wall A

Day 7

Activity	Description	Duration	xi	yi	zi	Pi	Qi	Ri	Dx	Dy	Dz	Af	SI
5	Smoke Dampers B	1	0	18	6	25	14	2	25	14	2		2
15	Smoke Conduit F	2	17	0	6	70	3	2	35	1.5	1		2

Aik	Bik	Cik	Dik	Eik	Fik
0	0	0	1	0	0

25 < or = 6017 xk + (1-Aik)*M pass PASS
52 < or = 6000 xi + (1-Bik)*M pass
32 < or = 6000 xi + (1-Cik)*M pass
3 < or = 18 xi + (1-Dik)*M pass
8 < or = 6006 xi + (1-Eik)*M pass
7 < or = 6006 xi + (1-Fik)*M pass

Activity	Description	Duration	xi	yi	zi	Pi	Qi	Ri	Dx	Dy	Dz	Af	SI
20	Smoke Wiring E	1	76	8	6	12	19	2	12	19	2		2
2	Stud Wall A	1	14	23	0	7	7	8	7	7	8		3

Aik	Bik	Cik	Dik	Eik	Fik
0	1	0	0	0	0

88 < or = 6014 xk + (1-Aik)*M pass PASS
21 < or = 76 xi + (1-Bik)*M pass
27 < or = 6000 xi + (1-Cik)*M pass
30 < or = 6008 xi + (1-Dik)*M pass
8 < or = 6000 xi + (1-Eik)*M pass
8 < or = 6006 xi + (1-Fik)*M pass

Activity	Description	Duration	xi	yi	zi	Pi	Qi	Ri	Dx	Dy	Dz	Af	SI
5	Smoke Dampers B	1	0	18	6	25	14	2	25	14	2		2
2	Stud Wall A	2	7	23	0	14	7	8	7	3.5	4		3

Aik	Bik	Cik	Dik	Eik	Fik
0	0	0	1	0	0

25 < or = 6007 xk + (1-Aik)*M pass FAIL
14 < or = 6000 xi + (1-Bik)*M pass
32 < or = 6000 xi + (1-Cik)*M pass
26.5 < or = 18 xi + (1-Dik)*M fail
8 < or = 6000 xi + (1-Eik)*M pass
4 < or = 6006 xi + (1-Fik)*M pass

Activity	Description	Duration	xi	yi	zi	Pi	Qi	Ri	Dx	Dy	Dz	Af	SI

6	Smoke Dampers C	2	0	0	6	11	18	2	5.5	9	1		2
2	Stud Wall A	2	7	23	0	14	7	8	7	3.5	4		3

Aik	Bik	Cik	Dik	Eik	Fik
1	0	1	0	0	0

5.5 < or = 7 xk + (1-Aik)*M pass PASS
14 < or = 6000 xi + (1-Bik)*M pass
9 < or = 23 xi + (1-Cik)*M pass
26.5 < or = 6000 xi + (1-Dik)*M pass
7 < or = 6000 xi + (1-Eik)*M pass
4 < or = 6006 xi + (1-Fik)*M pass

Activity	Description	Duration	xi	yi	zi	Pi	Qi	Ri	Dx	Dy	Dz	Af	SI
6	Smoke Dampers C	2	0	0	6	11	18	2	5.5	9	1		2
23	Signage	1	0	20	4	87	17	4	87	17	4		4

Aik	Bik	Cik	Dik	Eik	Fik
0	0	1	0	0	0

5.5 < or = 6000 xk + (1-Aik)*M pass PASS
87 < or = 6000 xi + (1-Bik)*M pass
9 < or = 20 xi + (1-Cik)*M pass
37 < or = 6000 xi + (1-Dik)*M pass
7 < or = 6004 xi + (1-Eik)*M pass
8 < or = 6006 xi + (1-Fik)*M pass

Activity	Description	Duration	xi	yi	zi	Pi	Qi	Ri	Dx	Dy	Dz	Af	SI
15	Smoke Conduit F	2	17	0	6	70	3	2	35	1.5	1		2
23	Signage	1	0	20	4	87	17	4	87	17	4		4

52 < or = 6000 xk + (1-Aik)*M pass PASS
87 < or = 6017 xi + (1-Bik)*M pass
1.5 < or = 20 xi + (1-Cik)*M pass
37 < or = 6000 xi + (1-Dik)*M pass
7 < or = 6004 xi + (1-Eik)*M pass
8 < or = 6006 xi + (1-Fik)*M pass

Activity	Description	Duration	xi	yi	zi	Pi	Qi	Ri	Dx	Dy	Dz	Af	SI
20	Smoke Wiring E	1	76	8	6	12	19	2	12	19	2		2
23	Signage	1	0	20	4	87	17	4	87	17	4		4

