OPTIMISED CRITICAL CHAIN METHOD IN SCHEDULING MANAGEMENT OF PIPELINE PROJECT

By

Mr. Yuqiang WEI

A Thesis Submitted in Partial Fulfillment of the Requirements

for Master of Engineering (ENGINEERING MANAGEMENT)

Department of INDUSTRIAL ENGINEERING AND MANAGEMENT

Graduate School, Silpakorn University

Academic Year 2019

-

โดย

Mr.Yuqiang Wei

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรวิศวกรรมศาสตรมหาบัณฑิต
สาขาวิชาการจัดการงานวิศวกรรม แผน ก แบบ ก 2 ปริญญามหาบัณฑิต
ภาควิชาวิศวกรรมอุตสาหการและการจัดการ
บัณฑิตวิทยาลัย มหาวิทยาลัยศิลปากร
ปีการศึกษา 2562

OPTIMISED CRITICAL CHAIN METHOD IN SCHEDULING MANAGEMENT OF PIPELINE PROJECT

By

Mr. Yuqiang WEI

A Thesis Submitted in Partial Fulfillment of the Requirements
for Master of Engineering (ENGINEERING MANAGEMENT)
Department of INDUSTRIAL ENGINEERING AND MANAGEMENT
Graduate School, Silpakorn University
Academic Year 2019

Title	Optimised Critical Chain Method in Scheduling Management of Pipeline Project
By	Yuqiang WEI
Field of Study	(ENGINEERING MANAGEMENT)
Advisor	Assistant Professor CHOOSAK PORNSING , Ph.D.

Graduate School Silpakorn University in Partial Fulfillment of the Requirements for the Master of Engineering

.... Dean of graduate school

(Associate Professor Jurairat Nunthanid, Ph.D.)

Approved by

.... Chair person

(Associate Professor PRACHUAB KLOMJIT , Ph.D.)

.... Advisor

(Assistant Professor CHOOSAK PORNSING , Ph.D.)

.... External Examiner

(Assistant Professor Tongtang Tonglim , Ph.D.)

61405302 : Major (ENGINEERING MANAGEMENT)
Keyword : SCHEDULING, PROJECT MANAGEMENT, PIPELINE, CRITICAL CHAIN METHOD

MR. YUQIANG WEI : OPTIMISED CRITICAL CHAIN METHOD IN SCHEDULING MANAGEMENT OF PIPELINE PROJECT THESIS ADVISOR : ASSISTANT PROFESSOR CHOOSAK PORNSING, Ph.D.

Nowadays, scheduling management becomes very essential for project management, which is very important as well for pipeline construction to improve the performance under the condition of resource constraints since a large number of pipelines have been expected to be completed within a certain period for petroleum transmission with the increment of energy demand. The technologies of CPM (Critical Path Method) and PERT (Program Evaluation and Review Technique) have been applied for scheduling management including the pipeline management. However, many projects were still failed to complete as the expected date by application of CPM and PERT due to ignorance the problem of insufficient resources in the project and the data selected for analysis seemed more subjective. Hence, CCM (Critical Chain Method) was developed which would emphasize the resources required to execute project task. This thesis is taken HDD (Horizontal Drill Crossing) construction as an example to study the scheduling management under constrained resources based on Critical Chain Method, and it aims to find out the solution to identify the critical chain and set up the buffers for optimizing the resources configuration and lower the risk of delay in completion. With the application of CCM method, the total duration would be shortened by 30% and the duration and cost of standby would be reduced by 50%. Furthermore, it Relieved the workload of management and most of stakeholder from different teams would like to accept it to arrange the resource under construction accordingly to improve the performance.

ACKNOWLEDGEMENTS

Many people have offered me valuable help in my thesis writing, including my tutor, my classmates and my family.

Firstly, I would like to give my sincere gratitude to my tutor, Assistant Professor Choosak Pornsing, PhD at Faculty of Engineering and Industrial Technology of Silpakorn University, Thailand, who give me great help by providing me great value advice and inspiration of new ideas with extraordinary patience and consistent encouragement. It is his suggestions that draw my attention to a number of deficiencies and make many things clearer. Without his strong support, the findings could not been present here.

Then, My heartfelt thanks also go to Assoc.Prof Prachuab Klomjit and Assistant Professor Kanate Puntusavase, my instructor of our courses, for their enlightening lectures from which I have benefited a great deal.

Besides, I am extremely grateful for all tutors who gave lectures to us in Silpakorn University for their comments and wise advices. I also owe my sincere gratitude to my friends and my fellow classmates who gave me their invaluable assistance throughout the preparation of the original manuscript.

Finally, my thanks would go to my beloved family for their loving considerations and great confidence in me all through these years.

Yuqiang WEI

TABLE OF CONTENTS

List of Figures

List of Tables

Page

Chapter 1 Introduction

1.1 Background of the Research

1.1.1 Global Energy Demand

In recent years, the global production of oil and gas is increasing stably. It was reported that Gross recoverable resource of oil is about 315.5 billion tons and 518.8 trillion square meters for gas around the world. Till the end of the year 2015, the proven recoverable reserves of oil all over the world were about 346.5 billion tons and 100 billion tons to be discovered. Remaining recoverable reserves was 200.8 billion tons. On the other hand, the proven recoverable reserves of gas all over the world were about 301.3 trillion square meters and 158.7 trillion square meters to be discovered. Remaining recoverable reserves was 221 trillion square meters (Wang Jianzhong, 2019).

In the year 2014, gross production of oil is 4.22 billion tons, 4.21 billion tons was for consumption, and the transaction amount is 2.78 billion tons. Additionally, the gross production of gas is 3.46 trillion square meters, 3.39 trillion square meters for consumption and transaction amount is 967.2 billion square meters. However, the distribution of petroleum resources nowadays could be divided into two part overall the world, one of which is the region of Middle East-Middle Asia-Russia and the other is the region of America. In the region of Middle East-Middle Asia-Russia as the biggest district of petroleum production, the production is supplied to the district of Asian-Pacific and Europe where the amount of consumption is greater than production as an import region that increment of consumption is growing fastest, but the Middle-East district is the main export area where the production is over the consumption. It was basically kept in balance between the consumption and production in Eur-asia continent. But petroleum resource is centrally distributed in areas of Russia, Middle-Asia and the North Sea, and mainly consumption is in developed countries in Europe. It was reported in 2013 that the oil production in this Region accounted for 46% of global production, 39% for gas production, and the amount of oil transaction accounted for 50% of the global transaction, 44% for the gas transaction. By contrast to the petroleum resources in the region of America, they were mainly supplied in its own area. It was reported in the year 2013 that the oil production in this district accounted for 28% of global production, 32% for gas production and the amount of oil for export in the region accounted for 20% of the global trading market, 16% for gas (Z. Quezhi, Peixia, D. , Hongju, W. , Qiuyang, L. I. , Chuanxi, Z. , & Ning, S. , et al, 2015).

Data of global import and export trade of petroleum resource had been collected in the year 2013 which shown in Table 1.1.

Table 1.1 Global Amount of Petroleum Transaction in the Year 2013

Region	Oil Production (Million Ton)				Gas Production (Billion Cube Meter)			
	Import of Crude Oil	Import of Product Oil	Export of Crude Oil	Export of Product Oil	Import by Pipeline	Import by LNG	Export by Pipeline	Export by LNG
North America	412	138.9	198.1	186.7	123.3	11.6	123.3	0.1
Mid and South America	25.1	78	151.3	32	18.6	19.6	18.6	25.5
Europe	463.8	159	18.9	96.6	397	51.4	194.3	8.8
Soviet Union	0.2	6.1	300.1	124.6	84.2	-	279.8	14.2
Mid-East	10.8	41.1	855.3	108.2	25.1	4.5	29.3	134.1
Africa	16.1	52.3	306.9	31	6.4	-	36.6	46.5
Asian-Pacific	691.2	404.9	244	-	55.9	177.2	28.6	95.9
Global	1878.3	858.8	1878.3	858.8	710.6	325.3	710.6	325.3

Source: (Baoli., 2016)

In accordance with the data shown in Table 1.1, the production in the region of America mainly satisfied the consumption demand of the USA and the production in the region of Middle-East, Middle-Asia and Russia mainly satisfied the demand of the region of Europe and Asian-Pacific. Gas was mainly transmitted by Pipelines for the transaction. The disequilibrium distribution between global production and consumption of oil and gas caused the increment of the transaction of petroleum production trading. Pipelines were developed and planned for transmission as per the global petroleum resource distribution.

1.1.2 Development of petroleum pipeline

The development period of pipeline construction started from the 1940s in the period of World War II, especially in North America where the pipelines were developed fastest in the period. By the year 1966, pipelines had been constructed all around the USA which indicated that the network of transmission pipeline had been initially established in America. Some pipelines were developed as well in Russia, said the Soviet Union, in the 1940s which made a great contribution to the victory of World War II.

At the beginning of the 1940s, two buried pipelines which were named as Big Inch and Little Big Inch pipeline were constructed in America for supplying the energy and ducking the attack from the enemy. These two pipelines were completed in the year 1942 to supply the petroleum resource from Texas to Pennsylvania. Mainline of Big Inch pipeline is 2,018 km in length, 24 inches in diameter, attaching branches 357 km in length and mainline of Little Big Inch pipeline is 2374 km in length attaching branches 385 km in length, 20 inches in diameter. During the same period, a gas pipeline from Saratoga to Moscow was constructed in the Soviet Union, and furthermore, Druzhba Pipeline, 9,912 km in length and well known as the Friendship Pipeline and the Comecon Pipeline, was constructed and put into use in 1964 in the Soviet Union which was the longest pipeline in distance for crude oil transmission by now.

In the year 1977, the Trans-Alaska Pipeline was built from Prudhoe Bay to Valdez in Alaska which started construction from the year 1974. This is the first oil transmission pipeline that constructed into Arctic circle, 1281 km in length and 48-inch in diameter, including 681 km above ground pipeline and 600 km buried pipeline. Petroline in Saudi Arabia, 1,202 km in length and named as East-West Crude Oil Pipeline as well, was put into production in the year 1983 and it became the first oil transmission pipeline crossing the desert in the world. Moreover, a parallel pipeline was constructed in 1987 as well.

In recent years, the longest offshore gas transmission in the world, Nord Stream, was inaugurated in the year 2011 which is from Vyborg in the Russian Federation to Greifswald in Germany and the length is about 1,222 km. Russia has built the largest scale of gas transmission network in the world.

Till the year 2017, 3,800 pipelines have been constructed around the world, over 1.9 million km in length totally, in which gas transmission accounted for 64.9%, and Most of pipelines were distributed mainly in regions of North America, Russia, Middle-Asia, Europe and Asian-Pacific, and accounted for 43%, 15%, 14%, 14% (Z. Quezhi, Chao, W. , Qiuyang, L. , Xueqin, Z. , Libo, Z. , Shanpu, G, 2017).

Table 1.2 Global Pipeline Distribution under Construction in 2017

Region/County	Length of Pipeline, Dia.< 30-inch, km		Length of Pipeline, Dia.> 30-inch, km	
	Gas pipeline	Oil pipeline	Gas pipeline	Oil pipeline
USA	928.2	2762.6	193.4	0
Canada	87.6	0	53.1	346.5
Europe	543.6	256	482.6	0
Asian-Pacific	992.8	0	1842.2	102.5
South America	164.8	385.4	746.2	0
Mid-East and Africa	42.6	148	643.8	110.4

Source: (Z. Quezhi, Chao, W. , Qiuyang, L. , Xueqin, Z. , Libo, Z. , Shanpu, G, 2017)

It was forecasted that during the period from 2017 to 2022, the increment rate of pipeline construction will not lower than 1.2%, but in Asian-Pacific district it will be the next largest scale marketing place of pipeline requirement and the increment rate will not lower than 4.0% considering the increasing demand of countries development requirement. So about 180 thousand kilometers is forecasted to be constructed in the following 4 years (Lin Yan, 2017).

Table 1.3 Proposed Pipeline to be Constructed from the year 2017 to 2022

Region	Length (km)	Percentage (%)
North America	57,645	39.7%
Europe	2,637	13.3%
Asian-Pacific	48,623	32.6%
South America	8,963	5.2%
Mid-East & Africa	20,358	9.2%

Source: (Lin Yan, 2017)

1.1.3 Project Management for Pipeline Construction

For one specific pipeline project nowadays, in order to achieve the objectives of the project in respects of scope, schedule, quality, and cost, etc., not only the knowledge and techniques have been applied for project management but more and more skills and tools also have been citated and developed as well for pipeline construction management. Furthermore, some software used for project management has been applied in pipeline project management which enables projects to be executed more effectively and efficiently. However, pipeline construction has some specific characteristics of a project like long distances, long duration, complicated procedures, complex and varied geographical conditions, public communities' coordination and liaison, which cause difficulties for management. Therefore, even though knowledge of pipeline management has been being developed in recent years, but it still is complicated to manage a pipeline project.

In addition, a large number of pipelines have been expected to be completed within a certain period for petroleum transmission to satisfy the increment of energy demand that promotes the development of the pipeline industry as well as other related industries. But for such an opportunity, it is impossible for enterprises to invest all their resources to build pipeline-related production lines considering the limited resources and long-term sustainable development because the demand for pipelines will not either expand without limitation. Hence, the available resources for pipeline construction are bound to be limited, which causes that the project schedule will often not be implemented as planned due to the lack of resource acquisition so that the pipeline couldn't be completed and inaugurated as expected date. As a result, the cost of the project and the return on investment will be affected that decrease the benefit from the project.

Hence, Scheduling management becomes very important essential for pipeline project management to improve the performance of a pipeline project under the condition of resource constraints.

1.2 Scheduling Management in Pipeline Projects

The difficulties of scheduling management in pipeline projects is to define the scope of processes and the relationship between processes since many processes are intersecting and parallel in practically. Critical Path Method, abbreviated CPM, was developed to provide the guidance that scheduling management should identify the critical tasks and critical paths in all processes that minimize the entire project duration and focus on monitoring and managing the identified critical tasks along critical paths. Program Evaluation and Review Technique, or PERT for short, was developed as well which could be applied to improve the estimation of processes' duration by calculating with optimistic, most likely and pessimistic values. However, many projects that were uncertain and risky were failed to complete as the expected date even though the application of CPM and PERT was in proper manners because of the inadequacy of the methods that the methods could logically link the relationship between processes and tasks but ignores the problem of insufficient resources in the project and the data selected for analysis seemed more subjective.

According to studies of project management methods based on CPM and PERT by Standish Group and others as of 1998, only 44% of projects typically finish on time. Projects typically complete at 222% of the duration originally planned, 189% of the original budgeted cost, 70% of projects fall short of their planned scope (technical content delivered), and 30% are cancelled before completion (StandishGroup).

The scheduling technologies like Critical Path Method (CPM) and Program Evaluation and Review Technique (PERT) had been developed and applied in pipeline construction project to provide the guidance to identify the critical tasks and critical paths in all processes that minimize the entire project duration and improve the estimation of processes' duration. However, many projects were still failed to complete as the expected date by application of CPM and PERT due to ignorance the problem of insufficient resources in the project and the data selected for analysis seemed more subjective. Hence, CCM (Critical Chain Method) could be applied in pipeline scheduling management which emphasizes the resources required to execute project task.

1.3 Objective of the Research

The objective of this thesis is to take HDD crossing construction as an example to study the scheduling management under constrained resources for pipeline project based on Critical Chain Method. The scheduling model for HDD construction will be established as a basis of the study.

The key points of the thesis will be as below as per the theory of CCM:

1) To identify the critical chain activities of HDD crossing construction.
2) To find out the method for setting up buffers.
3) To find out the method of monitoring the buffers during the execution of project.
4) To find out the advantages and the differences of Critical Chain Method comparing Critical Path Method in scheduling management.

Chapter 2 Literature Review

2.1 Overview

In order for best understanding the concept of scheduling management, it would be necessary to review the historical development of methodology and the typical methodologies that developed for project scheduling management.

At the early stage, there might be no the concept the scheduling management, but human had accomplished the project with the understanding of activities and sequencing so that all those activities could be organized integrally to complete the project as the due date that expected.

The Great Pyramid of Giza in Egypt is the best example which were built over 3,800 years ago. You may not be able to imagine how such the mega project was achieved during the 20 years period and it was estimated that about 2.3 million blocks were contained so that over 12 blocks in average had to be moved into place each hour day and night and fit them together with extremely high precision during the construction period (Petrie, 1883). Only the granite beam that support the roof of the burial chamber would require a workforce of several hundreds to hack them from the quarry for 10 years. The organizer had to designate teams to work in quarries in sufficient time to ensure the beams were available when required. Even though there is no evidence to verify how the project was managed but the organizers must have an appreciation of scheduling to accomplish the works.

Origins of Modern scheduling tools could be traced to 1765. At that time, the first timeline charts which was named as Chart of Biography was created by Joseph Priestley (1733-1804), which was used to visualize and compare the life spans of persons. Wiliam Playfair (1759 –1823) was inspired by the timelines and invented the bar chart in his T*he Commercial and Political Atlas* which was published in 1786. This would be the first bar chart in history (Beniger & Robyn, 1978).

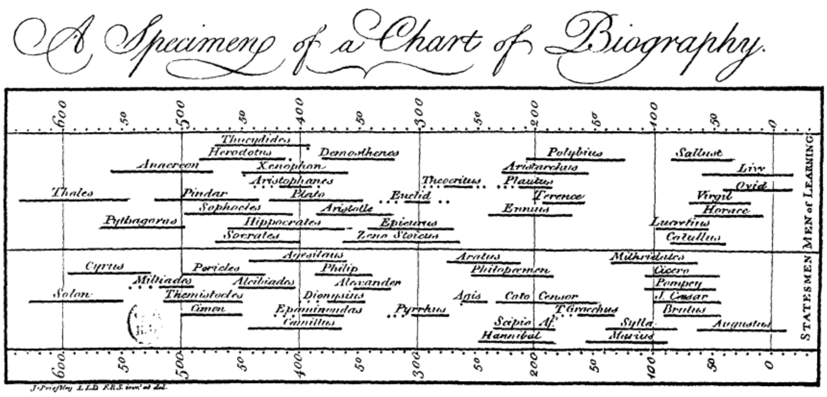


Figure 2.1 Joseph Priestley: A Chart of Biography

Source: https://en.wikipedia.org/wiki/William_Playfair

The bar chart developed by Playfair that published in 1786, showing in Figure 2.2, presented the Scotland's imports and exports to 17 countries from 1780 to 1781. It could be used for discrete measurement to solve the problem of discrete quantitative comparison but didn't indicate the data either in space or time. Additionally, 43 time-series plots that contained in the publication besides the bar chart had been created as well.

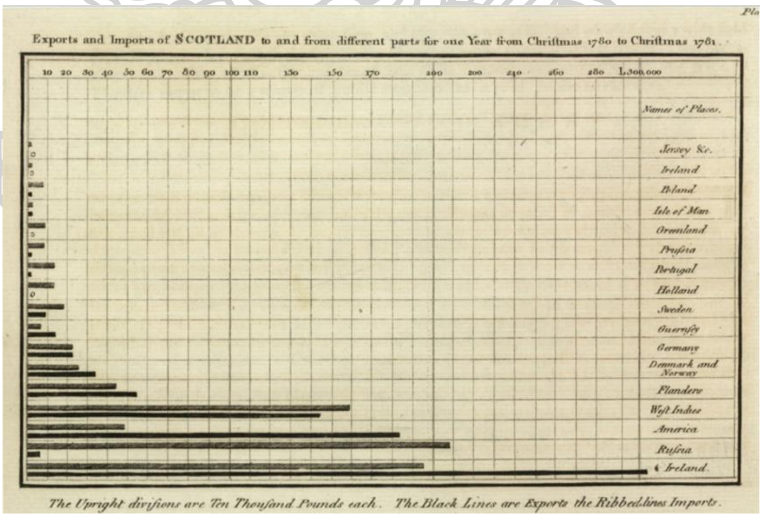


Figure 2.2 Exports and imports of Scotland to from different part for one Year from Christmas 1780 to Christmas 1781

Source: https://en.wikipedia.org/wiki/William_Playfair.

Dozens of years later after Wiliam Playfair, Karol Adamiecki, and another prominent management researcher in Europe, invented a means of displaying interdependent processes to enhance the visibility of production schedules in 1986 and in 1931 he develop his diagram known as the harmonogram or harmonograf. With minor modifications of Adamiechi's chart, Henry Gantt popularized a similar method around the years 1910 – 1915 which is quite familiar with as Gantt Chart (Morris, 1994). Gantt Charts were picked up by United States during World War I which would be the first major application in history (Clark, 1923).

Meanwhile, other techniques at the early part of the 20th century had been developed including Line of Balance (flow line) that used on the Empire State Building in the 1930s and Milestone Charts that regularly used by the 1950s.

Between 1940 and 1943, Dupont developed the precursors of Critical Path and put it into practice for the success of the Manhattan Project (Thayer, 1996). In the late 1950s, Morgan R. Walker of Dupont and James E. Kelley Jr of Remington Rand developed a project modeling algorithms for scheduling methodology based on the Activity-on-Arrow or Arrow Diagramming Method (ADM) which was named as Critical Path Method (CPM for short) afterwards (Kelley & Walker, 1959) . At the same time, Booz Allen Hamilton and the U.S. Navy developed Program Evaluation and Review Technique that known as PERT (Newell & Grashina, 2003). This technology was developed for the U.S. Navy Special Projects Office in 1957 to support the U.S. Navy's Polaris nuclear submarine project and it could simplify the planning and scheduling of large and complicated projects. Initially PERT is short for Program Evaluation Research Task and until renamed as Program Evaluation and Review Technique in 1959 (Malcolm, 1959). The main concepts of the PERT were described in details in The American Statistician published in 1959. After that, hundreds of publications on PERT and CPM were published between 1958 and 1968. Especially, the WBS (short for Work Breakdown Structural) approach was introduced in the publication for the PERT/COST system in 1962, which is developed by United States Department of Defense (DoD) National Aeronautics and Space Administration (NASA for short) and aerospace industry (*DOD and NASA Guide*). Furthermore, Milestone was incorporated in the application of PERT and CPM which could be an important reference for evaluating the progress of construction.

The key problem with milestones and bar charts is all of the dates and durations are based on heuristics (rules of thumb) and/or experience. It was possible to identify slippage, but any assessment of the impact of a delay was based on a personal view of the data rather than analysis. The key value contributed by CPM and PERT systems was the ability to model future outcomes based on progress to date and optimize the use of scarce resources.

However, the evolution of CPM scheduling closely tracked the development of computers. At that period, computers were not popularized because the system was a quite complex mainframe like behemoths and it would be months for a new scheduler to learn to use it, so most of the people working for scheduling have to draw on papers. For example, at early time, Gantt charts were drawn on paper and had to be redrawn entirely in order to adjust to schedule changes so that pieces of paper or blocks for Gantt chart bars had to be used as needed for the adjustments (Flouris, 2016).

In order to provide a non-computer alternative to CPM, the Precedence Diagramming Method (PDM) was developed in 1961, and the Metra Potential Method (MPM) was developed independently in Europe. Arguably, the evolution of modern project management is a direct consequence of the need to make effective use of the data generated by the schedulers in an attempt to manage and control the critical path.

With the development and popularization of computer in the following dozens of years, especially in the late 1980s, scheduling evolved into PC-based for project controls because of the advent of the micro-computer. And several scheduling software were developed for project scheduling management as well based on PERT and CPM methodologies.

In 1997, Eliyahu M. Goldratt's introduced the idea of Critical Chain Method (CCM) based on the Theory of Constrains (TOC) which application had been credited with achieving projects 10% to 50% faster and/or cheaper than PERT/CPM (StandishGroup).

In the period of 2002 – 2004, Event Chain Methodology was proposed and was applied in a number software (Virine, 2013). This methodology was based on the Monte Carlo simulation but the duration and cost for uncertainty tasks were defined by statistical distribution (Vose, 2008). By this methodology, results of analysis could be more accuracy using the statistical distribution that summarized with historical data about duration and cost from similar tasks in previous projects.

Time-Distance Diagram, known as March Chart as well, as a tool of Linear scheduling method for linear project like pipeline, had been applied for scheduling management successfully for pipeline project in 2012 (ZHANG Luming, 2012). Such the tool was originally applied in the aviation industry or scientific research to present the effects in respect to distance over time, and it could perfectly show all visible activities along construction site on an single diagram (CHORLEY, 1964). Based on this tool, the diagram could be drawn in MS Excel, AutoCAD, etc. Furthermore, a software called Tilos, short for Time Location Solution, was developed by Future Network Develop (FND) company which could provide a integrity solution for linear project.

In the following sections, details of the Methodologies for scheduling management will be reviewed, including theories, methods and tools.

2.2 Critical Path Method-CPM

As mentioned in section 2.1, the critical path method (CPM) is a project modeling algorithm for scheduling methodology based on the Activity-on-Arrow or Arrow Diagramming Method (ADM). In this method, all activities of the project will be linked logically in accordance with the sequence of the processes, and the duration of each activity will be estimated. Hence, the minimum total project duration could be calculated. Additionally, one project would be composed by many project activities and for each activity, the earliest possible start date and finish date in the project as well as the total float could be calculated as per the schedule model of CPM. In the Model, the means of a forward pass is applied to calculate the early start and early finish dates from a specific project date and the means of a backward pass is applied to determine the late start and late finish date as per the early finish date of the project that calculated by the forward pass calculation or a specific finish date.

In a pure CPM network, the total float should be zero or positive without various enhancement and it is a basic principle of CPM that each activity can start after its predecessors will be finished. Nowadays, the term CPM refers to the prevalent method used in modern scheduling tools. A brief review on CPM features will be introduced in the following sections.

2.2.1 Components

The essential technique for using CPM is to construct a model of the project that includes the following (Santiago & Magallon, 2009):

1. A list of all activities required to complete the project (typically categorized within a work breakdown structure),
2. The time (duration) that each activity will take to complete,
3. The dependencies between the activities and,
4. Logical end points such as milestones or deliverable items.

Using these values, CPM calculates the longest path of planned activities to logical end points or to the end of the project, and the earliest and latest that each activity can start and finish without making the project longer. This process determines which activities are "critical" (i.e., on the longest path) and which have "total float" (i.e., can be delayed without making the project longer). In project management, a critical path is the sequence of project network activities which add up to the longest overall duration, regardless if that longest duration has float or not. This determines the shortest time possible to complete the project. There can be 'total float' (unused time) within the critical path. For example, if a project is testing a solar panel and task 'B' requires 'sunrise', there could be a scheduling constraint on the testing activity so that it would not start until the scheduled time for sunrise. This might insert dead time (total float) into the schedule on the activities on that path prior to the sunrise due to needing to wait for this event. This path, with the constraint-generated total float would actually make the path longer, with total float being part of the shortest possible duration for the overall project. In other words, individual tasks on the critical path prior to the constraint might be able to be delayed without elongating the critical path; this is the 'total float' of that task. However, the time added to the project duration by the constraint is actually critical path drag, the amount by which the project's duration is extended by each critical path activity and constraint.

A project can have several, parallel, near critical paths; and some or all of the tasks could have 'free float' and/or 'total float'. An additional parallel path through the network with the total durations shorter than the critical path is called a sub-critical or non-critical path. Activities on sub-critical paths have no drag, as they are not extending the project's duration.

CPM analysis tools allow a user to select a logical end point in a project and quickly identify its longest series of dependent activities (its longest path). These tools can display the critical path (and near critical path activities if desired) as a cascading waterfall that flows from the project's start (or current status date) to the selected logical end point.

2.2.2 Visual Network of CPM

A network diagram can be created by hand or by using diagram software. There are two types of network diagrams, activity on arrow (AOA) and activity on node (AON). Activity on node diagrams are generally easier to create and interpret which shown in Figure 2.3 as an example. An AON diagram is to start with a node named start which "activity" has a duration of zero (0). Each activity could be linked with an arrow from start to each node. Since there are no activities that come after all activities, a node labeled finish is recommended (but again not required) to connect at the end.

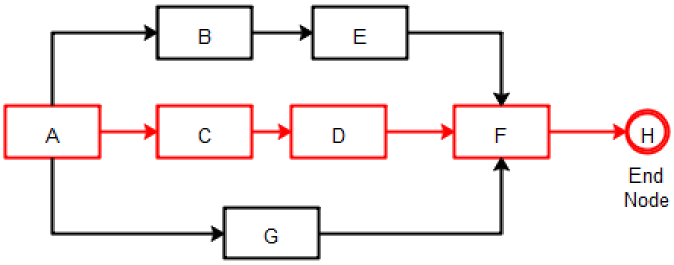


Figure 2.3 Activity-on-node diagram

A node could be used to display more information like activity name, estimated duration, early start time, early finish time, late start time, late finish time, total float or slack, etc. which shown in Figure 2.4.

Early Start	Activity: Duration	Early Finish
Late Start	Total Float	Late Finish

Figure 2.4 Elements in AOA Node

Activity-on-node diagram showing critical path schedule, along with total float and critical path drag computations. The results of CPM allow managers to prioritize activities for the effective management of project, and to shorten the planned critical path of a project by pruning critical path activities, by "fast tracking" (i.e., performing more activities in parallel), and/or by "crashing the critical path" (i.e., shortening the durations of critical path activities by adding resources).

Critical path drag analysis has also been used to optimize schedules in processes outside of strict project-oriented contexts, such as to increase manufacturing throughput by using the technique and metrics to identify and alleviate delaying factors and thus reduce assembly lead time (Sedore, 2014).

2.2.3 Crash duration

Crash duration is a term referring to the shortest possible time for which an activity can be scheduled (C. Hendrickson, Hendrickson, & Au, 1989). It can be achieved by shifting more resources towards the completion of that activity, resulting in decreased time spent and often a reduced quality of work, as the premium is set on speed (Brook, 1975). Crash duration is typically modeled as a linear relationship between cost and activity duration; however, in many cases a convex function or a step function is more applicable (C. T. Hendrickson & Janson, 1984).

2.2.4 CPM Application and Constrains

Since project schedules change on a regular basis, CPM allows continuous monitoring of the schedule, which allows the project manager to track the critical activities, and alerts the project manager to the possibility that non-critical activities may be delayed beyond their total float, thus creating a new critical path and delaying project completion. In addition, the method can easily incorporate the concepts of stochastic predictions, using the program evaluation and review technique (PERT) and event chain methodology. Currently, the CPM method of scheduling is used by most project management software is based on a manual calculation approach, and there are several software solutions available in industry.

However, the critical path method considered only logical dependencies between terminal elements. Since then, it has been expanded to allow for the inclusion of resources related to each activity, through processes called activity-based resource assignments and resource leveling. A resource-leveled schedule may include delays due to resource bottlenecks (i.e., unavailability of a resource at the required time), and may cause a previously shorter path to become the longest or most "resource critical" path.

Furthermore, a schedule generated using the critical path techniques often is not realized precisely, as estimations are used to calculate times: if one mistake is made, the results of the analysis may change. This could cause an upset in the implementation of a project if the estimates are blindly believed, and if changes are not addressed promptly. However, the structure of critical path analysis is such that the variance from the original schedule caused by any change can be measured, and its impact either ameliorated or adjusted for. Indeed, an important element of project postmortem analysis is the as-built critical path (ABCP), which analyzes the specific causes and impacts of changes between the planned schedule and eventual schedule as actually implemented.