Aik	Bik	Cik	Dik	Eik	Fik
0	1	0	1	0	0

88 < or = 6000 xk + (1-Aik)*M pass FAIL
87 < or = 76 xi + (1-Bik)*M fail
27 < or = 6020 xi + (1-Cik)*M pass
37 < or = 8 xi + (1-Dik)*M fail
8 < or = 6004 xi + (1-Eik)*M pass
8 < or = 6006 xi + (1-Fik)*M pass

Activity	Description	Duration	xi	yi	zi	Pi	Qi	Ri	Dx	Dy	Dz	Af	SI
20	Smoke Wiring E	1	76	8	6	12	19	2	12	19	2		2
15	Smoke Conduit F	2	17	0	6	70	3	2	35	1.5	1		2

Aik	Bik	Cik	Dik	Eik	Fik
0	0	0	1	0	0

88 < or = 6017 xk + (1-Aik)*M pass PASS
52 < or = 6076 xi + (1-Bik)*M pass
27 < or = 6000 xi + (1-Cik)*M pass
1.5 < or = 8 xi + (1-Dik)*M pass
8 < or = 6006 xi + (1-Eik)*M pass
7 < or = 6006 xi + (1-Fik)*M pass

Activity	Description	Duration	xi	yi	zi	Pi	Qi	Ri	Dx	Dy	Dz	Af	SI
20	Smoke Wiring E	1	76	8	6	12	19	2	12	19	2		2
6	Smoke Dampers C	2	0	0	6	11	18	2	5.5	9	1		2

Aik	Bik	Cik	Dik	Eik	Fik
0	1	0	0	0	0

88 < or = 6000 xk + (1-Aik)*M pass PASS
5.5 < or = 76 xi + (1-Bik)*M pass
27 < or = 6000 xi + (1-Cik)*M pass
9 < or = 6008 xi + (1-Dik)*M pass
8 < or = 6006 xi + (1-Eik)*M pass
7 < or = 6006 xi + (1-Fik)*M pass

Activity	Description	Duration	xi	yi	zi	Pi	Qi	Ri	Dx	Dy	Dz	Af	SI
15	Smoke Conduit F	2	17	0	6	70	3	2	35	1.5	1		2
6	Smoke Dampers C	2	0	0	6	11	18	2	5.5	9	1		2

Aik	Bik	Cik	Dik	Eik	Fik
0	1	0	0	0	0

52 < or = 6000 xk + (1-Aik)*M pass PASS
5.5 < or = 17 xi + (1-Bik)*M pass
1.5 < or = 6000 xi + (1-Cik)*M pass
9 < or = 6000 xi + (1-Dik)*M pass
7 < or = 6006 xi + (1-Eik)*M pass

7 < or = 6006 xi + (1-Fik)*M   pass

Activity	Description	Duration	xi	yi	zi	Pi	Qi	Ri	Dx	Dy	Dz	Af	SI
15	Smoke Conduit F	2	17	0	6	70	3	2	35	1.5	1		2
2	Stud Wall A	2	7	23	0	14	7	8	7	3.5	4		3

Aik	Bik	Cik	Dik	Eik	Fik
0	1	1	0	0	0

52 < or = 6007 xk + (1-Aik)*M   pass PASS
14 < or =   17 xi + (1-Bik)*M   pass
1.5 < or =   23 xi + (1-Cik)*M   pass
26.5 < or = 6000 xi + (1-Dik)*M   pass
7 < or = 6000 xi + (1-Eik)*M   pass
4 < or = 6006 xi + (1-Fik)*M   pass

Stud Wall A
Smoke Conduit F
Smoke Dampers C
Smoke Wiring E

Day 8

Activity	Description	Duration	xi	yi	zi	Pi	Qi	Ri	Dx	Dy	Dz	Af	SI
6	Smoke Dampers C	1	5.5	0	6	5.5	18	2	5.5	18	2		2
15	Smoke Conduit F	1	52	0	6	35	3	2	35	3	2		2

Aik	Bik	Cik	Dik	Eik	Fik
1	0	0	0	0	0

11 < or = 52 xk + (1-Aik)*M pass PASS
87 < or = 6006 xi + (1-Bik)*M pass
18 < or = 6000 xi + (1-Cik)*M pass
3 < or = 6000 xi + (1-Dik)*M pass
8 < or = 6006 xi + (1-Eik)*M pass
8 < or = 6006 xi + (1-Fik)*M pass

Activity	Description	Duration	xi	yi	zi	Pi	Qi	Ri	Dx	Dy	Dz	Af	SI
6	Smoke Dampers C	1	5.5	0	6	5.5	18	2	5.5	18	2		2
23	Signage	1	0	20	4	87	17	4	87	17	4		4