2.3 Program Evaluation and Review Technique-PERT

While similar in principle to CPM, the program evaluation and review technique (PERT) is focused on activity duration. PERT allows for random activity duration and weights the activity-estimated duration on the range of duration estimates provided by stakeholders. Further development of estimating techniques is provided in the Practice Standard for Project Estimating.

2.3.1 Duration Estimation Based on PERT

PERT has defined four types of duration required to accomplish an activity:

- Optimistic duration is the minimum activity duration under the most favorable conditions; this assuming everything proceeds better than is normally expected
- pessimistic duration is the maximum possible time required to accomplish an activity and it assuming everything goes wrong (but excluding major catastrophes).
- most likely duration is the activity duration that will occur most often and it is the best estimate of the time required to accomplish an activity, assuming everything proceeds as normal.
- expected duration: the best estimate of the time required to accomplish an activity, accounting for the fact that things don't always proceed as normal (the implication being that the expected time is the average time the task would require if the task were repeated on a number of occasions over an extended period of time).

Starting with a network diagram created based on CPM, PERT allows activity duration estimates to be determined with the uncertainty contained in the duration estimating process. Three duration estimates are required for estimation of each activity duration:

$$D_{PERT} = \frac{D_{Op} + 4 \times D_{ML} + D_{Pes}}{6} \quad (2.1)$$

Where:

D_{PERT} is Activity duration calculated per PERT;

D_{Op} stands for Optimistic duration;

D_{ML} stands for Most likely duration;

D_{Pes} stands for Pessimistic duration.

The durations determined by the previous equation are used in the PERT diagram as activity-estimated durations. Generally, durations are established at a specific statistical level of significance (for example, 95% confidence level). The weighting in the equation was a manual approximation of the statistical distribution. With more sophisticated calculations, mostly using computers, an implementation of statistical or multiple simulations PERT (SPERT) is possible, approaching the methods and results of Monte Carlo analysis. Sometime, standard deviation of time may be referred as well in PERT method which is the variability of the time for accomplishing an activity (σ_{te}). Where:

$$\sigma_{te} = (D_{Pes} - D_{Op})/6 \quad (2.2)$$

2.3.2 Advantages and Disadvantages of PERT

The scheduling of project activities could be done easily with the application of the PERT method by the project manager and to show the critical path in a well-defined manner. So the advantages of PERT could be summarized as below:

- PERT chart explicitly defines and makes visible dependencies (precedence relationships) between the work breakdown structure (commonly WBS) elements.
- PERT facilitates identification of the critical path and makes this visible.
- PERT facilitates identification of early start, late start, and slack for each activity.
- PERT provides for potentially reduced project duration due to better understanding of dependencies leading to improved overlapping of activities and tasks where feasible.
- The large amount of project data can be organized and presented in diagram for use in decision making.
- PERT can provide a probability of completing before a given time.

However, there are also some disadvantages of PERT which was summarized as below:

- There can be potentially hundreds or thousands of activities and individual dependency relationships.
- PERT is not easily scalable for smaller projects.
- The network charts tend to be large and unwieldy, requiring several pages to print and requiring specially sized paper.
- The lack of a timeframe on most PERT/CPM charts makes it harder to show status, although colours can help, e.g., specific colour for completed nodes.

2.3.3 Constrains of PERT Application

During project execution, however, a real-life project will never execute exactly as it was planned due to uncertainty. This can be due to ambiguity resulting from subjective estimates that are prone to human errors or can be the result of variability arising from unexpected events or risks. The main reason that PERT may provide inaccurate information about the project completion time is due to this schedule uncertainty. This inaccuracy may be large enough to render such estimates as not helpful.

One possible method to maximize solution robustness is to include safety in the baseline schedule in order to absorb the anticipated disruptions. This is called proactive scheduling. A pure proactive scheduling is a utopia; incorporating safety in a baseline schedule which allows for every possible disruption would lead to a baseline schedule with a very large make-span. A second approach, termed reactive scheduling, consists of defining a procedure to react to disruptions that cannot be absorbed by the baseline schedule.

2.4 Project Diagram Method-PDM

The original concept of CPM was a computerized modeling process using the activity-on-arrow style of diagramming. The precedence diagramming method (PDM) was introduced a few years later as a “noncomputerized approach to scheduling” offering a cleaner, easier to follow, graphical representation of the network; it depicted the activities involved in a project as boxes or nodes, and introduced enhanced logical relationships (in addition to finish-to-start) and the use of leads and lags. The resulting output is a precedence diagram, also known as project network diagram. The PDM approach to CPM was quickly computerized, and modern scheduling tools place the activities on nodes with arrows linking activities; activity nodes may contain information about duration, cost, resources, and constraints. The addition of multiple project calendars and project-specific constraints further complicate the CPM calculations and the analysis of the network. Today’s computerized scheduling applications make it much easier to deal with these factors during the schedule model calculation. The end result is that for most projects, the critical path is no longer a zero float path, as was present in early CPM. The resulting output is a precedence diagram, also known as project network diagrams. The PDM places activities on nodes with arrows linking activities; activity nodes may contain information about duration, cost, resources, and constraints. PDM takes fewer nodes than ADM to describe the same set of project data. Although the addition of multiple calendars and constraints further complicate the forward and backward pass calculations and the network analysis of the PDM network, today's computerized scheduling applications complete the additional calculations without problems. In most projects the critical path is no longer a zero float path, as it was in early CPM.

Precedence diagrams illustrate the relationships between activities left to right (time-phased), allowing project activities to flow from a project start milestone to the project complete milestone. Relationships between time-phased activities are represented by directional arrows. The logical relationships need to be satisfied.

To establish a meaningful critical path, it is necessary to develop a logic-based network of activities with empirically derived durations for execution in a realistic and practical manner. Open ends in a schedule are those activities that lack a predecessor and/or a successor activity, thereby creating a hole or gap in the schedule logic from project start to finish. The only open ends that should be expected are the project start and project finish milestones. The use of constraints, including leads and lags, should be restricted to those conditions that cannot be adequately defined and modeled by the application of activity logic.

In PDM, an activity can be connected from either its start or its finish. This allows a start-to-finish logic presentation with no need to break the work down further. Another characteristic of PDM diagrams is the use of lead and lag components.

2.5 Critical Chain Method-CCM

Since the critical path method considered only logical dependencies between terminal elements, the critical chain method was introduced into scheduling management, which attempts to protect activity and project durations from unforeseen delays due to resource constraints. it has been expanded to allow for the inclusion of resources related to each activity through processes called activity-based resource assignments and resource leveling.

The idea of Critical Chain Method (CCM) was introduced based on the Theory of Constrains (TOC). Resource availability competes with the ability to execute tasks on the planned dates. As such, many software programs allow resources to be leveled (so that they are not over tasked); this may stretch the project duration and scheduled start and finish dates for activities. The resultant schedule model, considering the availability of resources, is often called a resource constrained critical path and it is the starting point for critical chain scheduling. The critical chain method is developed from the CPM approach and considers the effects of resource allocation, resource leveling, and activity duration uncertainty on the CPM-determined critical path.

2.5.1 Theory of constraints - TOC

The theory of constraints (TOC), initiated by Goldratt, is a management paradigm that views any manageable system as being limited in achieving more of its goals by a very small number of constraints. The theory, sometimes referred to as 'constraint management', is a large body of knowledge with a strong guiding philosophy of growth, and there is a network of individuals and small companies loosely coupled as practitioners around the world.

There is always at least one constraint, and TOC uses a focusing process to identify the constraint and restructure the rest of the organization around it. A constraint is anything that prevents the system from achieving its goal. There are many ways that constraints can show up, but a core principle within TOC is that there are not tens or hundreds of constraints. There is at least one, but at most only a few in any given system. Constraints can be internal or external to the system. An internal constraint is in evidence when the market demands more from the system than it can deliver. If this is the case, then the focus of the organization should be on discovering that constraint and following the five focusing steps to open it up (and potentially remove it). An external constraint exists when the system can produce more than the market will bear. If this is the case, then the organization should focus on mechanisms to create more demand for its products or services. Types of (internal) constraints would be as below:

- Equipment: The way equipment is currently used limits the ability of the system to produce more salable goods/services.
- People: Lack of skilled people limits the system. Mental models held by people can cause behaviour that becomes a constraint.
- Policy: A written or unwritten policy prevents the system from making more.

In TOC, the constraint is used as a focusing mechanism for management of the system. Organizations have many problems with equipment, people, policies, etc. and They are the limiting factor that is preventing the organization from getting more throughput even when nothing goes wrong.

The thinking processes of TOC are a set of tools like the current reality tree (CRT) and future reality tree (FRT) to help managers walk through the steps of initiating and implementing a project (Vidal, 2008). When used in a logical flow, they help walk through a buy-in process:

1. Gain agreement on the problem
2. Gain agreement on the direction for a solution
3. Gain agreement that the solution solves the problem
4. Agree to overcome any potential negative ramifications
5. Agree to overcome any obstacles to implementation

Despite its origins as a manufacturing approach (Eliyahu M Goldratt & Cox, 2016), Goldratt's Theory of Constraints (TOC) methodology is now regarded as a systems methodology with strong foundations in the hard sciences. The thinking processes helped identify and manage constraints and guide continuous improvement and change in organizations (Schragenheim & Dettmer, 2000).

The process of change requires the identification and acceptance of core issues, the goal and the means to the goal. This comprehensive set of logical tools can be used for exploration, solution development and solution implementation for individuals, groups or organizations. While CRT (current reality tree) represents the undesirable effects of the current situation, the FRT (the future reality tree), NBR (negative branch) help people plan and understand the possible results of their actions. The PRT (prerequisite tree) and TRT (transition tree) are designed to build collective buy in and aid in the Implementation phase. The logical constructs of these tools or diagrams are the necessary condition logic, the sufficient cause logic and the strict logic rules that are used to validate cause-effect relationships which are modelled with these tools (Schragenheim, Dettmer, & Patterson, 2009).

A summary of these tools, the questions they help answer and the associated logical constructs used is presented in Table 2.1.

Table 2.1 Questions for associated constructs

Area	Sufficient thinking “If....... then”	Necessary Thinking “In order to...we must”
What to change	Current Reality Tree	
What to change to	Future Reality Tree Negative Branch Reservations	Evaporating cloud
How to change	Transition Tree	Prerequisite Tree

Source: https://www.vectorconsulting.in/blog/systems-thinking-innovation/theory–of-constraints-and-the-thinking-process/

2.5.2 Application of TOC

Four primary types of plants are introduced in the TOC Theory. They specify the general flow of materials through a system, and also provide some hints about where to look for typical problems. This type of analysis is known as VATI analysis as it uses the bottom-up shapes of the letters V, A, T, and I to describe the types of plants (Blackstone, 2013). The four types can be combined in many ways in larger facilities, e.g. "an A plant feeding a V plant".

- V-plant: The general flow of material is one-to-many, such as a plant that takes one raw material and can make many final products. Classic examples are meat rendering plants or a steel manufacturer. The primary problem in V-plants is "robbing," where one operation (A) immediately after a diverging point "steals" materials meant for the other operation (B). Once the material has been processed by A, it cannot come back and be run through B without significant rework.
- A-plant: The general flow of material is many-to-one, such as in a plant where many sub-assemblies converge for a final assembly. The primary problem in A-plants is in synchronizing the converging lines so that each supplies the final assembly point at the right time.

- T-plant: The general flow is that of an I-plant (or has multiple lines), which then splits into many assemblies (many-to-many). Most manufactured parts are used in multiple assemblies and nearly all assemblies use multiple parts. Customized devices, such as computers, are good examples. T-plants suffer from both synchronization problems of A-plants (parts aren't all available for an assembly) and the robbing problems of V-plants (one assembly steals parts that could have been used in another).
- I-plant: Material flows in a sequence, such as in an assembly line. The primary work is done in a straight sequence of events (one-to-one). The constraint is the slowest operation.

From the above list, one can deduce that for non-material systems one could draw the flow of work or the flow of processes, instead of physical flows, and arrive at similar basic V, A, T, or I structure. A project, for example, is an A-shaped sequence of work, culminating in a delivered product.

The key assumptions of TOC is that organizations can be measured and controlled by variations on three measures: throughput, operational expense, and inventory. Inventory is all the money that the system has invested in purchasing things which it intends to sell. Operational expense is all the money the system spends in order to turn inventory into throughput. Throughput is the rate at which the system generates money through sales. Before the goal itself can be reached, necessary conditions must first be met (Eliyahu M Goldratt, 1990).

The argument by reduction to absurdity is as follows: If there was nothing preventing a system from achieving higher throughput (i.e., more goal units in a unit of time), its throughput would be infinite — which is impossible in a real-life system. Only by increasing flow through the constraint can overall throughput be increased (Eliyahu M Goldratt & Cox, 2016).

Assuming the goal of a system has been articulated and its measurements defined, the continuous improvement method to increase throughput in any system of value creation should follow the following five steps:

1. Identify the system's constraint(s).
2. Decide how to exploit the system's constraint to optimize it.
3. Subordinate everything else that are non-constraints to the above decision.
4. Alleviate the system's constraint(s).
5. If in the previous steps a constraint's throughput capacity is elevated to the point where it is no longer the system's limiting factor, means that a constraint has been broken, the limiting factor is now some other part of the system or may be external to the system, then start back from the beginning, and do not let inertia cause a system's constraint (Eliyahu M Goldratt & Cox, 2016).

The goal of a commercial organization is: "Make more money now and in the future" (Cox III & Schleier, 2010), and its measurements are given by throughput accounting as: throughput, inventory, and operating expenses. The five focusing steps aim to ensure ongoing improvement efforts are centered on the organization's constraint(s). This is referred to as the process of ongoing improvement (POOGI).

The focusing steps of POOGI have been applied in the fields of operations, High-speed automated production lines, Supply chain and logistics, finance and accounting, project management, and marketing and sales.

TOC was introduced into Project Management as Critical Chain Method which is based on the idea that all projects look like A-plants: all activities converge to a final deliverable. As such, to protect the project, there must be internal buffers to protect synchronization points and a final project buffer to protect the overall project (Eliyahu M. Goldratt, 1997).

2.5.3 Methodology of CCM

With traditional project management methods, lost time and wasteful resources are typically caused by such as student syndrome, Parkinson's law, and lack of prioritization. If the resources are available in limited quantities, then the CCM would be an alternative to CPM. In a project plan, the critical chain is the sequence of both precedence-dependent and resource-dependent tasks that prevents a project from being completed in a shorter time, given finite resources. The basic steps of CCM for project management could be summarized in Figure 2.5 as below.

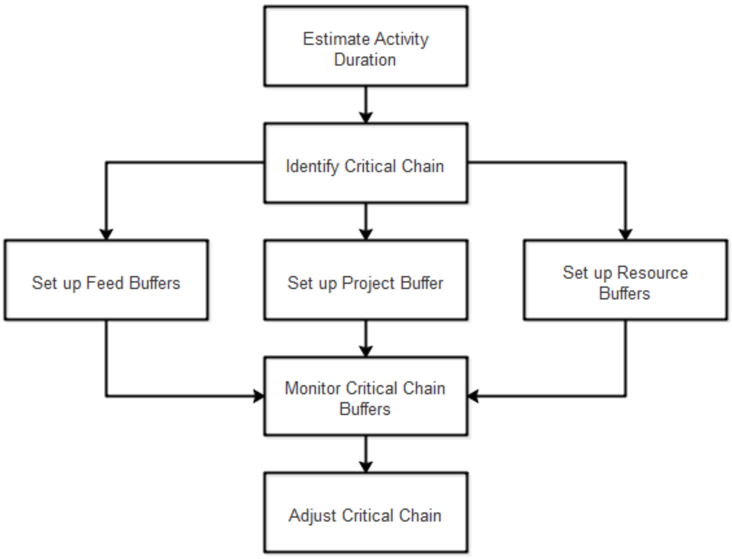


Figure 2.5 The Basic Steps of Critical Chain Method

In order to develop a scheduling model for schedule management, a project plan or work breakdown structure (WBS) should be created in much the same fashion as with critical path.