Aik	Bik	Cik	Dik	Eik	Fik
0	1	0	0	0	0

11 < or = 6000 xk + (1-Aik)*M pass FAIL
87 < or = 5.5 xi + (1-Bik)*M fail
18 < or = 6000 xi + (1-Cik)*M pass
37 < or = 6000 xi + (1-Dik)*M pass
8 < or = 6004 xi + (1-Eik)*M pass
8 < or = 6006 xi + (1-Fik)*M pass

Smoke Dampers C
Smoke Conduit F

Day 9

Activity	Description	Duration	xi	yi	zi	Pi	Qi	Ri	Dx	Dy	Dz	Af	SI
5	Smoke Dampers B	1	0	18	6	25	14	2	25	14	2		2
21	Smoke Wiring F	1	17	0	6	70	3	2	70	3	2		2

Aik	Bik	Cik	Dik	Eik	Fik
0	0	0	1	0	0

25 < or = 6017 xk + (1-Aik)*M pass PASS
87 < or = 6000 xi + (1-Bik)*M pass
32 < or = 6000 xi + (1-Cik)*M pass
3 < or = 18 xi + (1-Dik)*M pass
8 < or = 6006 xi + (1-Eik)*M pass
8 < or = 6006 xi + (1-Fik)*M pass

Activity	Description	Duration	xi	yi	zi	Pi	Qi	Ri	Dx	Dy	Dz	Af	SI
5	Smoke Dampers B	1	0	18	6	25	14	2	25	14	2		2
12	Smoke Conduit C	2	0	0	6	11	18	2	5.5	9	1		2

Aik	Bik	Cik	Dik	Eik	Fik
0	0	0	1	0	0

25 < or = 6000 xk + (1-Aik)*M pass PASS
5.5 < or = 6000 xi + (1-Bik)*M pass
32 < or = 6000 xi + (1-Cik)*M pass
9 < or = 18 xi + (1-Dik)*M pass
8 < or = 6006 xi + (1-Eik)*M pass
7 < or = 6006 xi + (1-Fik)*M pass

Activity	Description	Duration	xi	yi	zi	Pi	Qi	Ri	Dx	Dy	Dz	Af	SI
12	Smoke Conduit C	2	0	0	6	11	18	2	5.5	9	1		2
21	Smoke Wiring F	1	17	0	6	70	3	2	70	3	2		2

Aik	Bik	Cik	Dik	Eik	Fik
1	0	0	0	0	0

5.5 < or = 17 xk + (1-Aik)*M pass PASS
87 < or = 6000 xi + (1-Bik)*M pass
9 < or = 6000 xi + (1-Cik)*M pass
3 < or = 6000 xi + (1-Dik)*M pass
7 < or = 6006 xi + (1-Eik)*M pass
8 < or = 6006 xi + (1-Fik)*M pass

Activity	Description	Duration	xi	yi	zi	Pi	Qi	Ri	Dx	Dy	Dz	Af	SI
21	Smoke Wiring F	1	17	0	6	70	3	2	70	3	2		2

23	Signage	1	0	20	4	87	17	4	87	17	4		4

Aik	Bik	Cik	Dik	Eik	Fik
0	0	1	0	0	0

87 < or = 6000 xk + (1-Aik)*M pass PASS
87 < or = 6017 xi + (1-Bik)*M pass
3 < or = 20 xi + (1-Cik)*M pass
37 < or = 6000 xi + (1-Dik)*M pass
8 < or = 6004 xi + (1-Eik)*M pass
8 < or = 6006 xi + (1-Fik)*M pass

Activity	Description	Duration	xi	yi	zi	Pi	Qi	Ri	Dx	Dy	Dz	Af	SI
12	Smoke Conduit C	2	0	0	6	11	18	2	5.5	9	1		2
23	Signage	1	0	20	4	87	17	4	87	17	4		4

Aik	Bik	Cik	Dik	Eik	Fik
0	0	1	0	0	0

5.5 < or = 6000 xk + (1-Aik)*M pass PASS
87 < or = 6000 xi + (1-Bik)*M pass
9 < or = 20 xi + (1-Cik)*M pass
37 < or = 6000 xi + (1-Dik)*M pass
7 < or = 6004 xi + (1-Eik)*M pass
8 < or = 6006 xi + (1-Fik)*M pass

Activity	Description	Duration	xi	yi	zi	Pi	Qi	Ri	Dx	Dy	Dz	Af	SI
5	Smoke Dampers B	1	0	18	6	25	14	2	25	14	2		2
23	Signage	1	0	20	4	87	17	4	87	17	4		4

Aik	Bik	Cik	Dik	Eik	Fik
0	0	0	1	0	0

25 < or = 6000 xk + (1-Aik)*M pass FAIL
87 < or = 6000 xi + (1-Bik)*M pass
32 < or = 6020 xi + (1-Cik)*M pass
37 < or = 18 xi + (1-Dik)*M fail
8 < or = 6004 xi + (1-Eik)*M pass
8 < or = 6006 xi + (1-Fik)*M pass

Smoke Dampers B
Smoke Wiring F
Smoke Conduit C

Day 10

Activity	Description	Duration	xi	yi	zi	Pi	Qi	Ri	Dx	Dy	Dz	Af	SI
12	Smoke Conduit C	1	5.5	0	6	5.5	18	2	5.5	18	2		2
6	Smoke Dampers E	2	76	8	6	12	19	2	6	9.5	1		2

Aik	Bik	Cik	Dik	Eik	Fik
1	0	0	0	0	0

11	< or =	76 xk + (1-Aik)*M	pass	PASS
82	< or =	6006 xi + (1-Bik)*M	pass	
18	< or =	6008 xi + (1-Cik)*M	pass	
17.5	< or =	6000 xi + (1-Dik)*M	pass	
8	< or =	6006 xi + (1-Eik)*M	pass	
7	< or =	6006 xi + (1-Fik)*M	pass	

Activity	Description	Duration	xi	yi	zi	Pi	Qi	Ri	Dx	Dy	Dz	Af	SI
12	Smoke Conduit C	1	5.5	0	6	5.5	18	2	5.5	18	2		2
23	Signage	1	0	20	4	87	17	4	87	17	4		4

Aik	Bik	Cik	Dik	Eik	Fik
0	1	0	0	0	0

11	< or =	6000 xk + (1-Aik)*M	pass	FAIL
87	< or =	5.5 xi + (1-Bik)*M	fail	
18	< or =	6020 xi + (1-Cik)*M	pass	
37	< or =	6000 xi + (1-Dik)*M	pass	
8	< or =	6004 xi + (1-Eik)*M	pass	
8	< or =	6006 xi + (1-Fik)*M	pass	

Activity	Description	Duration	xi	yi	zi	Pi	Qi	Ri	Dx	Dy	Dz	Af	SI
6	Smoke Dampers E	2	76	8	6	12	19	2	6	9.5	1		2
23	Signage	1	0	20	4	87	17	4	87	17	4		4

Aik	Bik	Cik	Dik	Eik	Fik
0	1	1	0	0	0

82	< or =	6000 xk + (1-Aik)*M	pass	FAIL
87	< or =	76 xi + (1-Bik)*M	fail	
17.5	< or =	20 xi + (1-Cik)*M	pass	
37	< or =	6008 xi + (1-Dik)*M	pass	
7	< or =	6004 xi + (1-Eik)*M	pass	
8	< or =	6006 xi + (1-Fik)*M	pass	

Smoke Conduit C
Smoke Dampers E

Day 11

Activity	Description	Duration	xi	yi	zi	Pi	Qi	Ri	Dx	Dy	Dz	Af	SI
11	Smoke Conduit B	2	0	18	6	25	14	2	12.5	7	1		2
6	Smoke Dampers E	1	82	8	6	6	19	2	6	19	2		2

Aik	Bik	Cik	Dik	Eik	Fik
1	0	0	0	0	0

12.5 < or = 82 xk + (1-Aik)*M pass PASS
88 < or = 6000 xi + (1-Bik)*M pass
25 < or = 6008 xi + (1-Cik)*M pass
27 < or = 6018 xi + (1-Dik)*M pass
7 < or = 6006 xi + (1-Eik)*M pass
8 < or = 6006 xi + (1-Fik)*M pass

Activity	Description	Duration	xi	yi	zi	Pi	Qi	Ri	Dx	Dy	Dz	Af	SI
11	Smoke Conduit B	2	0	18	6	25	14	2	12.5	7	1		2
18	Smoke Wiring C	1	0	0	6	11	18	2	11	18	2		2

Aik	Bik	Cik	Dik	Eik	Fik
0	0	0	1	0	0

12.5 < or = 6000 xk + (1-Aik)*M pass PASS
11 < or = 6000 xi + (1-Bik)*M pass
25 < or = 6000 xi + (1-Cik)*M pass
18 < or = 18 xi + (1-Dik)*M pass
7 < or = 6006 xi + (1-Eik)*M pass
8 < or = 6006 xi + (1-Fik)*M pass

Activity	Description	Duration	xi	yi	zi	Pi	Qi	Ri	Dx	Dy	Dz	Af	SI
6	Smoke Dampers E	1	82	8	6	6	19	2	6	19	2		2
18	Smoke Wiring C	1	0	0	6	11	18	2	11	18	2		2

Aik	Bik	Cik	Dik	Eik	Fik
0	1	0	0	0	0

88 < or = 6000 xk + (1-Aik)*M pass PASS
11 < or = 82 xi + (1-Bik)*M pass
27 < or = 6000 xi + (1-Cik)*M pass
18 < or = 6008 xi + (1-Dik)*M pass
8 < or = 6006 xi + (1-Eik)*M pass
8 < or = 6006 xi + (1-Fik)*M pass