Step 1 Estimate Activity Durations

A duration is assigned to each task. Some software implementations add a second duration: one a "best guess," or 50% probability duration, and a second "safe" duration, which should have higher probability of completion (perhaps 90% or 95%, depending on the amount of risk that the organization can accept). Other software implementations go through the duration estimate of every task and remove a fixed percentage to be aggregated into the buffers.

Step 2 Identify Critical Chain

Resources are assigned to each task, and the plan is resource leveled, using the aggressive durations. The longest sequence of resource-leveled tasks that lead from beginning to end of the project is then identified as the critical chain. The justification for using the 50% estimates is that half of the tasks will finish early and half will finish late, so that the variance over the course of the project should be zero.

Step 3 Set up Buffers

Recognizing that tasks are more likely to take more time than less time due to Parkinson's law, Student syndrome, or other reasons, CCM uses "buffers" to monitor project schedule and financial performance. The "extra" duration of each task on the critical chain—the difference between the "safe" durations and the 50% durations—is gathered in a buffer at the end of the project. In the same way, buffers are gathered at the end of each sequence of tasks that feed into the critical chain. The date at the end of the project buffer is given to external stakeholders as the delivery date. Finally, a baseline is established, which enables financial monitoring of the project.

Buffers are used throughout the theory of constraints. They often result as part of the exploit and subordinate steps of the five focusing steps which stated in section 2.5.1. Buffers are placed before the governing constraint, thus ensuring that the constraint is never starved. Buffers are also placed behind the constraint to prevent downstream failure from blocking the constraint's output. Buffers used in this way protect the constraint from variations in the rest of the system and should allow for normal variation of processing time and the occasional upset (Murphy) before and behind the constraint.

Buffers can be a bank of physical objects before a work center, waiting to be processed by that work center. Buffers ultimately buy you time, as in the time before work reaches the constraint and are often verbalized as time buffers. There should always be enough (but not excessive) work in the time queue before the constraint and adequate offloading space behind the constraint.

Buffers are not the small queue of work that sits before every work center in a Kanban system although it is similar if you regard the assembly line as the governing constraint. A prerequisite in the theory is that with one constraint in the system, all other parts of the system must have sufficient capacity to keep up with the work at the constraint and to catch up if time was lost. In a balanced line, as espoused by Kanban, when one work center goes down for a period longer than the buffer allows, then the entire system must wait until that work center is restored. In a TOC system, the only situation where work is in danger is if the constraint is unable to process (either due to malfunction, sickness or a "hole" in the buffer – if something goes wrong that the time buffer cannot protect). Therefore, three types of buffers that were introduced into CCM are feeding buffers, resource buffers, and project buffers:

Feeding Buffers. A buffer (in duration) added to the schedule model at the merge of non-critical paths with the project critical path from the CPM.

Resource Buffers. The frequent passing of forecast finish dates to a predecessor activity alerting the resources of the successor activity to be prepared to start work on the forecast finish date of the predecessor activity.

Project Buffers. A duration added to the end of the project between the last project activity and the final delivery date or contracted completion date.

Buffers are statistically determined and aggregated safety margins assigned to individual chains of activities. Buffers are created by assigning aggressive activity realization times to remove any hidden safety margins and aggregating the resulting savings of planned times into buffers. Instead of spreading the safety margins among all activities, the safety margin is concentrated at the end of a chain and used only if risk (whatever it may be, resulting in resource and duration uncertainties) materializes. This effect is similar to managing the total float and free float in the CPM method.

Step 4 Monitor Critical Chain Buffers

There are many ways to apply buffers, but the most often used is a visual system of designating the buffer in three colors: green (okay), yellow (caution) and red (action required). Creating this kind of visibility enables the system as a whole to align and thus subordinate to the need of the constraint in a holistic manner. This can also be done daily in a central operations room that is accessible to everybody.

Step 5 Adjust Critical Chain

With the concept of the process of ongoing improvement (POOGI) in TOC theory, CCM also aims to ensure ongoing improvement efforts on the organization's constraint(s). If in the previous steps a constraint has been broken, then go back to the beginning. This may refer to resource-leveling, logical link adjustment and new technology applications etc. One example of CCM shown in Figure 2.6.

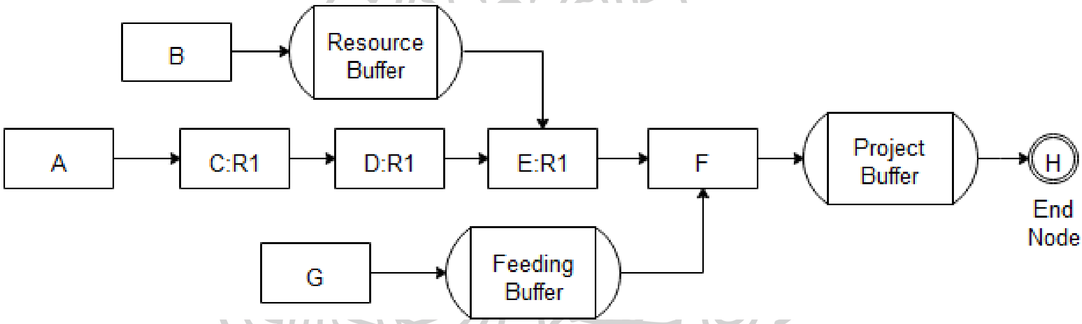


Figure 2.6 Example of CCM

2.5.4 Scheduling management on CCM

When the scheduling model was developed and the project is ready to start, the project network is fixed and the buffers' sizes are "locked" (i.e., their planned duration may not be altered during the project), because they are used to monitor project schedule and financial performance.

With no slack in the duration of individual tasks, resources are encouraged to focus on the task at hand to complete it and hand it off to the next person or group. The objective here is to eliminate bad multitasking. This is done by providing priority information to all resources. The literature draws an analogy with a relay race. Each element on the project is encouraged to move as quickly as they can: when they are running their "leg" of the project, they should be focused on completing the assigned task as quickly as possible, with minimization of distractions and multitasking. In some case studies, actual batons are reportedly hung by the desks of people when they are working on critical chain tasks so that others know not to interrupt. The goal, here, is to overcome the tendency to delay work or to do extra work when there seems to be time. The CCM literature contrasts this with "traditional" project management that monitors task start and completion dates. CCM encourages people to move as quickly as possible, regardless of dates.

The task duration has been planned at the 50% probability duration, there is pressure on resources to complete critical chain tasks as quickly as possible, overcoming student's syndrome and Parkinson's Law. The buffers were created during the planning stage.

A fever chart or similar graph can be created and posted to show the consumption of buffer as a function of project completion. If the rate of buffer consumption is low, the project is on target. If the rate of consumption is such that there is likely to be little or no buffer at the end of the project, then corrective actions or recovery plans must be developed to recover the loss. When the buffer consumption rate exceeds some critical value (roughly: the rate where all of the buffer may be expected to be consumed before the end of the project, resulting in late completion), then those alternative plans need to be implemented.

Within manufacturing operations and operations management, as an example, the solution seeks to pull materials through the system, rather than push them into the system. The primary methodology used for scheduling monitor is drum-buffer-rope (DBR) (E. F. Goldratt, Robert 1996) and a variation called simplified drum-buffer-rope (S-DBR) (Schragenheim & Dettmer, 2000).

Drum-buffer-rope is a manufacturing execution methodology based on the fact the output of a system can only be the same as the output at the constraint of the system. Any attempt to produce more than what the constraint can process just leads to excess inventory piling up (E. F. Goldratt, Robert 1996). The method is named for its three components. The drum is the rate at which the physical constraint of the plant can work: the work center or machine or operation that limits the ability of the entire system to produce more. The rest of the plant follows the beat of the drum. Schedule at the drum decides what the system should produce, in what sequence to produce and how much to produce (E. F. Goldratt, Robert 1996). They make sure the drum has work and that anything the drum has processed does not get wasted.

The buffer protects the drum, so that it always has work flowing to it. Buffers in DBR provide the additional lead time beyond the required set up and process times, for materials in the product flow. Since these buffers have time as their unit of measure, rather than quantity of material, this makes the priority system operate strictly based on the time an order is expected to be at the drum. Each work order will have a remaining buffer status that can be calculated. Based on this buffer status, work orders can be color coded into Red, Yellow and Green. The red orders have the highest priority and must be worked on first, since they have penetrated most into their buffers followed by yellow and green. As time evolves, this buffer status might change and the color assigned to the particular work order change with it (Eliyahu M Goldratt & Cox, 2016).

Traditional DBR usually calls for buffers at several points in the system: the constraint, synchronization points and at shipping. S-DBR has a buffer at shipping and manages the flow of work across the drum through a load planning mechanism (Schragenheim et al., 2009).

The rope is the work release mechanism for the plant. Orders are released to the shop floor at one "buffer time" before they are due to be processed by the constraint. In other words, if the buffer is 5 days, the order is released 5 days before it is due at the constraint. Putting work into the system earlier than this buffer time is likely to generate too-high work-in-process and slow down the entire system (Russell & Fry, 1997).

2.6 Event Chain Methodology

Event chain methodology is a network analysis technique that is focused on identifying and managing events and relationship between them (event chains) that affect project schedules. Event chain methodology is an extension of traditional Monte Carlo simulation of project schedules where uncertainties in task duration and costs are defined by statistical distribution (Hillson, David, Simon, & Peter, 2013). It is the next advance beyond critical path method and critical chain project management (Virine & Trumper, 2008). Event chain methodology helps to mitigate the effect of motivational and cognitive biases in estimating and scheduling. It improves accuracy of risk assessment and helps to generate more realistic risk adjusted project schedules (Virine, 2013).

Defining uncertainties using statistical distribution provide accurate results if there is a reliable historical data about duration and cost of similar tasks in previous projects. Another approach is to define uncertainties using risk events or risk drivers, which can be assigned to different tasks or resources (Hulett, 2010). Information about probabilities and impact of such events is easier to elicit, which improves accuracy of analysis. Risks can be recorded in the Risk register.

An alternate duration-estimation methodology uses probability-based quantification of duration using Monte Carlo simulation. In 1999, a researcher applied simulation to assess the impact of risks associated with each component of project work breakdown structure on project duration, cost and performance. Using Monte Carlo simulation, the project manager can apply different probabilities for various risk factors that affect a project component. The probability of occurrence can vary from 0% to 100% chance of occurrence. The impact of risk is entered into the simulation model along with the probability of occurrence. The number of iterations of Monte Carlo simulation depend on the tolerance level of error and provide a density graph illustrating the overall probability of risk impact on project outcome.

Once events and event chains are defined, quantitative analysis using Monte

Carlo simulation can be performed to quantify the cumulative effect of the events (Avlijaš, 2019). Probabilities and impacts of risks assigned to activities are used as input data for Monte Carlo simulation of the project schedule (Williams, 2004). In most projects it is necessary to supplement the event-based variance with uncertainties as distributions related to duration, start time, cost, and other parameters.

In Event chain methodology, risk can not only affect schedule and cost, but also other parameters such as safety, security, performance, technology, quality, and other objectives. In other words, one event can belong to different categories (Agarwal & Virine, 2017). The result of the analysis would show risk exposure for different categories as well as integrated project risk score for all categories. This integrated project risk score is calculated based on relative weights for each risk category.

Chapter 3 Research Methodology and a Case Application

3.1 Overview

A gas pipeline project in Thailand was selected as an experimental case study. The total length of the proposed pipeline is about 120 km and 30” diameter gas pipes would be constructed together with a fiber optical cable for communication. Normally, the methods of pipeline installation include Horizontal Directional Drill (HDD) method, Bored (Pipe Jacking) and Open Cut In this Research. Technologies of CPM were applied for scheduling management to configure and arrange the resources accordingly. On the other hand, the durations of each activities were estimated based on the necessary time other than the PERT or other methods because it would be difficult to estimate the pessimistic duration if there is no adequate collected data for a new project. On the basis of the schedule, it was common problems that the required resources may be standby or unavailable for some activities which caused the related tasks be failed to execute as scheduled, so that the management had to adjust the schedule frequently to arrange the resources to mitigate the impact and the whole schedule had to be postponed for completion.

HDD crossing construction as one of most importance work breakdown packages which was considered as the critical package to affect the whole schedule of the project, so HDD crossing construction was taken an example to study the scheduling management under constrained resources based on Critical Chain Method.

HDD Crossing Method for pipeline construction is usually used for trenchless installation of pipeline from ground to ground surfaces for crossings of major river/canal/khong, highway, railway, environmental sensitive areas, urban environments and so on, including three main stages of Pilot hole, Reaming and product pipeline installation during construction period. It was estimated that about 22 HDD crossings with 30” diameter gas pipes and 6” diameter fiber casing would be constructed during construction per the requirement of project and the average length of crossings would be 500 meters.

3.2 Methodology

Scheduling model have to be created in order to analyze the scheduling system for scheduling management. The general procedures for scheduling in Figure 3.1 that have been popularized nowadays, as per proposed by PMI, would be applied in a pipeline project.

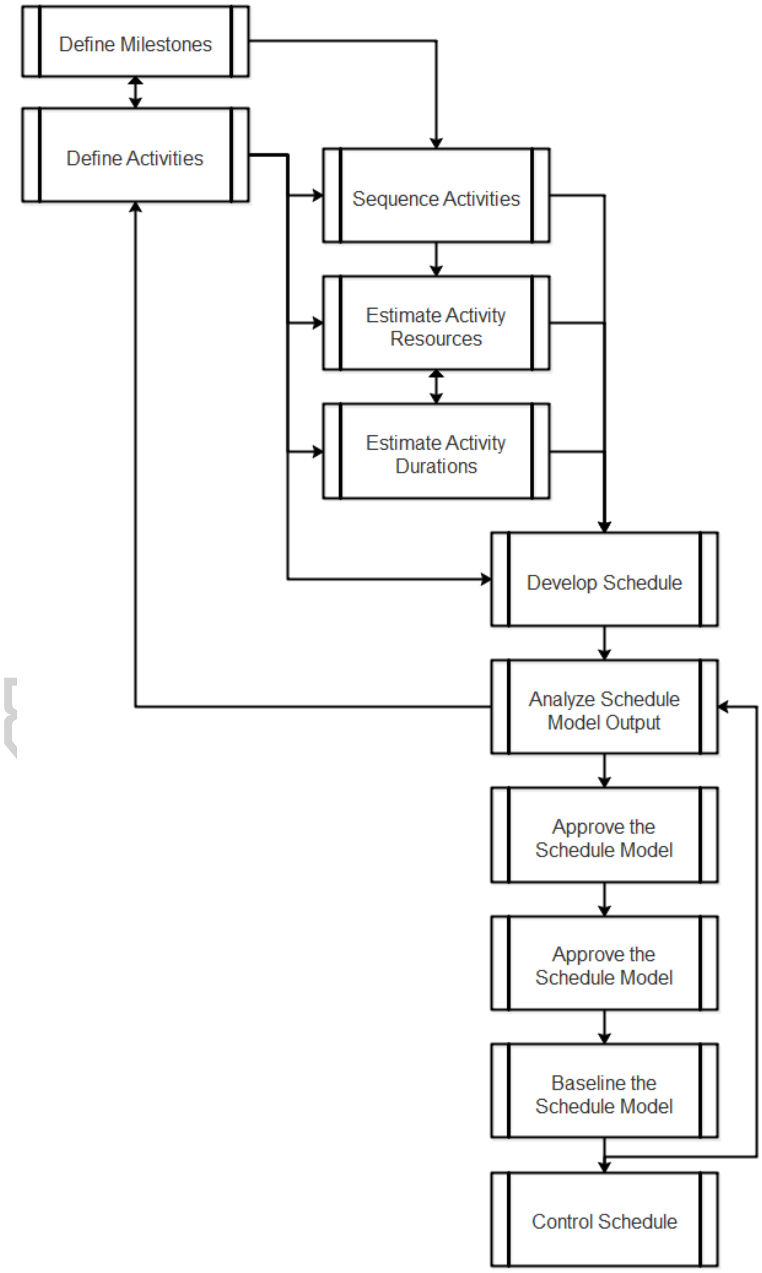


Figure 3.1 General Procedures for Scheduling in a Pipeline Project

Source: (Institute & Institute, 2011)

In order to establish the scheduling model for HDD crossing method, the general procedures have to be verified so that all activities could be sequenced logically. And the data of duration for each activity should be collected for distribution analysis.

For further analysis and discussion, the following principles should be considered for data collection during HDD crossing construction:

- Select one HDD crossing that would proceed as latest schedule in the whole project as the test subject, key information like required activities, logical relationship, actual durations etc. should be identified.
- Actual duration of each activity that recorded as per the actual work performance during construction, and data from ongoing HDD crossings performance would be collected and histogram data analysis would be applied for identify the distribution of the actual duration that spent for each activity.
- In accordance with the distribution of duration analysis, the duration of each activity for the selected test subject would be scheduled accordingly.
- All data should be converted into a typical usage as an example which should be comparable for further analysis of schedule performance.

An experiment was set up as per flowchart shown in Figure 3.2.

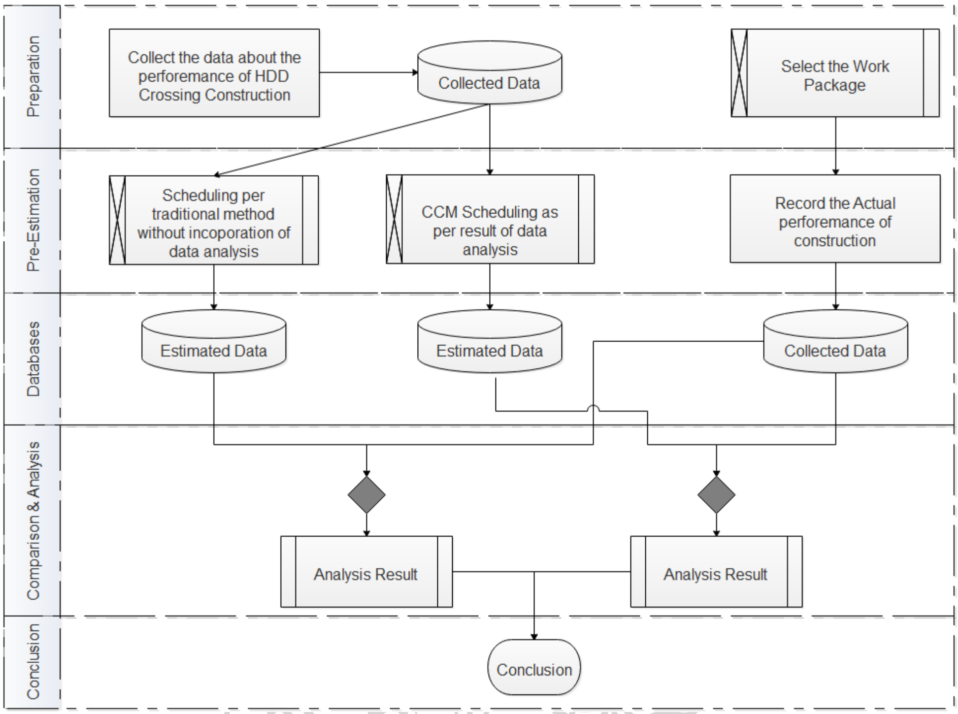


Figure 3.2 Research Design for Reliable Verification of the Data Analysis Method

The study of scheduling management in this thesis would follow the following step:

Step 1: Analyze the original CPM schedule on HDD crossing and develop a typical CPM schedule as the basis of the study.

Step 2: Collect all key information from the actual HDD crossing construction

Step 3: Analyze the performance on CPM schedule which was applied for scheduling management.

Step 4: Establish the scheduling model based on CCM theory

Step 5: Summarize the findings on application of CCM

Note: all standby or fast-tracking would be not considered for scheduling model establishment.

3.3 Original CPM Schedule Analysis

With the analysis of CPM schedule on HDD crossing method, 26 activities in general were identified that related pipe preparation, drilling and environment impact precautions. The details of the activities identified were listed below in Table 3.1. It was assumed that the HDD crossing for pipeline will commenced when Land was released for construction, so the Land Acquisition was set as Milestone of commencement of HDD construction.

Table 3.1 Identified Activities of HDD Construction Procedure

Code No.	Task Name	Task Type
A01	Land Acquisition	Milestone
A02	Site Entry Application and HDD Notification to Landowner	Activity
A03	Survey and Setting out	Activity
A04	Rig Access Construction	Activity
A05	Underground Service Conformation	Activity
A06	Pad Grading and Compaction	Activity
A07	Rig Mobilization and Installation	Activity
A08	Sheet Pile and Anchor Installation	Activity
A09	Exit Side Access Road, ROW Preparation,	Activity
A10	Pipe Stringing	Activity
A11	FOC Casing Welding	Activity
A12	Pipeline Welding and NDT and Hydrotest Header Installation	Activity
A13	Hydrotest-procedure	Activity
A14	Coating	Activity
A15	Guide Line Conformation	Activity
A16	Guide Line Set-up	Activity
A17	Drilling for FOC	Activity
A18	Pullback FOC Casing	Activity
A19	Reset Rig for mainline	Activity
A20	Drilling for Mainline pilot hole	Activity
A21	Reaming and Cleaning for Mainline	Activity
A22	Roller Set up and Walkdown Check up	Activity
A23	Mainline Pullback	Activity
A24	Current Drainage Test	Activity
A25	Embolization	Activity
A26	CR Notification to each Landowner for Land Release	Activity

In accordance with the guidance of scheduling that shown in Figure 3.1, All activities were sequenced and linked as per the logical relationship of work procedures and An Activity-on-node network diagram was establish which shown in Figure 3.3.

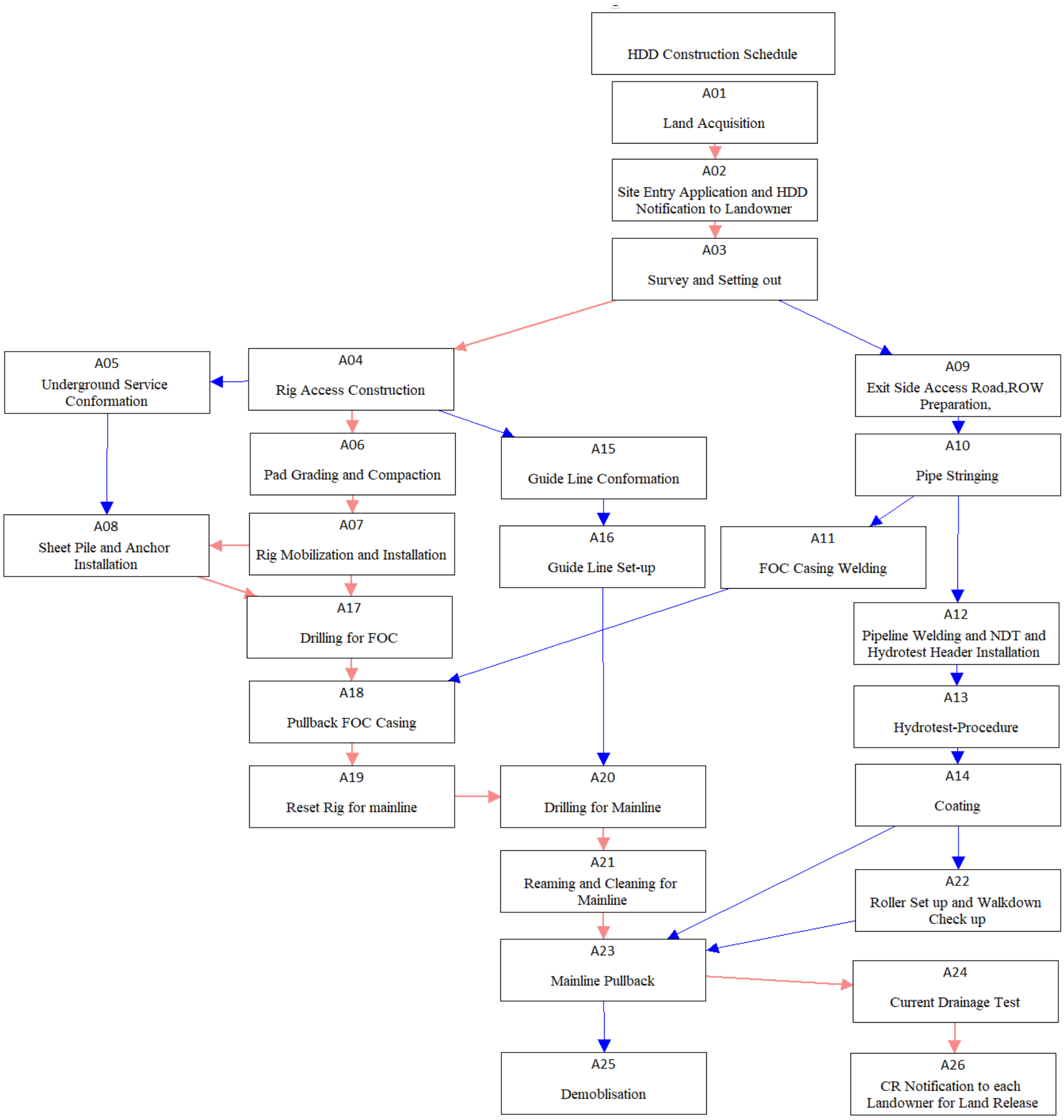


Figure 3.3 Activity-on-node network Diagram of HDD Crossing Construction

On the other hand, the durations of each activities were estimated based on the necessary time other than the PERT or other methods because it would be difficult to estimate the pessimistic duration if there is no adequate collected data for a new project. The details of estimated duration in CPM was listed in Table 3.2

Table 3.2 Estimation of Duration for each Activities of Selected Test Subject as per the practical experience

Code No.	Task Name	Estimated Duration
A01	Land Acquisition	1 day
A02	Site Entry Application and HDD Notification to Landowner	3 days
A03	Survey and Setting out	2 days
A04	Rig Access Construction	10 days
A05	Underground Service Conformation	3 days
A06	Pad Grading and Compaction	3 days
A07	Rig Mobilization and Installation	2 days
A08	Sheet Pile and Anchor Installation	3 days
A09	Exit Side Access Road, ROW Preparation,	4 days
A10	Pipe Stringing	2 days
A11	FOC Casing Welding	4 days
A12	Pipeline Welding and NDT and Hydrotest Header Installation	10 days
A13	Hydrotest-procedure	10 days
A14	Coating	5 days
A15	Guide Line Conformation	1 day
A16	Guide Line Set-up	2 days
A17	Drilling for FOC	2 days
A18	Pullback FOC Casing	1 day
A19	Reset Rig for mainline	1 day
A20	Drilling for Mainline pilot hole	2 days
A21	Reaming and Cleaning for Mainline	22 days
A22	Roller Set up and Walkdown Check up	2 days
A23	Mainline Pullback	1 day
A24	Current Drainage Test (CDT)	2 days
A25	Embolization	3 days
A26	CR Notification to each Landowner for Land Release	2 days

With the Activity-on-node network diagram shown in Figure and the estimated duration shown in Table 3.2, the CPM schedule for HDD crossing construction was established, which was used for scheduling management to configure and arrange the resources accordingly. And the critical path could be identified in the CPM.

In accordance with the CPM that was set up for HDD crossing construction, the total calendar duration is 55 days in average length of 500 meters from start date to finish date of the project, and details shown in Figure 3.4. The completion date would be Oct 15, 2019 as start date was set up as Aug 22, 2019

Task Name	Duration	Start	Finish
HDD Construction Schedule	55 days	8/22/2019	10/15/2019
A01	1 day	8/22/2019	8/22/2019
A02	3 days	8/23/2019	8/25/2019
A03	2 days	8/26/2019	8/27/2019
A04	10 days	8/28/2019	9/6/2019
A05	3 days	9/4/2019	9/6/2019
A06	3 days	9/4/2019	9/6/2019
A07	2 days	9/7/2019	9/8/2019
A08	3 days	9/7/2019	9/9/2019
A09	4 days	8/28/2019	8/31/2019
A10	2 days	9/1/2019	9/2/2019
A11	4 days	9/3/2019	9/6/2019
A12	10 days	9/5/2019	9/14/2019
A13	10 days	9/15/2019	9/24/2019
A14	5 days	9/25/2019	9/29/2019
A15	1 day	9/7/2019	9/7/2019
A16	2 days	9/8/2019	9/9/2019
A17	2 days	9/10/2019	9/11/2019
A18	1 day	9/12/2019	9/12/2019
A19	2 days	9/13/2019	9/14/2019
A20	2 days	9/15/2019	9/16/2019
A21	22 days	9/17/2019	10/8/2019
A22	2 days	10/5/2019	10/7/2019
A23	1 day	10/9/2019	10/9/2019
A24	2 days	10/12/2019	10/13/2019
A25	3 days	10/10/2019	10/12/2019
A26	2 days	10/14/2019	10/15/2019

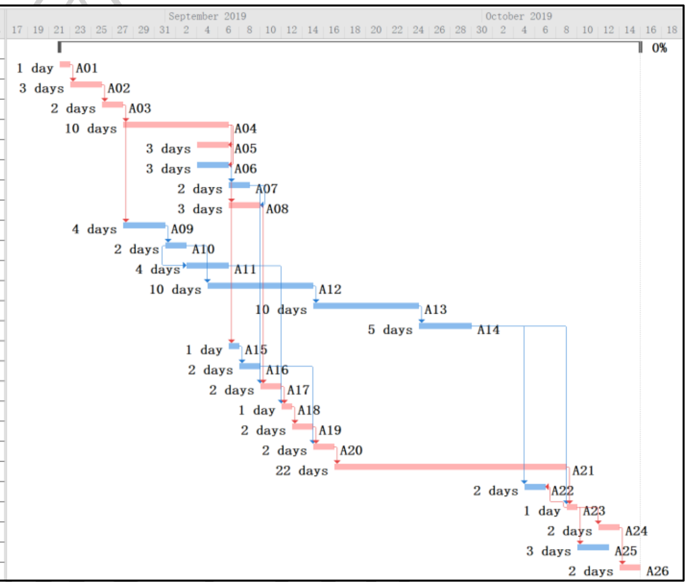


Figure 3.4 Schedule Model Instance Based on CPM

3.4 Scheduling Model Establishment and Performance Evaluation

During construction of the project, 19 HDD crossing work were monitored, and the durations were recorded for analysis. The length of HDD was considered which may impact the duration analysis. The length of each HDD crossing shown in Table 3.3.

Table 3.3 Length of Each HDD Crossing

HDD Or.	Qty	Unit	HDD Or.	Qty	Unit
1# HDD	334	meters	15# HDD	740	meters
2# HDD	420	meters	16# HDD	460	meters
3# HDD	338	meters	17# HDD	910	meters
4# HDD	950	meters	18# HDD	370	meters
5# HDD	550	meters	19# HDD	310	meters
6# HDD	709	meters	20# HDD	390	meters
7# HDD	333	meters	21# HDD	395	meters
10# HDD	471	meters	22# HDD	792	meters
12# HDD	587	meters	25# HDD	557	meters
14# HDD	365	meters	-	-	-

Among the duration collected for each activity, some of them would be depended on the length of HDD crossing, such as the activity of welding for pipeline, drilling and reaming, etc. so, the original duration couldn't be comparable for the work performance. In order to get a general performance evaluation for each activity, duration of these activities that affected according to length would be evaluated based on the rate of every 50 meters in length. These activities were identified and listed in Table 3.4.