Activity	Description	Duration	xi	yi	zi	Pi	Qi	Ri	Dx	Dy	Dz	Af	SI
23	Signage	1	0	20	4	87	17	4	87	17	4		4

18	Smoke Wiring C	1	0	0	6	11	18	2	11	18	2	2

Aik	Bik	Cik	Dik	Eik	Fik
0	1	0	0	1	0

87 < or = 6000 xk + (1-Aik)*M pass FAIL
11 < or = 0 xi + (1-Bik)*M fail
37 < or = 6000 xi + (1-Cik)*M pass
18 < or = 6020 xi + (1-Dik)*M pass
8 < or = 6 xi + (1-Eik)*M fail
8 < or = 6004 xi + (1-Fik)*M pass

Smoke Wiring C
Smoke Dampers E
Smoke Conduit B

Day 12

Activity	Description	Duration	xi	yi	zi	Pi	Qi	Ri	Dx	Dy	Dz	Af	SI
11	Smoke Conduit B	1	13	18	6	12	14	2	12	14	2		2
23	Signage	1	0	20	4	87	17	4	87	17	4		4

Aik	Bik	Cik	Dik	Eik	Fik
0	1	0	0	0	0

24.5 < or = 6000 xk + (1-Aik)*M pass FAIL
87 < or = 12.5 xi + (1-Bik)*M fail
32 < or = 6020 xi + (1-Cik)*M pass
37 < or = 6018 xi + (1-Dik)*M pass
8 < or = 6004 xi + (1-Eik)*M pass
8 < or = 6006 xi + (1-Fik)*M pass

Smoke Conduit B

Day 13

Smoke Wiring B
Signage

Appendix C: Permission/Indemnification letter

CONFIDENTIALITY AGREEMENT

This Agreement is entered into by and between The Catholic University of America (CUA), and Baltimore County Public Schools and any affiliates (hereinafter referred to as the "Company"), (collectively referred to as "the parties").

WHEREAS the parties are interested in sharing information relating to project scheduling and its respective uses; and it will be necessary for the parties to disclose to one another information, materials and technology which are confidential and proprietary to the other and the premature entry of which into the public domain would jeopardize property rights of the other.

NOW THEREFORE, in consideration of the mutual agreements and covenants hereinafter set forth, the parties agree as follows:

1. PUBLICATION AND ACADEMIC RIGHTS

a. The parties agree that all writings and drawings for non-commercial purposes (hereinafter referred to as "scholarly publications") that are prepared by CUA shall be disclosed to Company prior to publication by forty five (45) days' advance written notice by certified mail. Company shall notify University within thirty (30) days of receipt of such materials whether they describe any confidential information.

b. CUA agrees that all scholarly publications shall be prepared for publication in such a manner that no original information or data are described, depicted, or discernable. Company agrees that CUA has the right to prepare and publish scholarly publications that contain significantly processed, aggregate, average, or artificially created information or data that exhibit similar statistical properties to the original information or data supplied by Company. University investigators may discuss the Research Program with other investigators for scientific or research purposes but shall not reveal information which is Company's Confidential Information under Article 2.

2. CONFIDENTIAL INFORMATION

a. The parties may wish to disclose confidential information to each other in connection with work contemplated by this Agreement ("Confidential Information"). Each party will use reasonable efforts to prevent the disclosure of the other party's Confidential Information to third parties for a period of three (3) years after the termination of this Agreement, provided that the recipient party's obligation shall not apply to information that:

i. is not disclosed in writing or reduced to writing and marked with an appropriate confidentiality legend within thirty (30) days after disclosure;
ii. is already in the recipient party's possession at the time of disclosure;
iii. is or later becomes part of the public domain through no fault of the recipient party;
iv. is received from a third party having no obligations of confidentiality to the disclosing party;
v. is independently developed by the recipient party; or
vi. is required by law or regulation to be disclosed.

b. In the event that information is required to be disclosed pursuant to subsection (vi), the party required to make disclosure shall notify the other to allow that party to assert whatever exclusions or exemptions may be available to it under such law or regulation.

IN WITNESS WHEREOF, the undersigned, with authority to bind their respective institutions, has agreed, accepted and signed this Agreement this 23rd day of December, 2011.

For Company	For CUA
Kurt Buckle (signature)	Ralph Albano (signature)
Signature	Signature
Kurt Buckle	Ralph Albano
Name	Name
Administrator of Engineering & Construction	Associate Provost for Research
Title	Title

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References

Aickelin, U., Dowsland, K., 2002, “Enhanced Direct and Indirect Genetic Algorithm Approaches for a Mall Layout and Tenant Selection Problem.” *Journal of Heuristics*, n 8, p 503-514.