Table 3.4 Category of Data Analysis for Each Activity

Code No.	Task Name	Original or Rate per 50meter
A01	Land Acquisition	Original
A02	Site Entry Application and HDD Notification to Landowner	Original
A03	Survey and Setting out	Original
A04	Rig Access Construction	Original
A05	Underground Service Conformation	Original
A06	Pad Grading and Compaction	Original
A07	Rig Mobilization and Installation	Original
A08	Sheet Pile and Anchor Installation	Original
A09	Exit Side Access Road, ROW Preparation,	Rate / 50m
A10	Pipe Stringing	Rate / 50m
A11	FOC Casing Welding	Rate / 50m
A12	Pipeline Welding and NDT and Hydrotest Header Installation	Rate / 50m
A13	Hydrotest-procedure	Original
A14	Coating	Rate / 50m
A15	Guide Line Conformation	Original
A16	Guide Line Set-up	Original
A17	Drilling for FOC	Rate / 50m
A18	Pullback FOC Casing	Original
A19	Reset Rig for mainline	Original
A20	Drilling for Mainline pilot hole	Rate / 50m
A21	Reaming and Cleaning for Mainline	Rate / 50m
A22	Roller Set up and Walkdown Check up	Original
A23	Mainline Pullback	Original
A24	Current Drainage Test (CDT)	Original
A25	Embolization	Original
A26	CR Notification to each Landowner for Land Release	Original

All durations of activities were collected from the 19 HDD crossing work and analysed by Histogram method. Except the activities with Code No. of A01, A05, A15, A16, A18, A25, A26 which durations were uniform, the distribution of the duration for each activity shown in Appendix A.

Among the duration collected for each activity, some of them would be relay on the length of HDD crossing, such as the activity of welding for pipeline, drilling and reaming, etc. So, the original duration couldn't be comparable for the work performance. In order to get a general performance evaluation for each activity, duration of these activities that affected according to length would be evaluated based on the rate of every 50 meters in length. The analysis will convert the length into a basis with the length of 500 meters and the start date was assumed as Aug 22, 2019.

All durations of activities that collected from the 19 HDD crossing work were analysed by Histogram method and it was found that the duration distribution of 20 activities would comply with triangle distribution that shown in Figure 3.5, and 6 of 26 activities would comply with the uniform distribution. In triangle distribution, the parameter 'a' was definded as the minimun value of the durations that collected, and parameter 'b' was defined as the maximum value of the collected duration for one activity. And parameter 'c' was the most likely value where the quantity of the data targeted the maximum points.

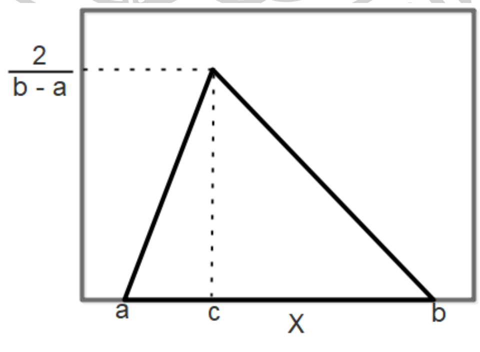


Figure 3.5 The plot of triangle distribution

As per the statistic distribution of duration of each activity, the Average value, standard deviation, maximum, minimum and most likely duration were calculated based on the collected data which shown in Table 3.5, in which all data was converted into a basis with the length of 500 meters.

Table 3.5 General Duration Analysis Based on the Collected Data

Code No.	Average Duration	Standard Deviation	Maximum Duration	Minimum Duration	Most Likely Duration
A01	1	0	1	1	1
A02	6.4	1.8	10	3	6
A03	2.2	0.4	3	2	2
A04	13.4	6.7	28	7	11
A05	3	0	3	3	3
A06	6.4	5.4	18	3	3
A07	5.1	3.1	14	2	5
A08	3.1	0.3	4	3	3
A09	7	4	14	2	5
A10	6	3	14	2	8
A11	5	2	10	2	6
A12	16	6	36	9	16
A13	9.2	1.9	14	5	11.75
A14	6	2	11	3	5
A15	1	0	1	1	1
A16	2	0	2	2	2
A17	4	3	12	1	3
A18	1	0	1	1	1
A19	2.5	0.9	5	1	2
A20	5	3	12	2	4
A21	15	6	37	8	15
A22	2.6	0.9	5	2	2
A23	1.9	0.3	2	1	2
A24	1.8	0.4	2	1	2
A25	3	0	3	3	3
A26	2	0	2	2	2

The software of Primavera Risk Analysis was applied for simulation with the functions of ‘triangle(a,b,c)’ and uniform(a, b). The function of ‘triangle(a,b,c)’ complies with the plot shown in Figure 3.5 and the formulation shown as below (Evans, Hastings, & Peacock, 2000).

$$triangle(a,b,c) = f(x|a,b,c) = \begin{cases} \frac{2(x-a)}{(b-a)(c-a)} & for\ \ a \leq x \leq c \\ \frac{2(b-x)}{(b-a)(b-c)} & for\ c < x \leq b \end{cases} \quad (3.1)$$

Where:

$a = \boldsymbol{D}_{Op}$;

$b = \boldsymbol{D}_{Pes}$;

$c = \boldsymbol{D}_{ML}$;

The duration uncertainty of each activity could be observed when the distribution functions were setup in Primavera Risk Analysis Software for simulation, which shown in Figure 3.6. The start date was assumed as Aug 22, 2019.

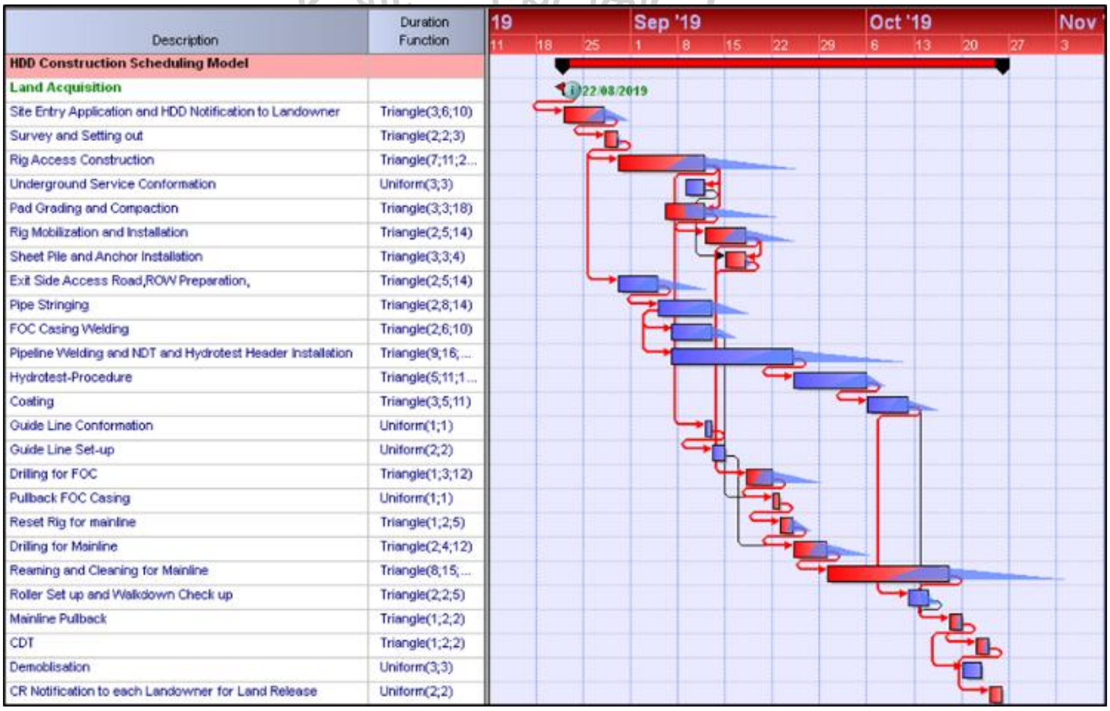


Figure 3.6 Distribution Function Setup for Simulation

The schedule model was analyzed for 500 iterations by using Latin Hypercube Sampling. The distribution graph would be available afterwards. The distribution of the date to complete the HDD crossing construction shown in Figure 3.7.

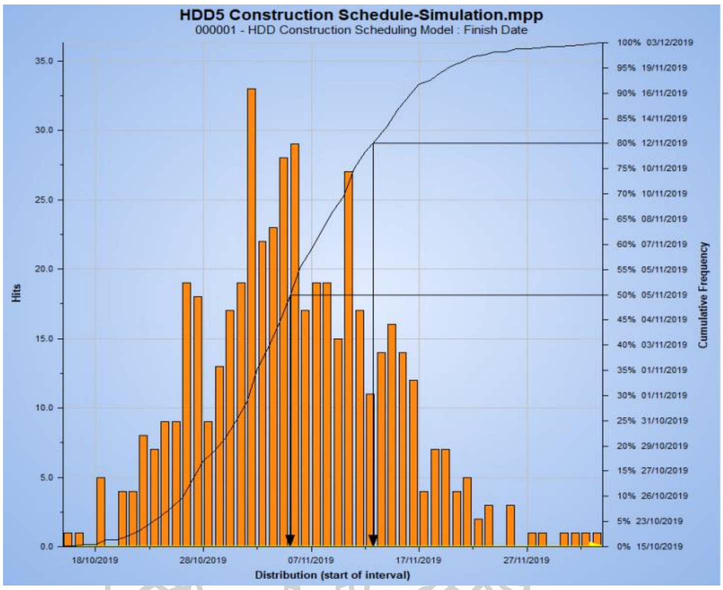


Figure 3.7 Completion date distribution of CPM Schedule

As per the result of simulation that shown in Figure 3.7, the probability to complete the crossing construction on Oct 15, 2019 is less than 1%, which means that it would be impossible to complete the construction on the target date that set in the original schedule. Hence, the new method of CCM was considered to apply for scheduling.

Chapter 4 Application of CCM

The key points to apply CCM is to identify the critical chain activities of HDD crossing construction; to find out the method for setting up buffers; to find out the method of monitoring the buffers during the execution of project.

4.1 Critical Chain Identification

In order to highlight the affects of resources, the usage of the resource was summarized and details shown in Table 4.1. Three activities should proceed in cooperation with two resources like activity Code No. A18, No.A23 and No.A25, for which the durations were 1 days, 2 days and 3 days in average.

Table 3.6 Summarized duration of resources for activities

Resources	Qty of Activity	Average Duration	Standard Deviation
Team Drilling	10	41	12
Team Civil	4	26	9
Team Welding	2	21	7
Team Pipeline	6	21	4
Team Hydrotesting	1	10	0
Team CR	3	9	2
Team Coating	1	5	2
Team Survey	1	2	0
Team Inspection	1	2	0
Total	29	137	

In accordance with the data in Table 4.1, it would be observed that Team Drilling should be responsible for 38% of 26 activities and the duration that spent accounted for 30% of all calendar duration. Hence, the resource would be the critical resource for HDD crossing construction and the activities related to this team should be scheduled in higher priority. All other activities should comply with the requirement of Team Drilling to proceed the construction smoothly. Hence, the feed buffers should be added for the cooperation activities with Team Drilling.

The team planner in Microsoft Project software was applied for adjusting the schedule for optimization, which would be the best tool till now for leveling the resources visually. The activities that proceeded by Team Drilling was scheduled in critical chain and the feed buffer and the resource buffer were added for the cooperation activities. Details shown in Figure 4.1.

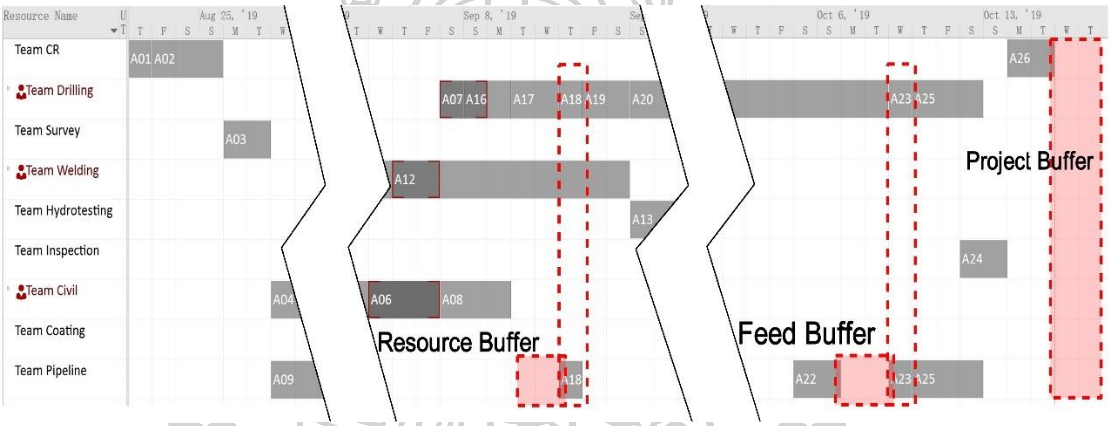


Figure 3.8 Identified critical chain and buffers

The resource buffer should be added for Team pipeline for activity Code No.A18, because the activity would be done by Team Drilling with the cooperation of Team Pipeline and shall mobilize the Team Pipeline timely to start the activity to avoid resource standby for Team Drilling. The activity Code No.23 need to proceed with the completion of the activity Code No.22 so that the feed buffer should be added after activity No.22 to avoid standby of activity Code No.23. The project buffer should be added at the end of all activities.

4.2 Calculation of Buffers

It would be the most important core technology of CCM to set up and calculate the buffers along the critical chain path. The buffers have been set up in section 3.2 and the main objects is to calculate the buffers which would be the best solution for resource arrangement. Long buffers may cause standby of other resources and on the contrary, short buffers may cause the delay of the whole schedule and standby of the constraint resources.

Buffer calculation on CCM normally refers to 50% probability duration. This method is to cut 50% of each task on the critical chain as the "safe" durations and gathered them in a buffer at the end of the project as well as at the end of each sequence of tasks that feed into the critical chain considering that tasks are more likely to take more time than less time due to Parkinson's law, Student syndrome, or other reasons when execute the tasks. This may be caused by concerns of cost of standby or waste of the resource. So, for management, the impact shall be mitigated so that most of the stakeholders could accept the arrangements.

I supposed a new method of buffers calculation incorporating with the concept of 50% probability duration and PERT to calculate the duration and buffers in this thesis in the basis of collected data for HDD crossing construction.

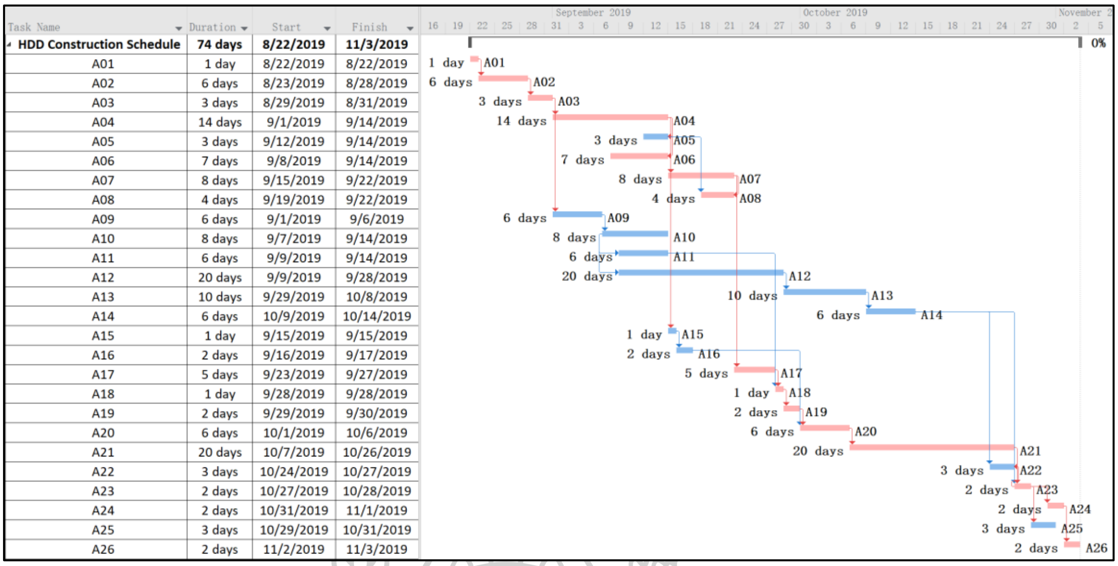
Firstly, the resource buffer in section 3.2 would be not necessary by assigning the task to Team Welding which is available on site with the equipment and manpower required to cooperate with Team Drilling to proceed the work.