Akinci, B., Fischer, M., Zabelle, T., 1998, “Proactive Approach for Reducing Non-Value Adding Activities Due to Time-Space Conflicts.” Proceedings IGLC.

(a)Akinci, B., Fischer, M., Kunz, J., Levitt, R., Carlson, R., April 2002, “Formalization and Automation of Time-Space Conflict Analysis” *Journal of Computing in Civil Engineering*, v 16, n 2, p 124-134.

(b)Akinci, B., Fischer, M., Kunz, J., Levitt, R., July/August 2002, “Representing Work Spaces Generically in Construction Method Models” *Journal of Construction Engineering and Management*, v 128, n 4, p 296-305.

(c)Akinci, B., Fischer, M., Kunz, J., July/August 2002, “Automated Generation of Work Spaces Required by Construction Activities.” *Journal of Construction Engineering and Management*, v 128, n 4, p 306-315.

Arditi, D., Tokdemir, O.B., Suh, K., November/December 2002, “Challenges in Line-of-Balance Scheduling.” *Journal of Construction Engineering and Management*, v 128, n 6, p 545-556.

Castillo, I., Kampas, F., Pinter, J.D., 2007, “Solving Circle Packing Problems by Global Optimization: Numerical Results and Industrial Applications.” *European Journal of Operational Research 191 (2008)*, p 786-802,.

Chau, K.W., Anson, M., Zhang, J.P., July/August 2004, “Four Dimensional Visualization of Construction Scheduling and Site Utilization.” *Journal of Construction Engineering and Management*, v 130, n 4, p 598-606.

Cheng, M., Su, C., You, H., January/February 2003, “Optimal Project Organizational Structure for Construction Management.” *Journal of Construction Engineering and Management*, v 129, n 1, p 70-79.

Chianq, Yi-Jen, Klosowski, J.T., Chanqkil, L., Mitchell, J.S.B., 1997, "Geometric Algorithms for Conflict Detection/Resolution in Air Traffic Management." *Proceedings of the 36th IEEE Conference on Decision and Control (Cat. No.97CH36124)*, p 1835-1840 vol.2.

Chua, D.K.H., Godinot, M., January 2006, "Use of a WBS Matrix to Improve Interface Management in Projects." *Journal of Construction Engineering and Management*, v 132, n 1, p 67-78.

Demeulemeester, E., De Reyck, B., Foubert, B., Herroelen, W., Vanhoucke, M., November 1998, "New Computational Results on the Discrete Time/Cost Trade-off Problem in Project Networks." *Journal of the Operational Research Society*, v 49, n 11, p 1153-1163.

Easa, S.M., June 1989, "Resource Leveling in Construction by Optimization." *Journal of Construction Engineering and Management*, v 115, n 2, p 302-316.

Echeverry, Diego, Ibbs, C. William, Kim, Simmon, March 1991, "Sequencing Knowledge for Construction Scheduling." *Journal of Construction Engineering and Management*, v 117, n 1, p 118-130.

Elazouni, A.M., Gab-Allah, A.A., February 2004, "Finance-Based Scheduling of Construction Projects Using Integer Programming." *Journal of Construction Engineering and Management*, v 130, n 1, p 15-24.

Elbeltagi, E., Hegazy, T., July/August 2004, "Dynamic Layout of Construction Temporary Facilities Considering Safety." *Journal of Construction Engineering and Management*, v 130, n 4, p 118-130.

El-Diraby, T.E., March 2006, "Web-Services Environment for Collaborative Management of Product Life-Cycle Costs." *Journal of Construction Engineering and Management*, v 132, n 3, p 300-313.

El-Rayes, Khaled, Jun, Dho Heon, November 2009, "Optimizing Resource Leveling in Construction Projects." *Journal of Construction Engineering and Management*, v 135, n 11, p 1172-1180.

El-Rayes, K., Moselhi, O., January/February 2001, "Optimizing Resource Utilization for Repetitive Construction Projects." *Journal of Construction Engineering and Management*, v 127, n 1, p 18-27.

Fan, S., Tserng, H.P., January 2006, “Object-Oriented Scheduling for Repetitive Projects with Soft Logics.” *Journal of Construction Engineering and Management*, v 132, n 1, p 35- 47.

Fischetti, M., Luzzi, I., July 2008, “Mixed-Integer Programming Models for Nesting Problems.” *J Heuristics (2009) 15*, Springer Science+Business Media, LLC 2008, p 201-226.

Formoso, C.T., Soibelman, L., De Cesare, C., Isatto, E.L., July/August 2002, “Material Waste in Building Industry: Main Causes and Prevention.” *Journal of Construction Engineering and Management*, v 128, n 4, p 316-325.

Galloway, P.D., July 2006, “Survey of the Construction Industry Relative to the Use of CPM Scheduling for Construction Projects.” *Journal of Construction Engineering and Management*, v 132, n 7, p 697-711.

Gehringer, A., 1958, “Line of Balance.” *Navy Management Review*, Vol IV, Issue 4, p 18-23.

Goodman, E. D., Tetelbaum, A. Y., Kureichik, V. M., July 1994,“A Generic Algorithm Approach to Compaction, Bin Packing and Nesting Problems.” Technical Report #940702, Case Center for Computer-Aided Engineering and Manufacturing, Michigan State University.

Guo, S., July/August 2002, “Identification and Resolution of Work Space Conflicts in Building Construction.” *Journal of Construction Engineering and Management*, v 128, n 4, p 287-295.

Harmelink, D.J., July/August 2001, “Linear Scheduling Model: Float Characteristics.” *Journal of Construction Engineering and Management*, v 127, n 4, p 255-260.

Hanks, D., February 1999, “Soft Logic – An Overview.” *Cost Engineering*, v 41, n 2, p 37-39.

Harris, R.B., June 1990, “Packing Method for Resource Leveling (Pack)” *Journal of Construction Engineering and Management*, v 116, n 2, p 331-350.

Hegazy, T., Ersahin, T., November/December 2001, “Simplified Spreadsheet Solutions. II. Overall Schedule Optimization.” *Journal of Construction Engineering and Management*, v 127, n 6, p 469-475.

Hegazy, T., May/June 1999, “Optimization of Resource Allocation and Leveling Using Generic Algorithms.” *Journal of Construction Engineering and Management*, v 125, n 3, p 167-175.

Hiyassat, M., May/June 2001, “Applying Modified Minimum Moment Method to Multiple Resource Leveling.” *Journal of Construction Engineering and Management*, v 127, n 3, p 192-198.

Huang, R., Sun, K., June 2006, “Non-Unit-Based Planning and Scheduling of Repetitive Construction Projects.” *Journal of Construction Engineering and Management*, v 132, n 6, p 585-597.

Jergeas, G., Van der Put, J., July/August 2001, “Benefits of Constructability on Construction Projects.” *Journal of Construction Engineering and Management*, v 127, n 4, p 281-290.

Jiang, G., Shi, J., September 2005, “Exact Algorithm for Solving Project Scheduling Problems under Multiple Resource Constraints.” *Journal of Construction Engineering and Management*, v 131, n 9, p 986-992.

Kandil, A., El-Rayes, K., May 2006, “Parallel Genetic Algorithms for Optimizing Resource Utilization in Large-Scale Construction Projects.” *Journal of Construction Engineering and Management*, v 132, n 5, p 491-498.

Kanoglu, A., 2003, “An Integrated System for Duration Estimation in Design/Build Projects and Organizations.” *Engineering, Construction and Architectural Management*, v 10, n 4.

Kelly, J., Walker, M. February 1989, “The Origins of CPM – A Personal History.” *The PM Network*, v3, n 2, p7-22.

Kim, Kyunghwan, de la Garza, Jesus, M., September/October 2003, “Phantom Float.” *Journal of Construction Engineering and Management*, v 129, n 5, p 507-517.

Koo, B., Fischer, M., July/August 2000, “Feasibility Study of 4D CAD in Commercial Construction.” *Journal of Construction Engineering and Management*, v 126, n 4, p 251-260.

Labbé, M., Laporte, G., Martello, S., May 2002, “Upper Bounds and Algorithms for the Maximum Cardinality Bin Packing Method.” *European Journal of Operational Research*, v 149 (2003), p 490-498.

Lee, H., Ryu, H., Yu, J., Kim, J., November 2005, “Method for Calculating Schedule Delay Considering Lost Productivity.” *Journal of Construction Engineering and Management*, v 131, n 11, p 1147-1154.

Leu, Sou-Sen, Chen, An-Ting, Yang, Chung-Huei, July 1999, “Fuzzy Optimal Model for Resource-Constrained Scheduling.” *Journal of Construction Engineering and Management*, v 13, n 3, p 207-216.

Lu, M., Lu, H., July/August 2003, “Resource-Activity Critical-Path Method for Construction Planning.” *Journal of Construction Engineering and Management*, v 129, n 4, p 412-420.

Lu, M., Lam, Hoi-Ching, September 2009, “Transform Schemes Applied on Non-Finish-to-Start Logical Relationships in Project Network Diagrams.” *Journal of Construction Engineering and Management*, v 135, n 9, p 863-873.

Lucko, G., Orozco, A., May 2009, “Float Types in Linear Schedule Analysis with Singularity Functions.” *Journal of Construction Engineering and Management*, v 135, n 5, p 368-377.

Mallasi, Z., Dawood, N. “A Generic Inclusion of Space Strategies with Activity Execution Patterns in 4D Tools.” *Construction Informatics Digital Library*, http://itc.scix.net/, paper w78-2003-213.content.