Secondly, the durations of all activities would be calculated based on both PERT and 50% probability method. The estimated durations were listed in Table 4.2.

Table 3.7 Estimated durations on PERT and 50% probability

Code No.	*PERT Method*	*50% Probability*	*Deviation*
A01	1	1	0
A02	6	6	0
A03	2	3	1
A04	13	14	1
A05	3	3	0
A06	6	7	2
A07	6	8	2
A08	3	4	1
A09	6	6	0
A10	8	8	0
A11	6	6	0
A12	18	20	2
A13	11	10	-1
A14	6	6	0
A15	1	1	0
A16	2	2	0
A17	4	5	1
A18	1	1	0
A19	2	2	0
A20	5	6	1
A21	18	20	3
A22	3	3	1
A23	2	2	0
A24	2	2	0
A25	3	3	0
A26	2	2	0

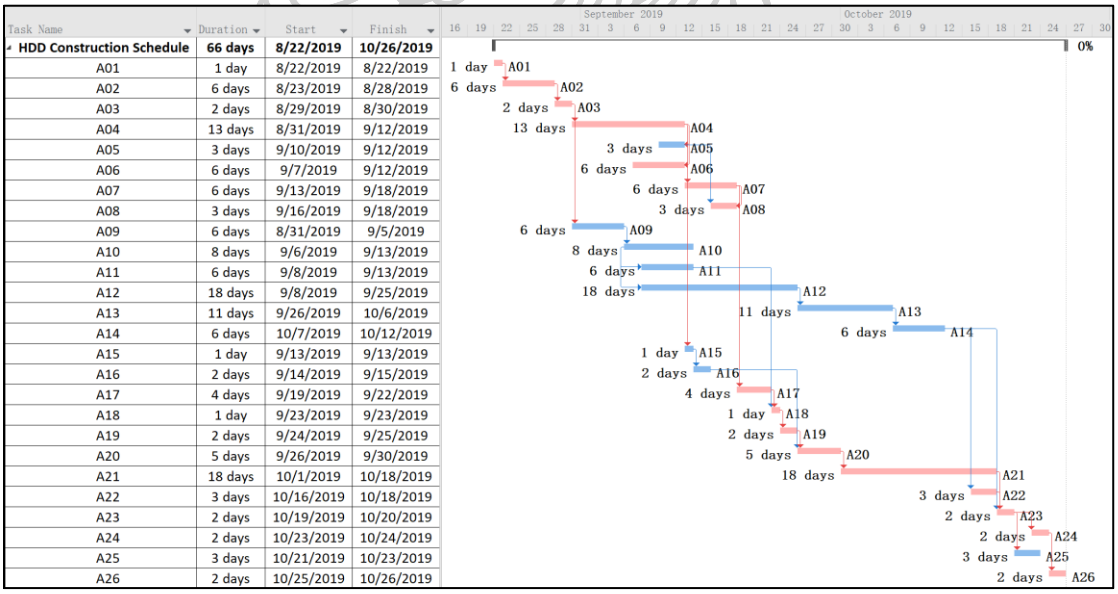
Thirdly, the scheduling model would be made based on 50% probability of deterministic as the major basis for guidance of construction which shown in Figure 4.2.



Task Name	Duration	Start	Finish
HDD Construction Schedule	74 days	8/22/2019	11/3/2019
A01	1 day	8/22/2019	8/22/2019
A02	6 days	8/23/2019	8/28/2019
A03	3 days	8/29/2019	8/31/2019
A04	14 days	9/1/2019	9/14/2019
A05	3 days	9/12/2019	9/14/2019
A06	7 days	9/8/2019	9/14/2019
A07	8 days	9/15/2019	9/22/2019
A08	4 days	9/19/2019	9/22/2019
A09	6 days	9/1/2019	9/6/2019
A10	8 days	9/7/2019	9/14/2019
A11	6 days	9/9/2019	9/14/2019
A12	20 days	9/9/2019	9/28/2019
A13	10 days	9/29/2019	10/8/2019
A14	6 days	10/9/2019	10/14/2019
A15	1 day	9/15/2019	9/15/2019
A16	2 days	9/16/2019	9/17/2019
A17	5 days	9/23/2019	9/27/2019
A18	1 day	9/28/2019	9/28/2019
A19	2 days	9/29/2019	9/30/2019
A20	6 days	10/1/2019	10/6/2019
A21	20 days	10/7/2019	10/26/2019
A22	3 days	10/24/2019	10/27/2019
A23	2 days	10/27/2019	10/28/2019
A24	2 days	10/31/2019	11/1/2019
A25	3 days	10/29/2019	10/31/2019
A26	2 days	11/2/2019	11/3/2019

Figure 3.9 Scheduling model based on 50% probability of deterministic

Fourthly, construction schedule would be made based on PERT method again which shown in Figure 4.3 to compare with the scheduling model and to find out the proper feed buffers for those cooperation activities.



Task Name	Duration	Start	Finish
HDD Construction Schedule	66 days	8/22/2019	10/26/2019
A01	1 day	8/22/2019	8/22/2019
A02	6 days	8/23/2019	8/28/2019
A03	2 days	8/29/2019	8/30/2019
A04	13 days	8/31/2019	9/12/2019
A05	3 days	9/10/2019	9/12/2019
A06	6 days	9/7/2019	9/12/2019
A07	6 days	9/13/2019	9/18/2019
A08	3 days	9/16/2019	9/18/2019
A09	6 days	8/31/2019	9/5/2019
A10	8 days	9/6/2019	9/13/2019
A11	6 days	9/8/2019	9/13/2019
A12	18 days	9/8/2019	9/25/2019
A13	11 days	9/26/2019	10/6/2019
A14	6 days	10/7/2019	10/12/2019
A15	1 day	9/13/2019	9/13/2019
A16	2 days	9/14/2019	9/15/2019
A17	4 days	9/19/2019	9/22/2019
A18	1 day	9/23/2019	9/23/2019
A19	2 days	9/24/2019	9/25/2019
A20	5 days	9/26/2019	9/30/2019
A21	18 days	10/1/2019	10/18/2019
A22	3 days	10/16/2019	10/18/2019
A23	2 days	10/19/2019	10/20/2019
A24	2 days	10/23/2019	10/24/2019
A25	3 days	10/21/2019	10/23/2019
A26	2 days	10/25/2019	10/26/2019

Figure 3.10 Schedule made based on PERT

Activity Code No. 22 should start on Oct 16, 2019 and finish on Oct 18, 2019 in the schedule in Figure 4.3. On the other hand, the activity Code No.21 in scheduling model in Figure 4.2 would finish on Oct 26, 2019 with 50% probability of

Deterministic to start the cooperation activity Code No.23. Hence, the feed buffer would be set up as 8 days for schedule monitor.

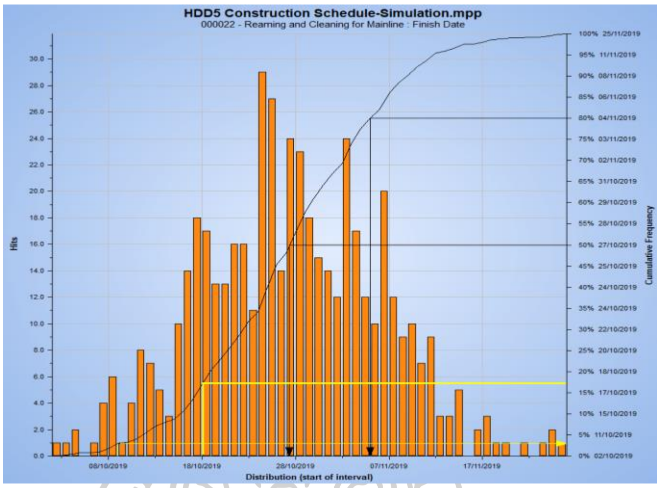


Figure 3.11 The distribution of finished date of activity Code No. A21

Furthermore, in accordance with the distribution of finished date of activity Code No. A21 which shown in Figure 4.4, the probability of finish date on Oct 18, 2019 should be 17% which accounts for 35% on basis of 50% deterministic probability.

As per the completion date distribution shown in Figure 3.7, 80% probability of Deterministic to complete the crossing construction would be on Nov 12, 2019 and it would be 90% probability to complete the whole work on Nov 16, 2019. Whereas， the completion date on basis of 50% deterministic probability in scheduling model in Figure 4.2 is on Nov 3, 2019, so the project buffer would be set up as 9 days per 80% or 13 days per 90% which would depend on the management budget for risk mitigation. Details of buffer calculation shown in Table 4.3.

Table 3.8 Buffers Calculation for Mainline Pullback

Butters Calculation Form		Feed Buffers	Project Buffers
		A21 Finish Date PERT Estimation	Completion Date 50% Probability
		10/18/2019	11/3/2019
A23 Start Date 50% Probability	10/26/2019	8	8
Completion Date 80% Probability	11/12/2019	17	9
Completion Date 90% Probability	11/16/2019	21	13

4.3 Buffer Monitor for Schedule Management

Since the buffers were set up for CCM, it would be necessary to set up the rules to supervise the buffers for scheduling management so that some precaution could be taken timely to mitigate the loss of time. Buffer tri-color diagram would be applied for management.

One buffer would be divided into three average parts with color of green, yellow and red which shown in Figure 4.5.

Figure 3.12 Buffer tri-color diagram

1) When the buffer reduced in green area, it means the activity with feed buffer should start if the team hasn't been mobilized.
2) When the buffer reduced in yellow area, it means the delay of the activity with feed buffer would impact the succeeding activities and need some actions to catch up the progress.

3) When the buffer reduced in red area, it means the delay of the activity with feed buffer would impact the project schedule and need to take actions to adjust the schedule or evaluate the impacts with risk analysis.

4.4 Discussion

With the application of CCM method, the performance was improved with the new scheduling model since it would be more practical than previous schedule model and the remaining HDD crossing could comply with the schedule. This would relieve the workload of management to adjust the schedule frequently to coordinate with the related resources and most of stakeholder from different teams would like to accept it and arrange the resource to work accordingly. Because the new scheduling model will mitigate the probability of team standby.

Even though the construction performance would be variance that impacted by the seasons in Thailand, HDD crossing construction would be the one that has less impact on rain or storm, so the established model would be reliable.

Furthermore, the scheduling model was established without consideration of actual idle time between two linked activities except necessary gaps or lags, because this was calculated in the concept of uncertainty which is treated as Murphy effect.

The key points to apply CCM for scheduling management is to identify the critical chain and set up buffers. The critical chain in this thesis was identified based on the usage of resources and duration and buffers were calculated based on the PERT and 50% probability method. However, there would be many methods to get the targets and the methods stated in this Thesis was specified for HDD crossing construction in a specific project, but it may be proper to be applied for other similar project as a reference.

It would be doubted that the new proposed scheduling model has longer duration than the original one which may not have the benefit to shorten the duration of the schedule, but it would be true that a reliable schedule model would bring more benefit than a shorten schedule which is not practical for resources arrangement. This would also reduce the necessary cost of standby and make better use of resources.

Chapter 5 Conclusions and Recommendations

Critical Chain Method as a new technology for scheduling management has been being developed recent years and it could be considered as a optimization of CPM. The buffer was the new concept incorporated by CCM which bring more benefit to relieve the workload of management and eliminate the affect of Parkinson's law or Student syndrome. With the application of CCM method, the work performance could be improved. In this case study, the full duration as per simulation is 104 days in accordance with the actual performance but it would be 74 days if based on the method of CCM hereby. So, the total duration would be shortened by 30%. Additionally, it was 50% probability to start Activity No.23 on Oct 27, and originally, pipeline team proceed the work from Oct 5 to 8, but with the proposal in this thesis, the team was proposed to proceed the work from Oct 16 to 18. So, 10 days were shortened for standby, which reducing by 50% and the cost of standby would be reduced by 50%. The Following aspects could be summarized as an conclusion of the application of CCM in this Thesis.

Firstly, ranking method based on the usage of resources was applied for identification of the critical chain activities of HDD crossing construction. Then, all these identified activities were scheduled in higher priority based on CPM.

Secondly, the Monte Carlo method that assembled Primavera Risk Analysis Software was applied for collected data analysis which was used to find out the distributions of all activity durations. In accordance with the result of the analysis, the evaluation of the proposed schedule could be done. Additionally, the buffers was calculated based on the variations of the results that calculated in the methods of PERT and simulation. The baseline of the proposed schedule was mainly set up as per the deterministic probabilities of the simulation.

Finally, the rules based on buffer tri-color diagram was set up to supervise the buffers for scheduling management so that some precaution could be taken timely to mitigate the loss of time.

Comparing with CPM, Critical Chain Method could solve the problem of such lost time and wasteful resources as that typically caused by such as student syndrome, Parkinson's law, and lack of prioritization. Hence, CCM would be an alternative to CPM in case that the resources are constrained. The methods proposed in this thesis had reduced the necessary cost of standby and make better use of resources during construction. The workload of management was relieved to adjust the schedule frequently for resources coordination and it could be accepted by most of stakeholder from different teams to mitigate the probability of team standby.

The core of the tools would be estimation of duration and buffer calculation for CPM and CCM which would be on the basis of historical information from previous project or activities. And Supervision of the buffers would be one of the important missions for scheduling management when the scheduling model was established.

Hence, some recommendations would be provided for reference for scheduling management as below:

1) Extra 'safe' duration may be considered at the beginning of the project before contract was awarded, like biding period since the stakeholders may concern the panelty for failure of the completion stated in the contract, this would be balanced by considering the management budget as a risk management.

2) Extra 'safe' duration would not be estimated during construction period since most of stakeholder make best usage of resource to bring more benefit from the project, on the contrary, they would like to estimate all the duration in the optimistic conditions and make assumptions for start of the activities, which could be the claims to contractors.

3) A practical scheduling model would be much better than a short one, so 50% probability duration method would not be suitable for all conditions, especially for the activities under construction. And proper durations and buffers have to be

calculated for scheduling model for management.

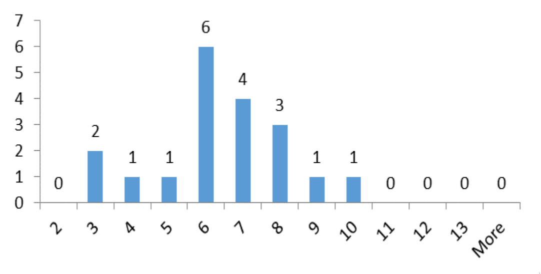
4) It would be necessary to establish a database for data collection regarding the duration spent in previous project which would be used for duration estimation and scheduling model analysis, this would make the established model more practical and efficient.

5) Supervision of buffers would be important, and the hierarchical management was highly recommended to be established with precaution of failure adjustment and mitigation responses.