Mawdesley, M.J., Al-jibouri, S.H., Yang, H., September/October 2002, “Generic Algorithms for Construction Site Layout in Project Planning.” *Journal of Construction Engineering and Management*, v 128, n 5, p 418-426.

Moselhi, O., El-Rayes, K., December 1993, “Scheduling of Repetitive Projects with Cost Optimization.” *Journal of Construction Engineering and Management*, v 119, n 4, p 681-697.

Nassar, K.M., Hegab, M.Y., June 2006, “Developing a Complexity Measure for Project Schedules.” *Journal of Construction Engineering and Management*, v 132, n 6, p 554-561.

Nepal, M.P., Park, M., Son, B., February 2006, “Effects of Schedule Pressure on Construction Performance.” *Journal of Construction Engineering and Management*, v 132, n 2, p 182-188.

Nosbisch, M.R., Winter, R.M., July 2006, “Managing Resource Leveling.” *Cost Engineering*, v 48, n 7, p 24-34.

O'Brien, W.P., Fischer, M.A., September/October 2000, "Importance of Capacity Constraints to Construction Cost and Schedule." *Journal of Construction Engineering and Management*, v 126, n 5, p 366-373.

Pollard, C., Green, T.J., Conway, R.G., "Channel Tunnel Construction Planning and Logistics." Proceedings of the Institution of Civil Engineers, 1992, p 103-126.

Que, B.C., March/April 2002, "Incorporating Practicability into Genetic Algorithm-Based Time-Cost Optimization." *Journal of Construction Engineering and Management*, v 128, n 2, p 139-143.

Riley, D., Sanvido, V., December 1995, "Patterns of Construction-Space use in Multistory Buildings." *Journal of Construction Engineering and Management*, v121, n 4, p464-473.

Sabzehparvar, M., Seyed-Hosseini, S. M., June 2008, "A Mathematical Model for the Multi-Mode Resource-Constrained Project Scheduling Problem with Mode Dependent Time Lags." *Journal of Superconducting*, v44, n 3, p 257-273.

Sacks, R., Partouche, R., "Empire State Building Project: Archetype of Mass Construction", *Journal of Construction Engineering and Management*, v136, n 6, June 1, 2010, p702-710.

Shah, K.A., Farid, F., Baugh, J.W., 1993, "Optimal Resource Leveling Using Integer-Linear Programming." *Computing in Civil and Building Engineering*, p 501-508.

Song, Y., Chua, D.K.H., December 2006, "Modeling of Functional Construction Requirements for Constructability Analysis", *Journal of Construction Engineering and Management*, 1314-1326.

Taylor, W.C (2011). "Practically Radical: Not-so-crazy ways to transform your company, shake up your industry, and challenge yourself". HarperCollins Publishers.

Tam, C.M., Tong, T.K.L., 2005, "Multiple GMDH Models for Estimating Resource Requirements." *Construction Innovation*, v 5, p 115-131.

Thabet, W. Y., Beliveau, Y. J., January 1997, "SCaRC: Space-Constrained Resource-Constrained Scheduling System", *Journal of Computing in Civil Engineering*, v 11, n 1, 48-59.

Thabet, W. Y., Beliveau, Y. J., March 1994, "Modeling Work Space to Schedule Repetitive Floors in Multistory Buildings", *Journal of Construction Engineering and Management*, 96-116.

Thabet, W. Y., Beliveau, Y. J., June 1993, "A Model to Quantify Work Space Availability for Space – Constrained Scheduling within a CAD Environment", *Computing in Civil and Building Engineering*, Proceedings of the Fifth International Conference (V-ICCCBE), 110-116.

Tsai, Jung-Fa, Li, Han-Lin, September 2006, "A Global Optimization Method for Packing Problems." *Engineering Optimization*, v 38, n 6, p 687-700.

Vanhoucke, M., January 2006, "Work Continuity Constraints in Project Scheduling." *Journal of Construction Engineering and Management*, v 132, n 1, p 14-25.

Wei, L., Zhang, D., Chen, Q., March 2008, "A Least Wasted First Heuristic Algortihm for the Rectangular Packing Problem." Computers & Operations Research, n 36, p 1608-1614.

Winch, G.M., North, S., May 2006, "Critical Space Analysis." *Journal of Construction Engineering and Management*, v 132, n 5, p 473-480.

Yamin, R.A., Harmelink, D.J., September/October 2001, "Comparison of Linear Scheduling Model (LSM) and Critical Path Method (CPM)." *Journal of Construction Engineering and Management*, v 127, n 5, p 374-381.

Zouein, P.P., Tommelein, I.D., March/April 2001, "Improvement Algorithm for Limited Space Scheduling." *Journal of Construction Engineering and Management*, v 127, n 2, p 116-124.