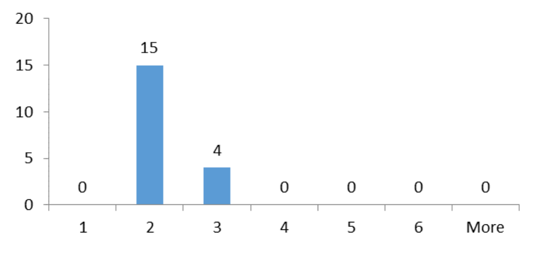
APPENDICES

Appendix A The Distribution of the Duration for Each Activity

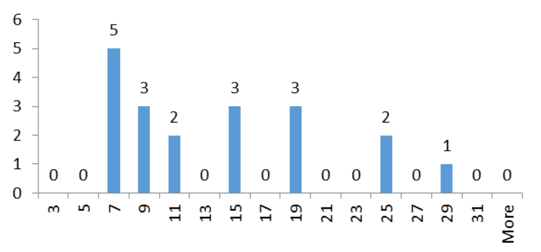
A02



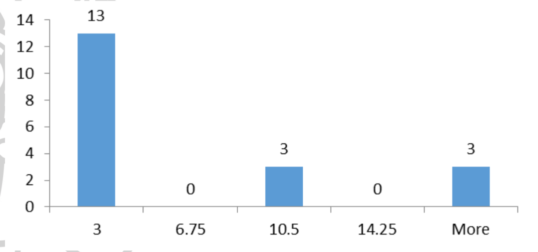
A03



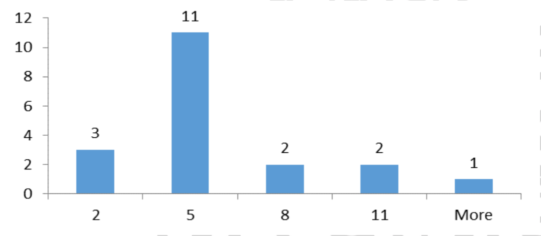
A04



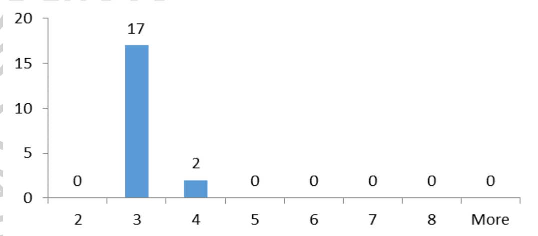
A06



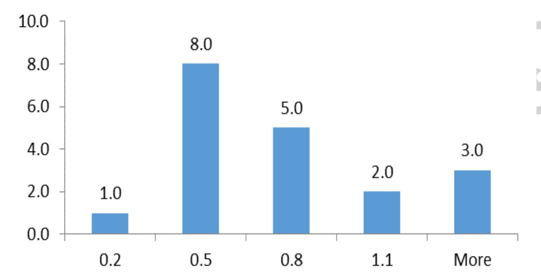
A07



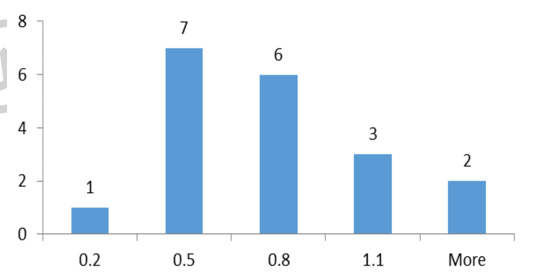
A08



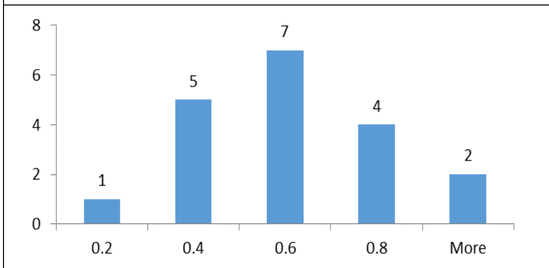
A09



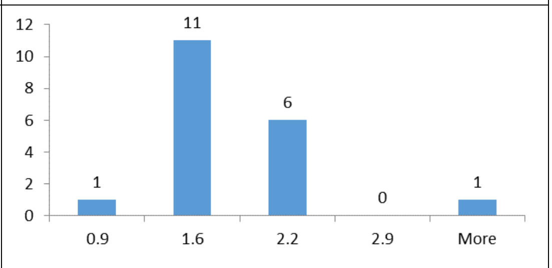
A10



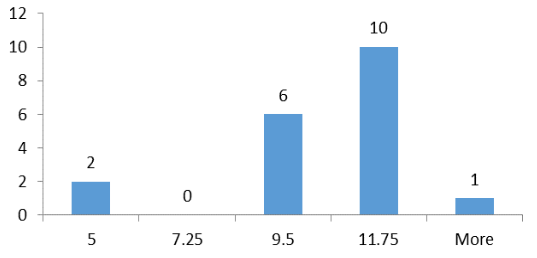
A11



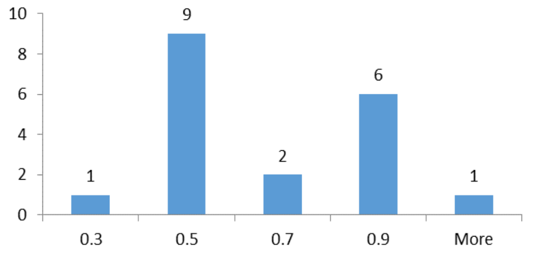
A12



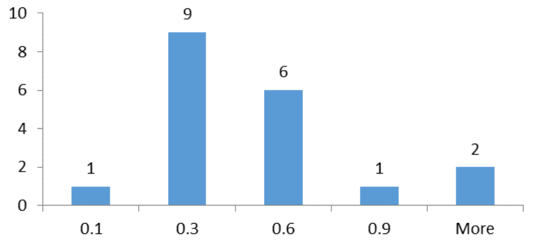
A13



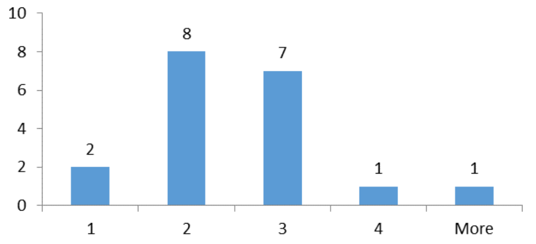
A14



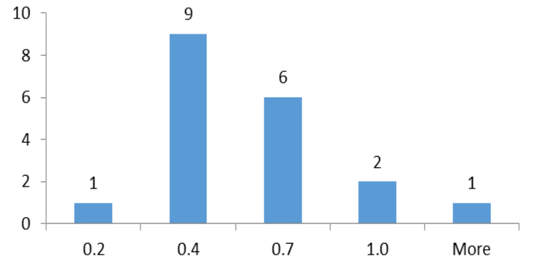
A17



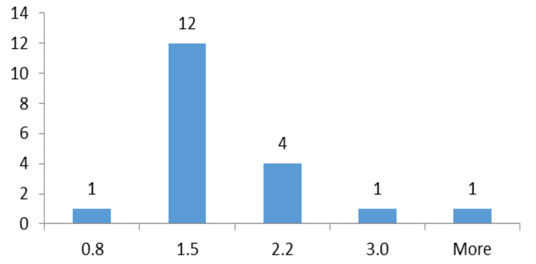
A19



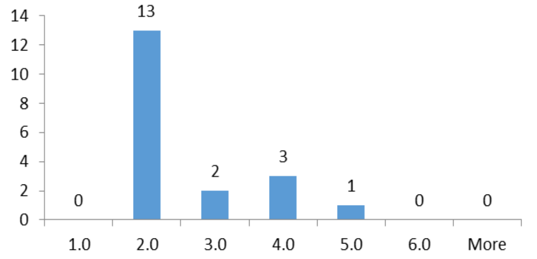
A20



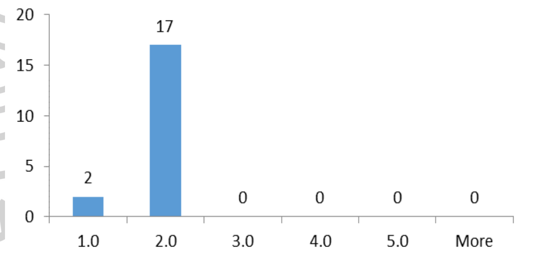
A21



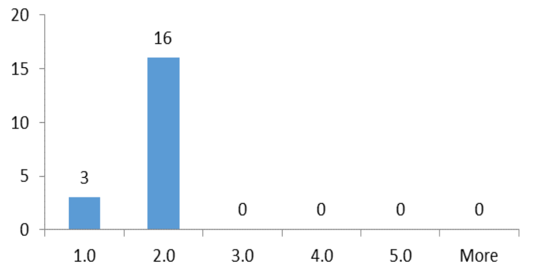
A22



A23



A24



/

/

REFERENCES

Agarwal, R., & Virine, L. (2017). *Monte Carlo Project Risk Analysis*.
Avlijaš, G. (2019). Examining the value of monte carlo simulation for project time management. *Management: Journal of Sustainable Business and Management Solutions in Emerging Economies, 24*(1), 11-23.
Baoli., Z. (2016). Practice on Development of Oversea Petroleum Pipeline. *Journal of Beijing Petroleum Managers Training Institute, 1*, 5.
Beniger, J. R., & Robyn, D. L. (1978). Quantitative Graphics in Statistics: A Brief History. *American Statistician, 32*(1), 1-11.
Blackstone, J. (2013). APICS Dictionary. The essential supply chain reference.[pdf] Chicago: APICS. In (13th ed., pp. 186). Chicago.
Brook, F. (1975). The mythical man-month: Essays on software engineering. *Reading, Mass: Addison-Weley*.
CHORLEY, R. (1964). Developments in engine instrument displays(Aircraft engine instrument display types in discussing ease of reading, accuracy, complexity and space). *AEROPLANE AND COMMERCIAL AVIATION NEWS, 108*, 20.
Clark, W. (1923). *The Gantt Chart: A Working Tool of Management*.
Cox III, J., & Schleier, J. (2010). *Theory of Constraints Handbook*: McGraw-Hill.
DOD and NASA Guide.
Evans, M., Hastings, N., & Peacock, B. (2000). Triangular distribution. *Statistical distributions, 3*, 187-188.
Flouris, T. G. L., Dennis (2016). *Managing Aviation Projects from Concept to Completion*: Ashgate Publishing.
Goldratt, E. F., Robert (1996). *The Race* (1 ed.). Croton-on-Hudson, New York: North River Press.
Goldratt, E. M. (1990). *Theory of constraints*: North River Croton-on-Hudson.
Goldratt, E. M. (1997). *Critical Chain*. Great Barrington, Massachusetts: North River Press.
Goldratt, E. M., & Cox, J. (2016). *The goal: a process of ongoing improvement*: Routledge.
Hendrickson, C., Hendrickson, C. T., & Au, T. (1989). *Project management for construction: Fundamental concepts for owners, engineers, architects, and builders*: Chris Hendrickson.
Hendrickson, C. T., & Janson, B. N. (1984). A common network flow formulation for several civil engineering problems. *Civil Engineering Systems, 1*(4), 195-203.
Hillson, David, Simon, & Peter. (2013). Practical Project Risk Management: The ATOM Methodology--Second Edition. *Pm Network*.
Hulett, D. (2010). *Integrated cost-schedule risk analysis*: Gower Publishing, Ltd.
Institute, P. M., & Institute, P. M. (2011). *Practice Standard for Scheduling*.
Kelley, J. E., & Walker, M. R. (1959). *[ACM Press Papers presented at the December 1-3, 1959, eastern joint IRE-AIEE-ACM computer conference - Boston, Massachusetts (1959.12.01-1959.12.03)] Papers presented at the December 1-3, 1959, eastern joint IRE-AIEE-ACM computer conference on - IRE-AIEE.* Paper presented at the Papers Presented at the December, Eastern Joint Ire-aiee-acm Computer Conference.
Lin Yan, e. a. (2017). The distribution status and development trend of global oil & gas

pipelines. *oil & gas storage & transportation, 36*, 6. doi:10.6047/j
Malcolm, D. G., J. H. Roseboom, C. E. Clark, W. Fazar. (1959). Application of a Technique for Research and Development Program Evaluation. *OPERATIONS RESEARCH, 7*. doi:10.1287/opre.7.5.646
Morris, P. W. G. (1994). *The Management of Projects*.
Newell, M., & Grashina, M. (2003). The Project Management Question and Answer Book.
Petrie, S. W. M. F. (1883). *The Pyramids and Temples of Gizeh*.
Quezhi, Z., Chao, W. , Qiuyang, L. , Xueqin, Z. , Libo, Z. , Shanpu, G. (2017). Development status and trend of global oil and gas pipelines. *oil & gas storage & transportation, 36*, 6. doi:10.6047/j
Quezhi, Z., Peixia, D. , Hongju, W. , Qiuyang, L. I. , Chuanxi, Z. , & Ning, S. , et al. (2015). Current situations and future development of oil and gas pipelines in the world. *oil & gas storage & transportation, 34*, 5. doi:10.6047/j
Russell, G. R., & Fry, T. D. (1997). Order review/release and lot splitting in drum-buffer-rope. *International Journal of Production Research, 35*(3), 827-845.
Santiago, J., & Magallon, D. (2009). Critical path method. *CEE320, Winter 2013*.
Schragenheim, E., & Dettmer, H. W. (2000). Simplified drum-buffer-rope: A whole system approach to high velocity manufacturing. *Goal Systems International*.
Schragenheim, E., Dettmer, H. W., & Patterson, J. W. (2009). *Supply chain management at warp speed: Integrating the system from end to end*: CRC Press.
Sedore, B. W. C. (2014). *Assembly lead time reduction in a semiconductor capital equipment plant through constraint based scheduling.* Massachusetts Institute of Technology,
StandishGroup. The standish group report chaos.
Thayer, H. (1996). Management of the Hanford Engineer Works in World War II, How the Corps, DuPont and the Metallurgical Laboratory fast tracked the original plutonium works. *oikos, 120*, 7. doi:10.1111/j.1600-0706.2010.18937.x
Vidal, C. (2008). The future of scientific simulations: from artificial life to artificial cosmogenesis. *arXiv preprint arXiv:0803.1087*, 285-318.
Virine, L. (2013, April 22–23,2013). *Integrated Qualitative and Quantitative Risk Analysis of Project Portfolios.* Paper presented at the Enterprise Risk Management Symposium, Chicago, IL.
Virine, L., & Trumper, M. (2008). Project Decisions: The Art and Science. *Project management journal, 39*(3), 127-127.
Vose, D. (2008). *Risk Analysis: A Quantitative Guide* (3rd ed.): Great Britain: Wiley.
Wang Jianzhong, L. F., Huang Shujun，Li Fubing，Huang Shujun, etc . . (2019). The Oil and gas cooperation progress and proposals of countries of the belt and road *China Mining Magazine, 28*, 7. doi:10.12075/j
Williams, T. (2004). Why Monte Carlo simulations of project networks can mislead. *Project management journal, 35*(3), 53-61.
ZHANG Luming, L. X., & WU Kuiyuan. (2012). Application of March Chart in Scheduling Management of Pipeline Project Planning. *Journal of Oil and Gas Technology, 34*(08X), 4.

VITA

NAME	Wei Yuqiang
DATE OF BIRTH	31 May 1983
PLACE OF BIRTH	Liaoning of China
INSTITUTIONS ATTENDED	Liaoning SHIHUA University
HOME ADDRESS	Langfang City, Hebei Province, China
PUBLICATION	Five articles and standards that have been published in oil & gas relevant magazines and industry’s codes in China
AWARD RECEIVED	Two findings prizes were awarded honored by China construction enterprises association